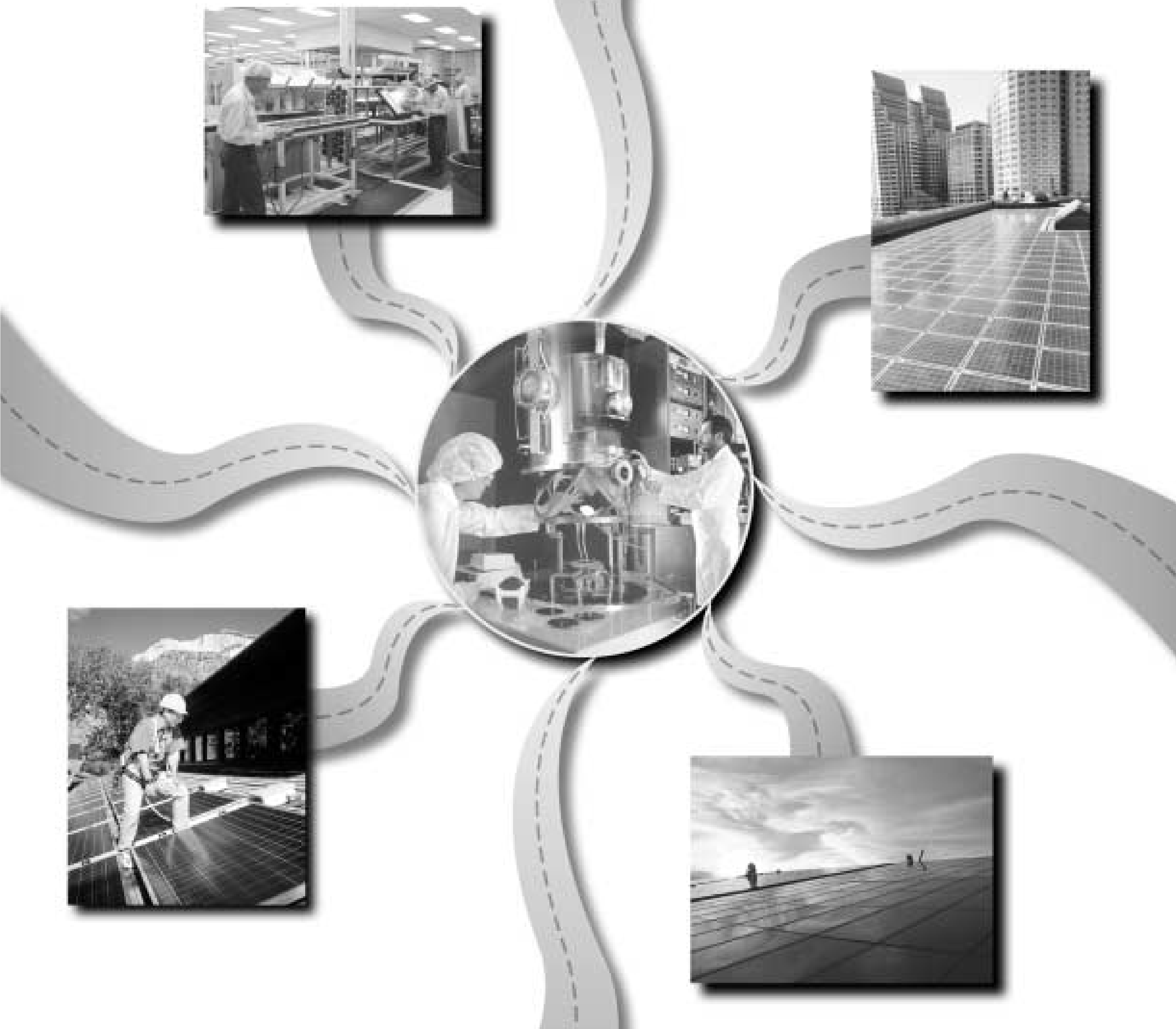
Photovoltaic Energy Program Contract Summary

Fiscal Year 2000



U.S. Department of Energy

Introduction

The goal of the Department of Energy's (DOE's) Office of Power Technologies is to create clean, competitive power technologies for the 21st century. In support of this goal, the mission of the DOE National Photovoltaics (PV) Program is to make PV a significant and vital part of the domestic economy in the years ahead, both as an industry and as an energy resource. Photovoltaic technology made major advances toward the promise of competitive electricity this year-with more record efficiencies and a rapidly growing industry. The Program's successes are described in the publication, *Photovoltaic Energy Program Overview, Fiscal Year 2000.*

The foundation of the Program's scientific success continues to rest in the partnership between the federal PV Program, universities, and industry. Direct research, as well as management of the bulk of subcontracted research performed by companies and universities in the Program, are provided by the two lead laboratories in the National Center for Photovoltaics (NCPV)─the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). Brookhaven National Laboratory spearheads the efforts in environmental, safety, and health research. The Golden and Albuquerque DOE Field Offices also oversee subcontracted industry and university research.

This Contract Summary for fiscal year (FY) 2000 documents some 179 research projects supported by the PV Program, performed by 107 organizations in 32 states, including 69 projects performed by universities and 60 projects performed by our industry partners. Of the total FY 2000 PV Program budget of $65.9 million, the industry and university research efforts received $36.9 million, or nearly 56%. And, of this amount, more than 93% was for contractors selected on a competitive basis. Much of the funding to industry was matched by industry cost-sharing. Each individual effort described in this summary represents another step toward improving PV manufacturing, performance, cost, and applications, and another step toward accomplishing the DOE PV Program's overall mission.

Two additional documents were published during FY 2000 to guide the Program's direction and strategy. The report, U.S. *Photovoltaics Industry: PV Technology Roadmap Workshop,* sets industry's ambitious goals for annual installed production capacity and PV system cost through the year 2020. The new *National Photovoltaics Program Plan, 2000-2004: Photovoltaics, Energy for the New Millennium,* details the R&D plan and accomplishments needed to make the journey charted out in the PV Industry Roadmap. The results presented in this summary show steady progress toward the Program's technical, performance, and economic milestones. The partnership that the Program has forged among industry, universities, and DOE represents a winning strategy-one that we will continue to rely on to maintain US. leadership in PV technology in the years ahead.

Program and Document Organization

The DOE National Photovoltaics Program supports efforts to make PV an important part of our economy through three main program elements: Research and Development, Technology Development, and Systems Engineering and Applications. The research activities are carried out in a coordinated manner by researchers from the national laboratories, industry, and universities.

Following is a brief description of the three main program elements:

- **Research and Development** activities generate new ideas, test the latest scientific theories, and push the limits of PV efficiencies in laboratory and prototype materials and devices. Other activities define environmental health and safety issues for facilities engaged in manufacturing PV products and for organizations engaged in PV research and development.

- **Technology Development** activities apply laboratory innovations to products to improve PV technology and the manufacturing techniques used to produce PV systems for the market.

- **Systems Engineering and Applications** activities help to improve PV systems and validate the improvements through tests, measurements, and deployment of prototypes. In addition, research on applications helps to validate sales, maintenance, and financing mechanisms worldwide.

The overall PV Program is a balanced effort of research, manufacturing development, and market development. All activities within the Program are planned and carried out in close collaboration and partnership with the U.S. PV industry. Critical to the success of this strategy is the PV Program's push to reduce the cost of electricity generated by photovoltaics. The program is tackling this goal in three primary ways: by making devices more efficient, by making PV systems less expensive, and by validating the technology through measurements, tests, and prototypes.

This document is organized into three main sections corresponding to the PV Program elements. The fourth section describes projects aimed at outreach and program planning, analysis, and management. Within each of the main sections, the first level of ordering of the projects is by the subareas listed in the Table of Contents. Individual projects are then ordered alphabetically according to the name of the performing organization. The appendices provide an indexing of the projects by name of the performing organization, state where the work is performed, and PV technology area. The following codes are used for the organization types:

CU	College, Univ, or Trade School (Non-HBCU)	**ST**	Regional State, or Local Gov't Facility
HB	Historically Black College or University	**TA**	Trade or Professional Organization
FF	Federally funded (R&D Lab Operated for Profit)	**US**	Federal Agency
IN	Private Industry	**ZZ**	Foreign
NP	Foundation or Lab (Non-Profit)		

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Research and Development

Fundamental and Exploratory Research

High-Resolution Chemical Electron Microscope

Contract #: AAD-0-30624-01	**Contract Period:** 8/25/00–9/30/01

<table>
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<tr><td>Organization Type: CU</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
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E-mail: robert_mcconnell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information: none</td></tr>
<tr><td>DOE Funding Allocation:
2000: $945,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Arizona State University shall acquire a high-resolution transmission electron microscope suitable for studying chemical reactions in real time under controlled atmosphere conditions. The instrument will be equipped with a field-emission electron source because of its enhanced capacity for small-probe microanalysis. The point resolution in the conventional phase-contrast high-resolution mode will be 0.20 nm or better. The instrument should be able to perform chemical and electronic structure nanoanalysis with a spatial resolution of better than 0.25 nm in X-ray or electron-energy-loss nanospectroscopy modes, and it should have an energy resolution of 0.8 eV or better in electron-energy-loss mode. The microscope should also be capable of spectrum and energy-selected imaging. The microscope will be configured for controlled atmosphere electron microscopy with additional apertures to facilitate differential pumping in the vicinity of the specimen chamber.

Approach/Background: The Conference Report on H.R. 2605, FY 2000 Energy and Water Development (EWD) Appropriations Act (House of Representatives – September 27, 1999) states: "*Photovoltaic systems research and development*…….From the amount provided, the conferees have provided $1,000,000 for the Materials Science Center in Tempe, Arizona." This subcontract with Arizona State University fulfills this congressional requirement. DOE Headquarters directed NREL, through its National Center for Photovoltaics (NCPV), to implement the requirement through a non-competitive subcontract.

Status/Accomplishments: Arizona State University ordered the microscope.

Planned FY 2001 Activities: Arizona State University will certify delivery of the microscope.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Fundamental and Exploratory Research

Standards for Future Generation PV Technologies

Contract #: AAD-9-18668-18	**Contract Period:** 5/19/99–7/18/02

<table>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $120,000
2000: $61,260</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The global objective of this project is to identify, explore, evaluate, and develop future generations of photovoltaic technologies that can meet the long-term goal of producing low-cost electricity from sunlight. The specific objectives of this project are two fold: (i) Develop qualification test standards for future generation PV technologies, and (ii) Explore absolute performance measurement issues for future generation PV technologies. The future generation PV technologies include CdTe, CIS and concentrators.

Approach/Background: Crystalline and amorphous silicon flatplate photovoltaic (PV) modules are currently listed or certified as meeting testing standards UL 1703 (Underwriters Laboratories), IEEE 1262 (Institute of Electrical and Electronic Engineers), and/or IEC 1215/1646 (International Electrotechnical Commission). The tests involved in these qualification standards provide assurance that the modules are durable, reliable, and safe. The existing test specifications in these test standards generally exclude, or are inappropriate for new technologies such as concentrator, CIS and CdTe. As a result, existing specifications must be expanded, or new test specifications developed, for each new technology.

New generation technologies are often developed by organizations that do not have the financial, equipment, or personnel resources to carry out the qualification testing. The developers of new technologies need access to a testing laboratory that will test at reasonable prices and test in a timely manner. Arizona State University - Photovoltaic Testing Laboratory (ASU-PTL) has long been involved in certifying the crystalline and amorphous silicon flatplate PV modules as per UL1703, IEEE 1262 and /or IEC 1215/1646 qualification test standards. With the current financial assistance of DOE/NREL, ASU-PTL is expanding its qualification test facility to accommodate the new generation technologies. During the course of this project, ASU-PTL will collaborate with NREL to develop the qualification test standards for new generation technologies.

Accurate measurement of absolute module performance is essential in order to: a) compare different technologies, b) measure module degradation and c) provide the buyer with assurance that they are getting what they pay for. ASU-PTL can measure large-area module performance with uncertainties of 3.6% or better for crystalline silicon modules, but accurate test methods have not been defined, developed or verified for the large area modules of other technologies. Furthermore, some of the new technologies do not lend themselves to performance testing by pulse type solar simulators. During the course of this project, ASU-PTL will develop OUTDOOR test methods for the accurate performance measurements of large area modules of new generation technologies.

Status/Accomplishments: Several important milestones were met during this reporting period of Oct/99-Sep/00. Three most important accomplishments are:

- Purchased/built equipment for the qualification testing of PV concentrator modules as per IEEE 1513-Draft standard: *Recommended Practice for Qualification of Photovoltaic (PV) Concentrator Modules*
- Verified the performance of the purchased/built equipment related to the concentrator modules' testing
- Implemented the successful balloting of the IEEE 1513 standard

Status/Accomplishments (continued):
In addition, two ASU-PTL staff members participated in the IEEE standards meeting and NREL's annual PV review meeting. Major equipment which were purchased/built during this reporting period are listed below:

- *Thermal shock chamber*
  A conventional environmental chamber was retrofitted for the thermal shock properties as per IEEE 1513. This chamber even exceeds the standard's most stringent thermal cycling requirement: 18 thermal cycles per day between 110°C and –40°C with a dwell time of at least 10 minutes at high and low temperatures. The purpose of this test is to determine whether receiver sections have adequate resistance to failures due to differential thermal expansion of component parts and bonding materials.
- *2-axis trackers*
  Two 2-axis trackers were purchased and installed, and their operation has been verified. One of these trackers will be used for side-by-side current-voltage measurements while the other will be used for the outdoor exposure tests of PV concentrators.
- *Water spray test station*
  A special station has been built to evaluate the PV module's electrical insulation under wet operating conditions. This test simulates rain or dew on the array and its wiring and verifies that moisture will not enter active portions of the array's electrical circuitry where it may cause corrosion, cause ground faults, or poses an electrical safety hazard to personnel or equipment.
- *Wind load tester*
  A versatile wind load tester has been designed and developed to test smaller and larger new generation flat-plate PV modules with or without frames. This unique tester can test PV modules for both static and wind loads with 50 psf pressure, exceeding the current standards' wind load requirement of 30 psf.

During this reporting period, several tests unique to concentrator PV modules were carried out and they include: Dark current-voltage measurements of concentrator receiver sections, side-by-side current-voltage measurements of liner concentrator modules supplied by Photvoltaic International (PVI), water spray testing of PVI modules and humidity-freeze testing of concentrator lenses. Also, several small and large area frameless flat-plate modules have also been successfully tested for ten to fifteen thousand wind load cycles.

ASU-PTL was also mandated to implement successful balloting of IEEE 1513-Draft standard document by September 1, 2000. The Draft was submitted to IEEE for balloting in August. Voting by the IEEE standard's committee members was completed during the first week of November 2000.

Planned FY 2001 Activities:
- Attend ASTM/IEEE standards meetings
- Identify and purchase equipment for CIS and CdTe technologies, if required
- Identify absolute performance measurement issues for new generation technologies

Major Reports Published in FY 2000:
IEEE 1513-Draft standard: *Recommended Practice for Qualification of Photovoltaic (PV) Concentrator Modules*, Implemented for the successful balloting by September 1, 2000.

Major Articles Published in FY 2000:
G. TamizhMani, B. Hammond and L. Ji, "Standards for New Generation Technologies: CONCENTRATORS," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064 (2000).

Fundamental and Exploratory Research

Low-Temperature, High Throughput Process for Thin, Large-Grained Poly Si

Contract #: AAD-9-18668-03	**Contract Period:** 5/24/99–7/25/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	California Institute of Technology Thomas J. Watson Laboratory of Applied Physics Pasadena, CA 91125 **Organization Type**: CU	**Congressional District**: 27
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Harry A. Atwater **Phone:** 626-395-2197 **Fax:** 626-449-5678 **E-mail:** haa@daedalus.caltech.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $63,720 2000: $70,318	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The overall project goal is to understand the fundamental gas phase, surface and interface science issues relevant to low temperature (T < 600 ^{o}C synthesis of polycrystalline silicon films on low-cost (e.g., glass) substrates. This understanding will be used to delineate the path to break through existing barriers to high-rate synthesis of high-quality thin films for polycrystalline silicon photovoltaics applications. In this context, high quality refers to large grain size (> film thickness) and long (> film thickness) minority carrier diffusion length.

Approach/Background: The approach to high rate synthesis of large-grained films at low temperatures is twofold, consisting of

- Selective nucleation and solid phase epitaxy (SNSPE) growth to form a thin (< 1 □m thick) large-grained polycrystalline silicon template film from amorphous silicon starting material. The rate of solid phase crystallization is greatly enhanced relative to that for pure amorphous silicon via dopant-enhanced or silicide-enhanced crystallization, enabling large grain structures to be achieved at < 600 ^{o}C in reasonable times.
- High rate epitaxial growth of a thicker (1-30 □m thick) layer of silicon on the large-grained polycrystalline silicon template film by hot-wire chemical vapor deposition (HWCVD). The research on HWCVD is focused on both modeling and simulation of gas phase kinetic processes and film growth. Modeling efforts include quantitative models of gas phase species and reaction kinetics between the wire and substrate using particle-based direct simulation Monte Carlo methods appropriate for low pressure reacting flows, as well as *ab-initio* calculations of the thermochemistry and kinetics of relevant silicon-hydride reactions. Experiments include quadrupole mass spectrometry of gas phase species as well as film growth and characterization by reflection high energy electron diffraction, transmission electron microscopy, atomic force microscopy and Rutherford backscattering spectrometry.

Status/Accomplishments:

Hot Wire Chemical Vapor Deposition:

- Experimentally determined the low-coverage nucleation kinetics of silicon on silicon dioxide substrates.
- Performed *ab-initio* quantum chemical study of the silicon/silane reaction that identified gas phase di-silicon species formation kinetics
- Developed and applied a two-dimensional direct simulation Monte Carlo modeling of the HWCVD reactor under conditions relevant to high quality polycrystalline and epitaxial silicon.
- Performed quantitative measurements of gas phase radicals, via threshold ionization mass spectrometry, that play a role in the growth of high quality polycrystalline and epitaxial silicon.

Selective Nucleation and Solid Phase Epitaxy:

- Developed inkjet printing of Ni nanoparticles onto Si substrates as a low cost mask-free method metal-induced nucleation in solid phase crystallization of amorphous Si layers.
- Demonstrated SNSPE growth with low Ni content. Probed Ni content in Ni-mediated crystallized Si template layers and a microns thick epitaxial layer atop the template layer (deposited by molecular beam epitaxy) with x-ray fluorescence microprobe at Advanced Light at Lawrence Berkeley National Laboratories.

- Estimated vacancy depth profile in doped Si films, from positron annihilation spectroscopy and progressive etchback of the film surface, in collaboration with Washington State University.

Planned FY 2001 Activities:

Hot Wire Chemical Vapor Deposition:

- Quantitative model of nucleation kinetics relevant to growth of polycrystalline silicon by HWCVD
- Growth of epitaxial HWCVD films on Si(100) and large grain poly-Si templates
- Minority carrier diffusion length (and lifetime) measurements in HWCVD films
- Map of radical species distributions over parameter space (total pressure, hydrogen dilution, wire temperature) relevant to growth of high-quality polycrystalline and epitaxial films**.**

Selective Nucleation and Solid Phase Epitaxy:

- Determine Ni location in poly-Si thin films (substitutional, interstitial, grain boundary, silicide particles), and Ni incorporation during epitaxial Si growth on poly-Si templates.
- Relate crystallographic properties (grain size, orientation, dislocation density) of films grow by SNSPE to measurements of minority carrier diffusion length.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

"Manipulation and Control of Nucleation and Growth Kinetics with Hydrogen Dilution in Hot-Wire CVD Growth of Poly-Si," J. K. Holt, M. Swiatek, D. G. Goodwin, and Harry A. Atwater, Spring 2000 Materials Research Society Meeting, San Francisco, CA.

"Manipulation and Control of Nucleation and Growth Kinetics with Hydrogen Dilution in Hot-Wire CVD Growth of Poly-Si," M. Swiatek, J.K. Holt, D.G. Goodwin, and Harry A. Atwater, Spring 2000 Materials Research Society Meeting, San Francisco, CA.

"Large-grained polycrystalline Si films obtained by selective nucleation and solid phase epitaxy," R. A. Puglisi, H. Tanabe, C. M. Chen, H. A. Atwater, Materials Science And Engineering B-Solid State Materials For Advanced Technology **73**: (1-3) 212-217 (2000).

"A Relation Between Surface Oxide And Oxygen-Defect Complexes In Solid-Phase Epitaxial Si Regrown From Ion-Beam-Amorphized Si Layers," M. P. Petkov, C. M. Chen, H. A. Atwater, S. Rassiga, K. G. Lynn, Applied Physics Letters 76: (11) 1410-1412 (2000).

"Study of Vacancy and Impurity Complexes in Si Solid-Phase Epitaxial Crystallization with Positron Annihilation Spectroscopy" Claudine M. Chen, Stefano Rassiga, Marc H. Weber, Mihail P. Petkov, Kelvin G. Lynn and Harry A. Atwater in Si Front-End Processing-Physics and Technology of Dopant-Defect Interactions II, Mater. Res. Soc. Proc. **610**, edited by A. Agarwal, L. Pelaz, H-H. Vuong, P. Packan, and M. Kase, Warrendale, PA, (2000).

J.K. Holt, M. Swiatek, D.G. Goodwin, and H.A. Atwater, "Gas Phase and Surface Kinetic Processes in Polycrystalline Silicon Hot-Wire Chemical Vapor Deposition," 1st International Conference on Cat-CVD (Hot-Wire CVD) Process, Kanazawa, Japan.

R.P. Muller, J.K. Holt, D.G. Goodwin, and William A. Goddard, III, "Si + SiH_4 Reactions and Implications for Hot-Wire CVD of a-Si:H: Computational Studies," Spring 2000 Materials Research Society Meeting, San Francisco, CA.

Fundamental and Exploratory Research

Elastic Properties of Thin-Film Silicon

Contract #: AAD–9–18668–12	**Contract Period:** 6/24/99–8/23/02

<table>
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<tr><td>Directing Organization:
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1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
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E-mail: rick_matson@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 62,250
2000: $ 64,918</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Thin–film silicon holds great promise as a semiconductor that can be produced economically on a large scale. Its exceptional properties for photovoltaic energy conversion have already been demonstrated and are the subject of intensive study worldwide. Yet the entire field of heterogeneous thin–film silicon (often referred to as polycrystalline silicon) is remarkably poorly understood. This is not too surprising, given our limited understanding of one of its constituents, amorphous silicon, in particular in its hydrogenated form. In the thin–film silicon, the interfaces between crystalline grains and between crystalline and amorphous regions appear to be of particular importance, since they are likely to lead to the exceptionally large optical absorption observed in these films, which exceeds that of both c–Si and a–Si:H. The understanding of the interfacial regions is, however, entirely lacking. What is their fractional volume, and how can it be controlled? Where is the hydrogen located in these films, and what is its role in their electronic properties? A better understanding of these fundamental questions is crucial for the development of better photovoltaic devices, and for any other technological application as well. This is the objective of the present study.

We will use the same elastic measuring technique used previously to study crystalline and amorphous films, utilizing the extensive experience and skills in film preparation and characterization available at NREL. Through such measurements, we hope to contribute to the understanding of heterogeneous solids in general, and to the development of better and more durable photovoltaic devices in particular.

Approach/Background: The thin films are deposited on a double–paddle oscillator etched out of high purity silicon. The bare paddle has an extremely small damping, and is therefore highly sensitive to any disorder in the film.

Status/Accomplishments: In the first stage of the work carried out under this contract, we have measured the internal friction of thin-film silicon produced by PECVD. By increasing the ratio of the hydrogen to silane gas, films with increasing crystallinity were prepared. Since it is generally believed that the structural disorder in the amorphous films is the major cause for the large internal friction observed, it seemed natural to assume that in the increasingly more crystalline films, because of their decreasing disorder, the internal friction would decrease. Much to our surprise, the opposite was found: in the fully amorphous films, the internal friction was somewhat smaller than is typically found in amorphous films, like in a-Si films produced by sputtering. With increasing crystallinity, the internal friction increased. Finally, in the films which should be fully ordered—crystalline—the internal friction approached that of the sputtered, fully amorphous films! Since we suspected hydrogen gas inclusions to be the cause for some of the internal friction in the crystalline films, and had previously shown that large inclusions of this gas produce a characteristic internal friction peak at the triple point (13.8K), we carefully searched for that. However, no such peak was found. A new and very prominent internal friction peak which grows with the increase of the crystalline fraction, was observed around 60K. Its origin is unknown, but it is, of course, clear evidence of some disorder in these films. Thus, our work so far has shown our technique to be highly sensitive in detecting disorder in thin-film silicon with increasing crystalline fraction. Whether this disorder is located between the crystalline grains, or within them, and how it may effect the optical and electronic properties of these films, is the subject of further study. We are now extending our work to the study of crystalline films produced by HWCVD with hydrogen dilution.

Contract #: AAD–9–18668–12

Since the sensitivity of this technique is critically dependent on the background damping of the double-paddle oscillator, we have spent large effort on improving our understanding of its origin. We have, in particular, tried to understand why the different normal modes of this oscillator, which vibrate at different frequencies, have such widely differing damping. Using a Finite Element Method, we have been able to show that the damping is connected with the magnitude of the force required to hold the paddle in its mount. Thus, this technique can now be used to design paddles with different frequencies and with controlled and small damping, which should greatly enhance the usefulness of elastic measurements for the study of thin-film disorder.

Planned FY 2001 Activities:
We plan to continue the study of HWCVD films with increasing crystalline fractions. In order to investigate the role that hydrogen—either in atomic or in molecular form—may play for the anomalous internal friction we have observed, we plan to study films with hydrogen gas inclusions of controlled small size. From this, we hope to learn how the anomaly which had been seen at 13.8K depends on the size of the inclusions. These films will be supplied by Dr. Guha from the United Solar Systems Corp. We will try to control the size of these inclusions through heat treatment of the films. We will continue our effort to improve the elastic quality of our oscillators, in order to improve their sensitivity. At present, all of our work is limited to one single mode, with a frequency of ~ 5 kHz, since that is the only mode for which our oscillators have the high quality necessary for this investigation. We plan to develop oscillators that can be used at different frequencies, in order to have frequency as a parameter for our further work.

Major Reports Published in FY 2000:
NCPV Program Review Meeting, 2000, April 16-19, 2000, Denver, CO: "Disorder in Thin Film Silicon," C.L.Spiel, B.P.Nelson, R.S.Crandall, R.O.Pohl

Major Articles Published in FY 2000:
C.L.Spiel, R.O.Pohl, A.T.Zehnder, "Normal modes of a Si(100) Double-Paddle-Oscillator," to appear in Rev. Sci. Instrum.

Fundamental and Exploratory Research

Project Management

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

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Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Robert McConnell **Phone:** 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	
Technical Monitor: Satyen Deb **Phone**: 303-384-6405 **Fax**: 303-384-6481 **E-mail** satyen_deb@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $500,000 2000: $500,000	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective:

- Support fundamental research needed to help near-term and mid-term solar electric technologies meet long-term cost and performance goals
- Support exploratory research directed towards non-conventional solar electric technologies having the potential to produce inexpensive electricity.

Approach/Background:

- In 1998 we solicited proposals from universities to explore future generation photovoltaic technologies. In 1999, we funded 18 university research projects in this area.
- Continue to fund 9 universities for basic research in crystalline silicon to enhance the likelihood of creating new knowledge or information that may be useful for today's leading solar electric technology.
- Solicit research proposals from US companies and universities to explore beyond the horizon of our present knowledge of solar electric technologies.
- Fund undergraduates at 8 historically black colleges and universities to explore possible careers in solar electric technologies.
- Provide oversight and task management support for the solar electric research tasks in NREL's Center for Basic Sciences and serve as liaison for DOE Office of Science activities in photovoltaics.

Status/Accomplishments:

- At the National Center for Photovoltaics Program Review meeting held in April, 2000, we conducted the first formal review of research progress for the 18 university contracts in the *Future Generation Photovoltaic Technologies* program begun in 1999. The reviewers provided their opinions on strengths in each of the university projects, their recommendations for future research, and ranked the 18 projects by research quality. We sent this guidance to each principal investigator for their consideration and possible action. Overall, the research progress was judged to be favorable, consistent with the many publications in refereed journals noted in the university annual reports in the following pages. Some researchers have published their results in the prestigious international scientific journal, Nature. All *Future Generation Photovoltaics Technologies* contracts, listed in the pages ahead, are numbered 9-18668-xx, ignoring the first three letters in the Contract #.
- NREL has facilitated the *Workshop on Crystalline Silicon Solar Cell Materials and Processes* for the past ten years. The tenth workshop, held in August, 2000, in Copper Mountain, Colorado again served to highlight the results of the universities funded for fundamental research on crystalline silicon and to be a portal for industry research issues. The theme of the 10th Workshop: *Si Photovoltaics: 10 years of Progress and Opportunities for the Future* led to a wrap-up session to gather as much input as possible from industry, government, and academia about research issues in the decade ahead. A voting process, involving the 15 international PV companies in attendance, led to the identification of 6 technical challenges facing the industry: 1) Develop replacement for, or vastly improve, screen printed metallization, 2) Develop low-cost, non-vacuum, hydrogenation technique, and improve understanding of Si_3N_4 hydrogenation, 3) Develop methods of handling and processing thin wafers with high yield, 4)

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Status/Accomplishments (continued):

Develop new emitter technologies such as selective emitters, heterojunction emitters, etc., and 5) Discover how to neutralize bad regions and shunts. A suggestion by one attendee led to a proposal for research teams, with representatives from industry, academia, and government to address the above issues. We expect to follow this suggestion by including these topics in the solicitation for university research in crystalline silicon in FY2001.

- *Photovoltaic Technologies Beyond the Horizon* is the title of a new initiative scheduled to begin in FY 2001 and designed to explore technologies beyond the horizon of our present knowledge of photovoltaics. We issued the solicitation on April 14, 2000 with responses due June 15, 2000. We issued one amendment to the RFP that changed the due date for responses to July 24, 2000. We received 85 proposals with their evaluation scheduled for early Fiscal Year 2001. The technologies chosen for further exploration will be embryonic, risky, and may or may not be successful. However, they all have the potential for high efficiency and low cost. And the research groups working on them are expected to have extremely good capabilities to explore them.
- The *2nd DOE/NREL Renewable Energy Academic Partnership (REAP) Conference*, to review progress at the 8 Historically Black Colleges and Universities (HBCUs), was held at NREL on August 8-11, 2000. Conference attendance included more than 55 participants from NREL, each of the universities, and as far away as Senegal, West Africa. Advisors and students gave comprehensive presentations about their research projects, participated in professional development workshops, and learned from other renewable energy experts. We also funded over one dozen HBCU summer interns with most of them interning at NREL.
- We provided support for team meetings of the Thin Film Silicon Team and Next Generation Photovoltaics Team in the High Efficiency Photovoltaics project within the Center of Excellence for the Synthesis and Processing of Advanced Materials (CSP) funded by Basic Energy Sciences in the DOE Office of Science.

Planned FY 2001 Activities:

- Conduct the second year formal review of university research under the 18 Future Generation Photovoltaic Technologies contracts at the *Photovoltaics for the 21st Century Symposium* at the 199th ECS Meeting in Washington DC in March, 2001.
- Solicit research proposals from universities for fundamental research in crystalline silicon on topics identified in FY2000 and award the new contracts during FY2001. Provide oversight and support for the *11thWorkshop on Crystalline Silicon Solar Cell Materials and Processes* scheduled for August, 2001.
- Complete the evaluation of the PV Beyond the Horizon proposals and award new contracts during FY2001.
- Conduct the 3rd REAP Conference to review HBCU progress and develop opportunities for HBCU summer interns.
- Provide support to the DOE/BES CSP activities.
- Assess viability of the dye-sensitized solar cell to accomplish a milestone in the DOE Five-Year PV Program Plan. This assessment will be partly met with a special group of 13 international presentations at the *Photovoltaics for the 21st Century Symposium* at the 199th ECS Meeting in Washington DC in March, 2001.

Major Reports Published in FY 2000:

B. Sopori and Program Committee, (2000), "10th Workshop on Crystalline Silicon Solar Cell Materials and Processes," 247 pp. NREL/BK-520-28844, Golden, CO: National Renewable Energy Laboratory

Major Articles Published in FY 2000: none

Fundamental and Exploratory Research

Computational Photovoltaic Materials Science

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99-9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory Basic Science Center Golden, CO 80401 **Organization Type**: FF	 **Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Su-Huai Wei **Phone:** 303-384-6666 **Fax:** 303-384-6432 **E-mail:** swei@nrel.gov	
Technical Monitor: Satyen Deb **Phone**: 303-384- **Fax**: 303-384-6481 **E-mail**: satyen_deb@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 2000: $442,000	**Cost Share Information**: None **Cost Share Funding:**

Project Objective: This task performs fundamental research to establish the basic knowledge infrastructure of photovoltaic materials using the state-of-the-art computational tools. Our FY2000 project objectives are

- Study hydrogen-hydrogen interaction and clustering in silicon and the microscopic model for the Staebler-Wronski effect.
- Study the physics of p-type doping in CdTe.
- Maintain, update and system-administrate the CMS/SST Computer Network and develop new computer program for large-scale computations on PV materials.

Approach/Background: Hydrogenated amorphous silicon and microcrystalline silicon are important thin-film solar cell materials. The understanding of the role of H in Si is essential to Si based photovoltaic technology. Using the first-principles total energy calculations, we determined the H energetics in c-Si that affects the efficiency of H passivation of defects and provide a structure model for the cluster phases in a-Si:H that controls H evolution, thermal effects, and possibly the Staebler-Wronski metastability.

One of the main limiting factors of increasing the efficiency of CdTe-based solar cell is the low p-type dopability in CdTe. The mechanism of this low p-type dopability is not well understood. Using the first-principles band structure method, we calculated systematically the formation energies and transition energy levels of intrinsic and extrinsic defects and defect complexes in CdTe to understand the general trends of doping and identify the best p-type dopants for CdTe

Maintaining and upgrading the CMS/SST computer network and developing new scientific computing program are crucial for us to carry out the activities above.

Status/Accomplishments: *Study hydrogen-hydrogen interaction [1-2]:* We calculated the $(H2^*)_n$ clusters that are aggregation of the H2* molecules. We find the following: (1) the initial low energy pathways (n=7) towards larger platelets involves the accumulation of H2*s in the mono-hydride form. (2) Low energy di-hydride Si can form when n=2. There is, however, an additional energy cost to form the di-hydride relative to the mono-hydride, for example 0.25 eV for n = 2. (3) Tri-hydride Si may also form in n=3 clusters, but the additional energy cost are small, e.g., 0.17 eV for n=3. From these results, we concluded that multi- hydrides are important in H clusters. We have also studied the H platelet formation in Si. We discover that there are three regions of the platelet dilation where the double-layer platelet of the H2* transforms to single-layer platelet and then to a platelet involving also the tri-hydride.
Study the physics of p-type doping in CdTe[3-7]: We find that (1) the p-type doping in CdTe is not limited by the spontaneous formation of intrinsic defects. Instead, under equilibrium growth condition, the p-type doping is limited either by the self compensation (e.g., in the case of Na_{Cd}), the low solubility of the dopant (e.g., in the case of N_{Te} and P_{Te}), or by the fact that the transition energy levels of the dopants are too deep (e.g., Cu_{Cd}). We suggest that higher hole carrier density is achievable if one can enhance the incorporation of N or P in CdTe, possibly through non-equilibrium process (e.g., ion implantation, electron beam annealing, etc.). We have also studied the effectiveness of codoping in enhancing the dopability of CdTe. We find that, in general, co-doping does not reduce the formation energies of the defect complexes below that of the constituent point defects. Furthermore, the transition energy level can be lowered only if the defect complex consists of a single donor and a single acceptor, e.g., V_{Cd}+Cl_{Te}.

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Status/Accomplishments (continued):
Maintain, update and system-administrate the CMS/SST Computer Network and develop new computer program: This is an ongoing project to support activities 1 and 2. We upgraded the 16 CPU SGI origin2000 parallel computer to higher speed. We are in the process of optimizing the FLAPW code used in our calculation.

Planned FY 2001 Activities: We planned three activities in FY2001.

- Studying the surface structures and the surface energies of $CuInSe_2$ and related compounds.
- Studying the defect compensation mechanism in CdTe and other II-VI semiconductors.
- Developing new computer programs for large-scale computation on PV materials.

Major Articles Published in FY 2000:
S. B. Zhang and H. M. Branz, "Nonradiative electron-hole recombination by a low-barrier pathway in hydrogenated silicon semiconductors", Phys. Rev. Lett. **84**, 967 (2000).

S. B. Zhang and H. M. Branz, "A novel biexcitonic, non-radiative electron-hole recombination mechanism and its application in hydrogenated silicon semiconductors", *25th International Conference on the Physics of Semiconductors*, Osaka, Japan, 18-22, September 2000.

S.-H. Wei and S. B. Zhang, "Structure stability and carrier localization in CdX (X=S, Se, Te) semiconductors", Phys. Rev. B **62**, 6944 (2000).

S.-H. Wei, and S. B. Zhang, "ZB/WZ band offsets and carrier localization in CdTe solar cells", *Program and Proceedings: NCPV Program Review Meeting 2000*, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 293-294 (2000).

Y. Yan, M. M. Al-Jassim, K. M. Jones, S.-H. Wei, and S. B. Zhang, "Observation and first-principles calculation of buried wurtzite phases in zinc-blende CdTe thin films", Appl. Phys. Lett. **77**, 1461 (2000).

S. B. Zhang, S.-H. Wei and Yanfa Yan, "The Thermodynamics of codoping: How does it work", *9th International Conference on Shallow Level Centers in Semiconductors*, Awaji Island, Japan, 25-28, September 2000.

S.-H. Wei and S. B. Zhang, "Electronic structures and defect physics of Cd-based semiconductors", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Other PV related publication in FY2000:
S.-H. Wei, S. B. Zhang, and A. Zunger, "Band structure and stability of ternary semiconductor polytypes", Jap. J. Appl. Phys. (in press).

C.-H. Chang, S.-H. Wei, J. W. Johnson, R. N. Bhattacharya, B. J. Stanbery, R. Duran, and T. J. Anderson, "Long and short range ordering of $CuInSe_2$", Jap. J. Appl. Phys. (in press).

C.-H. Chang, S.-H. Wei, N. Leyarovska, J. W. Johnson, S. B. Zhang, B. J. Stanbery, T. J. Anderson, R. Duran, and G. Bunker "Local structure of $CuIn_3Se_5$", *Program and Proceedings: NCPV Program Review Meeting 2000*, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 247-248 (2000).

S.-H. Wei and S. B. Zhang, "First-principles study of cation distribution in eighteen closed shell $A^{II}B_2^{III}O_4$ and $A^{IV}B_2^{II}O_4$ spinel oxides", Phys. Rev. B (in press).

S.-H. Wei, "Electronic structure and stability of spinel oxides", Jap. J. Appl. Phys. (in press).

S. B. Zhang and S.-H. Wei, "Nitrogen solubility and induced defect complexes in epitaxial GaAs:N", Phys. Rev. Lett. (in press).

S. B. Zhang, S.-H. Wei, and A. Zunger, "Intrinsic n-type vs. p-type doping asymmetry and the defect physics of ZnO", Phys. Rev. B (in press).

"Nitrogen solubility and nitrogen induced defect complexes in epitaxial grown GaAsN", S. B. Zhang and S.-H. Wei, *25th International Conference on the Physics of Semiconductors*, Osaka, Japan, 18-22, September 2000.

Fundamental and Exploratory Research

Photochemical Solar Cell Project

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory Center for Basic Sciences Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Arthur Nozik **Phone:** 303-384-66032 **Fax:** 303-384-6655 **E-mail:** arthur_nozik@nrel.gov	
Technical Monitor: Satyen Deb **Phone**: 303-384-6405 **Fax**: 303-384-6481 **E-mail** satyen_deb@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $210,000 2000: $215,000	**Cost Share Funding:**

Project Objective: To develop and optimize a new solar cell technology based on dye-sensitized nanocrystalline titanium dioxide that is low-cost, durable, and efficient (>11%). The overall objective is to define and solve the problems that limit the efficiency and commercial viability of dye-sensitized nanocrystalline TiO_2 solar cells.

Approach/Background: Dye-sensitized solar cells are a promising new kind of PV cell; they have demonstrated solar efficiencies of 10%–11% in a cell based on inexpensive materials and low-energy processing techniques. They have also been successfully employed in self-powered electrochromic windows. We are exploring methods of optimizing the performance and stability of the existing device while also exploring improved designs. To achieve these goals we are optimizing the parameters that affect cell efficiency, such as the dye molecule, the redox relay system, electrolyte composition and modifications of TiO_2 and its surface. Our improved designs are focused on an all-solid-state version of the dye cell and a tandem dye cell with an electron – injecting dye on the anode and a hole-injecting dye on the cathode. In parallel, with support from DOE's Office of Science (SC), Chemical Sciences Division, we are also conducting theoretical and experimental studies to understand the underlying processes governing the performance of dye-sensitized nanocrystalline TiO_2 solar cells.

Status/Accomplishments: (a) Setup screen-printing-related equipment (screen printer, disperser, 3-roll mill, etc.) and started evaluating critical screen-printing parameters, formulating TiO_2 screen-printing pastes, and fabricating films; semi-automated procedure will improve reproducibility of PV characteristics and lower cell-fabrication costs. (b) Developed a method to prepare thick (12 µm) crack-free nanoporous *rutile* TiO_2 films and demonstrated that the performance of these rutile based TiO_2 solar cells is remarkably close to that of the conventional anatase cell, especially at this early stage of rutile material development; fabrication cost of rutile based TiO_2 solar cells is expected to be lower than that of comparably thick anatase based TiO_2 cells. (c) Discovered that electron transport is slower in rutile than in anatase films and that the slower transport stems from the difference in the size of the particles. This discovery gives important insight into the synthesis conditions for further improving the electron-transport rate in rutile films and thus increasing J_{sc}. (d) Developed the first model that accurately and quantitatively predicts how the charge-collection efficiency of a cell depends on the charge-collection and recombination kinetics. This model allows evaluation of the charge-collection, which is one of three factors that limit the photocurrent-conversion efficiency. It also advances quantitative understand of the influence of recombination and electron transport on the charge-collection efficiency. (e) Established the main cause of a low photocurrent (< 18 mA/cm^2) in TiO_2 solar cells and suggested possible ways to improve it. This work raises questions regarding the current understanding of the electron transport mechanism. (f) Elucidated that the origin of the non-linear electron-transport kinetics observed in nanocrystalline TiO_2 films is due to an exponential distribution of surface states and resolved a long-standing controversy about the use of an effective electron diffusion coefficient to describe the electron transport kinetics in nanoporous films. (g) Introduced and confirmed the concept of ambipolar diffusion to understand electron transport and ion transport in TiO_2 solar cells (collaboration with E. A. Schiff, Syracuse Univ.) (h) Resolved a recent debate regarding the mechanism creating the cell photovoltage by showing unequivocally by electrical impedance measurements that the photopotential of a dye-sensitized solar cell is *caused by* the buildup of photoinjected electrons in the TiO_2 film. (i) Improved instrumental capability to optimize film deposition procedure and determine the influence of pore size and surface area on ion transport in the electrolyte and on cell performance. Extended measurement capabilities from the microsecond to the nanosecond time domain to study transport and recombination processes. (j) Showed that the presence of certain adsorbed cations can improve – via the phenomenon of band edge movement – the charge injection efficiency by altering both the energy and number of excited state levels of the dye that participates in electron injection. (k) Strongly passivated recombination sites at the SnO_2/solution interface and at the TiO_2/solution interface by exposing the film to CH_3SiCl_3 vapor. This makes it possible for the first time to use kinetically fast redox couples in dye sensitized solar cells. (l) Discovered that charge recombination at the SnO_2/solution interface is clearly distinguishable from recombination at the TiO_2/solution interface. Dark currents probe mainly the former reaction, although the latter may be the dominant recombination

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Status/Accomplishments (continued): mechanism under illumination. Thus the dark current is not a true measure of the interfacial processes that determine the photovoltaic effect. (m) Dye sensitized nanoporous electrodes were prepared from bilayer semiconductors consisting of TiO_2 covered by a thin layer of Nb_2O_5. The Nb_2O_5 layer improves the average efficiency of our cells by about one third by inhibiting interfacial recombination. (n) Synthesized high surface area p-type semiconductors such as NiO, $CuAlO_2$, Cu_2O and $SrCuO_2$ and have initiated some of the first studies of hole photo injection into p-type semiconductors.

Planned FY 2001 Activities: These planned activities are an integrated effort of EE/PV and DOE's Office of Science (SC), Chemical Sciences Division. Our plans are to **a)** explore the possibility of improving the performance of rutile based solar cells by varying the conditions of nanoparticle synthesis and particle film treatment to increase the surface area and reduce the surface density of recombination centers. The aim is to prepare smaller particles to increase the total amount of adsorbed dye for improved photocurrent and to study the effect of lowering the annealing temperature on the surface recombination kinetics. Recent studies of rutile based TiO_2 solar cells indicate that their performance and fabrication cost may compare favorably to that of the conventional anatase based TiO_2 cells. We will **b)** extend work on developing a state-of-the-art semi-automated procedure for fabricating low-cost and high quality, reproducible dye-sensitized nanocrystalline TiO_2 solar cells. The work includes formulating TiO_2 pastes for screen printing, optimizing screen printing parameters (snap-off distance, pressure of squeegee on TiO_2 paste, print speed, etc.), optimizing the conditions for thermally sealing cells and introducing the dye and redox electrolyte, and characterizing the performance of the resultant cell. We will **c)** explore a new material concept for improving electron transport. The idea is that an electric field-induced conductive pathway through the TiO_2 films can be created by electronically doping the TiO_2 particles. Creating an electric field is expected to improve the electron transport dynamics thereby increase the charge-collection efficiency. We will **d)** model by the Monte-Carlo approach and study by time-resolved techniques the electron transport dynamics in nanocrystalline semiconducting particle films. The studies will examine the influence of the trap-state energy distribution, the capture cross-section of traps, the mobility of free electrons, the light intensity, and the film thickness on the electron transport dynamics. We will **e)** continue to delineate factor limiting cell performance and stability. Finally, we will **d)** investigate the mechanism of temperature activated electron transport in dye-sensitized nanocrystalline titanium dioxide films by transient photocurrent measurements in collaboration with E. A. Schiff (Syrause University).

Major Articles Published in FY 2000:

J. van de Lagemaat, N.-G. Park, and A.J. Frank, "Influence of Electrical Potential Distribution, Charge Transport and Recombination on the Photopotential and Photocurrent Conversion Efficiency of Dye-Sensitized Nanocrystallline TiO_2 Solar Cells: A Study by Electrical Impedance and Optical Modulation Techniques" *J. Phys. Chem. B.* **104,** 2044 (2000).

N. Kopidakis, E.A. Schiff,; N.-G. Park, J. van de Lagemaat, and A.J. Frank, "Ambipolar Diffusion of Photocarriers in Electrolyte-Filled, Nanoporous TiO_2" *J. Phys. Chem. B.* **104**, 3930 (2000).

J. van de Lagemaat and A.J. Frank "Effect of the Surface-State Distribution on Electron Transport in Dye-Sensitized TiO_2 Solar Cells: Non-Linear Electron-Transport Kinetics" *J. Phys. Chem. B.* **104**, 4292 (2000).

N.-G. Park, J. van de Lagemaat, and A.J. Frank, "Comparison of Dye-Sensitized Rutile- and Anatase-Based TiO_2 Solar Cells" "Comparison of Dye-Sensitized Rutile- and Anatase-Based TiO_2 Solar Cells" *J. Phys. Chem. B.* **104**, 8989 (2000).

N.-G. Park, S.-H. Chang,. J. van de Lagemaat, K.-J. Kim, and A.J. Frank, "Effect of Cation on the Open-Circuit Photovoltage and the Charge-Injection Efficiency of Dye-Sensitized Rutile TiO_2 Solar Cells" *Bull. Korean Chem. Soc.* in press.

N.-G. Park, S.-H. Chang,. J. van de Lagemaat, and A.J. Frank, "Photovoltaic Characteristics of Dye-Sensitized Rutile TiO_2 Solar Cells" In *Proc. 3rd Korea-Japan Joint Symposium on Photovoltaics*, Pusan, Korea, 30-31 October 2000, pp. 113-118 (2000).

G. Schlichthörl, Park, N.-G. Park, and A.J. Frank, "Estimation of the Charge-Collection Efficiency of Dye-Sensitized Nanocrystalline TiO_2 Solar Cells" *Z. Phys. Chem. (Munich)* **212**, 45 (1999).

F. Pichot and B.A. Gregg, "The Photovoltage-Determining Mechanism in Dye-Sensitized Solar Cells" *J. Phys. Chem. B.* **104**, 6 (2000).

A. Zaban, S. T. Aruna, S. Tirosh, B.A. Gregg, and Y. Mastai, "The Effect of the Preparation Conditions of TiO_2 Colloids on Their Surface Structure" *J. Phys Chem. B.* **104**, 4130 (2000).

F. Pichot, J.R. Pitts, and B.A. Gregg, "Low Temperature Sintering of TiO_2 Colloids: Application to Flexible Dye-Sensitized Solar Cells" *Langmuir* **16**, 5625 (2000).

F. Pichot, S. Ferrere, J.R. Pitts, B.A. Gregg, "Flexible Solid-State Photoelectrochromic Windows" *J. Electrochem. Soc.* **146**, 4324 (1999).

Fundamental and Exploratory Research

Solid State Spectroscopy of Photovoltaic Materials

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory Center for Basic Sciences Golden CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator** Angelo Mascarenhas **Phone:** 303-384-6608 **Fax:**303-384-6481 **E-mail:** angelo_mascarenhas@nrel.gov	
Technical Monitor: Satyen Deb **Phone**: 303-384-6405 **Fax**: 303-384-6481 **E-mail** satyen_deb@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $330,000 2000: $399,000	**Cost Share Funding:**

Project Objective:

Recombination studies with submicron resolution in polycrystalline materials:
We completed the construction of an Optical Parametric Oscillator which is to be used for high rep rate (80 MHz) pumping of CdTe with ultra-fast light pulses and the installation of an ultra-fast Streak Camera which will be used as the detector for the radiative recombination studies. Our cryogenic Near-Field Scanning Optical Microscopy system is now working with a spatial resolution of 0.2 µm. We began studies on the effects of grain boundaries on Photoluminescence in bi-crystals of CdTe. During the coming year we will begin high spatial resolution mapping ultra-fast studies on the effects of grain boundaries on radiative recombination in 1) bicrystals of CdTe and 2) polycrystalline CdTe. A systematic study on the effects of chemical treatments and passivation of grain boundaries will be conducted.

Electronic properties of Nitrogen doped GaAs:
The GaAsN alloy is of potential importance for use in high efficiency solar cells. We propose to continue our very detailed spectroscopic investigations on why the transport properties in the conduction band of this alloy are so poor. The investigations will be based on electroreflectance measurements, Raman scattering measurements, and temperature dependent conductivity measurements. The attempt will be to understand the reason for the high conduction band effective mass, the low mobility, and the giant band gap bowing in the dilute alloy The research should reveal whether the above mentioned problems can be circumvented.

Approach/Background: Although Atomic Force Microscopy and Scanning Tunneling Microscopy can achieve nano-scale surface topographic measurements, such structural data is only indirectly related to solar cell performance. Information on the electronic properties measured with microscopic resolution is certainly more desirable. Our approach can provide optical information on the submicron length scale, thus directly measuring the relationship between microstructure and photovoltaic properties. Low-temperature scanning confocal, near-field and Solid Immersion lens imaging techniques as well as conventional micro-PL will be used in our lab to make these kinds of measurements. Photoluminescence, electro-reflectance and Raman scattering will be used to characterize III-V:N alloys.

Status/Accomplishments: A micro-photoluminescence (□-PL) study of poly-crystalline CdTe films on SnO_2 was performed to help in the interpretation of earlier □-PL data which we believe shows microscopic evidence of sulfer interdiffusion across the CdTe / CdS junction and subsequent formation of $CdTe_xS_{1-x}$ alloys within the CdTe layer.

A low-temperature Near-field Scanning Optical Microcopy/Spectroscopy (NSOM / NSOS) study of an as-grown thin-film polycrystalline CdTe/CdS solar cell (treated with $CdCl_2$) was completed. Using our near-field microsope, we were able to simultaneously acquire the photoluminescence spectrum at each point in the topographic image. The study showed a correlation between the grain structure in the material and the PL spectra, the first measurement of it's kind in CdTe. While these measurements did show an enhancement of the CdS_xTe_{1-x} alloy PL emission near grain boundaries, they also showed that, within the individual grains, the emission is similar to that of bulk CdTe.

Low temperature spatially-resolved spectra were acquired in the vicinity of the boundary between two crystalline phases of a CdTe bi-crystal using a Solid Immersion Lens microscopy technique developed in our lab. By examining the spatial-spectral data, we were able to directly observe carrier capture at the grain boundary: spectra taken at the boundary showed that the de-localized excitonic emission was strongly suppressed relative to locations removed from the boundary, while the donor-acceptor emission (already localized) was relatively unaffected.

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Status/Accomplishments (continued):
We applied the photo-reflectance technique to CdTe/CdS thin film polycrystalline solar cells, and have demonstrated that this is a very powerful technique that can address a few key issues: e.g., Is the p-n junction a hetero-junction or homo-junction? Is there a strong electric field near the interface and where does it locate? Our measurements were able not only to answer these questions qualitatively but also to give accurate values for the band gap and electric field as well as the location of the field. We have also demonstrated the improvement in the optical quality of the CdTe film by performing the $CdCl_2$ treatment.

We have been studying samples of GaAs:N using several optical spectroscopic techniques and have established that the anomalous band gap lowering in this alloy occurs due to the formation of an impurity band. The objective of this research is to address the technological challenge of obtaining a good 0.5 eV band gap semiconductor for use as a TPV absorber.

Planned FY 2001 Activities: Use of high spatial resolution Photoluminescence imaging techniques to probe recombination processes at defects in photovoltaic materials. The electrical properties of hetero-junctions in solar cells will be studied w.r.t electric fields and alloying. Our research efforts at attempting to see if the alloy properties of GaAs:N can be regularized will be continued.
Technical Approach:

- Near-Field Scanning Optical Microscopy (NSOM) and Solid Immersion Lens (SIL) based confocal photoluminescence mapping techniques will be used to identify recombination loss mechanisms in polycrystalline CdTe using.
- We recently demonstrated the ability to measure the electric-field at the CdTe/CdS heterojunction by observing Franz-Keldysh oscillations in modulated reflectivity measurements. The degree of alloying at the junction was also revealed. CdTe and CIS based solar cells will be studied using this technique.
- We will continue collaborations with University researchers funded by the PV program in an effort to understand how to regularize the properties of GaAs:N for use as a PV material.

Major Reports Published in FY 2000:
Y. Zhang, A. Mascarenhas, S. K. Deb, H. P. Xin, and C. W. Tu, Heavily Nitrogen-Doped III-V Semiconductors For High-Efficiency Solar Cells, *Proc. 28th IEEE-PV meeting* (in press).

R. A. Ahrenkiel, A. Mascarenhas, S. W. Johnston, Y. Zhang, D. J. Friedman, and S. M. Vernon, Photoconductive Properties of GaAs1-xNx double Heterostructures as a Function of Excitation Wavelength, *Mat. Res. Soc. Symp. Proc.* 607, 265 (2000).

Major Articles Published in FY 2000:
Zhang, Y.; Mascarenhas, A.; Xin, H.P.; Tu, C.W. "Valence-band splitting and shear deformation potential of dilute GaAs1-xNx alloys." *Phys. Rev B61*, 4433 (2000).

Zhang, Y.; Mascarenhas, A.; Xin, H.P.; Tu, C.W. "Formation of an impurity band and its quantum confinement in heavily doped GaAs:N." *Phys. Rev B61*, 7479 (2000).

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Fundamental and Exploratory Research

Solid State Theory of PV Materials

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory Center for Basic Sciences Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Alex Zunger **Phone:** 303-384-6672 **Fax:** 303-384-6432 **E-mail:** alex_zunger@nrel.gov	
Technical Monitor: Satyen Deb **Phone**: 303-384-6405 **Fax**: 303-384-6481 **E-mail** satyen_deb@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: \$730,000 2000: \$308,000	**Cost Share Funding:**

Project Objective:
1. Suggest methods to dope n-type CIGS.
2. Explore theoretically the properties of BAs-GaAs as potential high-efficiency PV material.

Approach/Background:
- Whereas n-type doping of $CuInSe_2$ is attainable, that of Cu $(GaIn)Se_2$ is difficult. Thus, devising new methods to accomplish this is crucial for CIGS cells and for future tandem structures with wide-gap components.
- Whereas, Nitrogen doping of GaAs *reduces* the band gap and leads to the desired ~1eV gap for solar cells, Boron doping of GaAs leads to *increase* of the band gap. We need to find out why this is so, and establish the viability of this new material to PV.

Status/Accomplishments:

1. *Suggest methods to dope n-type CIGS:* Completed. Two approaches of co-doping were given 12/00 to the CIS experimentalists (R. Noufi, Ramanathan), so this can be tested:
   (a) Cu-poor CIGS: Cl-on-Se site or Br-on-Se-site.
   (b) Cu-rich CIGS: Cd-on-Ga site plus two Cl-on-Se-site.

   Further theoretical progress awaits feedback from experimentation with the above-suggested co-doping recipe. The potential benefit is the possibility to use Ga-rich alloys while still being able to dope them.

2. *Explore theoretically the properties of BAs-GaAs as potential high-efficiency PV material:* Completed. A detailed paper entitled "Electronic Structure of BAs and boride III-V alloys" by G. Hart and A. Zunger was published in Phys. Rev. B and the results were first given to the relevant NREL experimentalists (J. Geist). This work predicts the band structure and bonding characteristics of the novel material BAs and the properties of the BGaAs. Highlights include the prediction that addition of BAs to GaAs will not lead to a ~1eV band gap (unlike addition of GaN), and that the band structure of BAs resembles, surprisingly, that of Si, not III-V's. The benefit of this work is in creating a knowledge base for the largely unexplored high-efficiency material BGaAs.

3. *Additional unplanned accomplishments:*
   (a) *Theory of clustering and alloy evolution in GaAsN:* By randomly and gradually adding nitrogen atoms to a large (~10,000 atom) supercell of GaAs and calculating the electronic structure, we predicted how the properties of GaAsN develop, starting from isolated impurities, going through impurity-pairs, triples, and finally the fully developed alloy. Three papers written, in collaboration with ER program.
   (b) *Theoretical model for the low-energy sub-gap emission in ordered $GaInP_2$:* Published a paper in Physical Review Letters explaining the previously puzzling sub-gap emission as arising from "sequence mutations" in the GaP/InP layers. Also, published another Physical Review Letter explaining how surface segregation leads to surface ordering in $GaInP_2$. These two publications represent a significant breakthrough in our understanding of the structure of the high-efficiency material $GaInP_2$.

(c) *Explanation of In segregation in InGaAs:* Indium segregates to the surface when growing (e.g., TPV) InGaAs films. This also affects ordering. Our recent Physical Review Letters article explains these effects.

4. Other Accomplishments:
- Published a paper in "Nature."
- Published two papers in Phys. Rev. Letters.
- Published two papers in Rapid Communications.
- Awarded the John Bardeen award for FY01.

Planned FY 2001 Activities: The goals and objectives for the solid state theory work are: (1) For the theory and predictions of transparent conducting solids (SnO_2; $CuAlO_2$), our objective is to develop the first systematic theoretical understanding of the causes of p and n-type conductivity in normally insulating oxides, and to use this understanding to suggest novel transparent conducting materials for PV applications; (2) A second objective is to model theoretically the microstructure of InGaAsN and its effect on the electronic and transport properties, including carrier localization.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:
PV-Related Publications:
G. Hart and A. Zunger, "Electronic structure of BAs and boride III-V alloys", Phys. Rev. B **63**, 13,522-13,537 (2000).

J.-H. Cho, S. B. Zhang, and A. Zunger, "Indium-indium pair correlation and surface segregation in InGaAs alloys", Physical Review Letters **84**, 3654 (2000).

S. B. Zhang, S. H. Wei, and A. Zunger, "The microscopic origin of the doping rule", Physical Review Letters **84**, 1232-1235 (2000).

P. Kent and A. Zunger, "N-N pairs and N-N-N triplets in GaAs", submitted to Phys. Rev. B.

S. B. Zhang, S. H. Wei, and A. Zunger, "P *vs*. n doping asymmetry and defect physics in ZnO", Phys. Rev. B (in press).

S. H. Wei, S. B. Zhang, and A. Zunger, "Band structure and stability of ternary semiconductor polytypes", Jpn. J. Appl. (in press).

Novel Growth Methods for GaInNAs for High-Efficiency Solar Cells

Contract #: AAD-9-18668-08	**Contract Period:** 5/26/99–7/25/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	North Carolina State University Department of Electrical and Computer Engineering Raleigh, NC 27695-7514	
	Organization Type: CU	**Congressional District**: 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Salah M. Bedair **Phone:** 919-515-5204 **E-mail:** bedair@eos.ncsu.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $59,590 2000: $72,338	**Cost Share Funding:**

Project Objective: We propose to investigate the $Ga_{1-y}In_yAs_{1-x}N_x$ material system for the bottom cell of the cascade structure. Lattice matching to GaAs can be achieved by adjusting the values of both x and y. A decrease in the band gap from that of GaAs can be achieved by increasing the value of either x or y or both, while maintaining the lattice matching condition. Thus this quaternary alloy can offer, for the first time, the long awaited material system that can make possible optimum bottom cell performance in a cascade solar cell structure.

Approach/Background: GaInAsN suffers currently from incompatible growth conditions inherent to the chemistry of the material system. For example, (i) optimum growth temperatures of the respective GaN and GaAs compounds are ~1000 °C and ~700 °C respectively, (ii) the relatively low AsH_3/TMGa ratio required to allow for N incorporation in GaInAsN is not optimum for growth of good quality GaAs, and (iii) very poor incorporation efficiency of N due to the lack of efficient N sources at very low growth temperatures of ~600 °C or less. Conventional growth techniques such as MOCVD and MBE do not offer enough flexibility to address these incompatible growth conditions, resulting in the current status of relatively poor GaInAsN. We propose to use new techniques, developed in our lab, such as Atomic Layer Epitaxy (ALE) and Molecular Stream Epitaxy (MSE) where more flexibility can be offered by having separate exposures to column III and column V precursors. Precise control of exposure times to As and N containing precursors with optimum fluxes will benefit the controlled sequential growth of either the As or N sublattices. These techniques also allow growth at low temperatures since metal atoms (Ga or In) have higher mobility in the absence of column V species (As or N). Also, column V precursors decompose more readily on a growth surface occupied by metal species.

Status/Accomplishments: We have conducted and continue to develop models of carrier transport, and internal quantum efficiency, η in GaAsP/InGaAsN and related MQW structures. Carrier transport and η are modeled by the carrier escape from the (InGaAsN) wells, with the efficiency typically depending on the carrier lifetime in the well, τ_r, relative to the escape time from the well, τ_e. If $\tau_r >> \tau_e$, carriers will escape from the well much faster than their lifetime, and high values of η will be obtained. It is possible to achieve an η of ~100% if $\tau_r >> \tau_e$. The values of these lifetimes are determined by a number of key parameters. These include intrinsic material properties such as carrier effective masses, band discontinuities, quantum well and barrier width, and external factors such as temperature and field strength. Both radiative and nonradiative recombination processes can be important in determining carrier lifetime τ_r. For the strained InGaAs and GaAsP ternaries in the composition range to be considered with defect free interfaces (no dislocations) it is expected that the recombination rate be basically determined by the radiative lifetime. τ_r can be represented by $\tau_r = \alpha T^\beta$ where $\beta = 0\text{-}2$. Carrier escape time, τ_e from the wells can be presented as $1/\tau_e = 1/\tau_{TH} + 1/\tau_{tn}$, where τ_{TH} and τ_{tn} are escape time due to thermionic emission and tunneling processes. For the proposed MQW structures with fairly thick barriers and operating temperature at 300 K or even higher (for high solar concentration) it can be shown that $\tau_{tn} > \tau_{TH}$. In these SLS based solar cell structures, the carriers main escape process from the well is expected to be mainly due to thermionic emission, i.e., $\tau_e \sim \tau_{TH}$. The above approach has been applied for several QW structures such as GaAsP/InGaAs, GaAsP/InGaAsN, BGaAs/InGaAs and BGaAs/InGaAsN. We have performed preliminary calculations based on carrier escape by thermionic emission from the MQW structures described above. Both strain and quantum size effects are included in our estimates. Assuming well widths of 100 Å, and limits of N and B content of 1% and 3% respectively, plots have been made of escape lifetime and η vs. effective band gap, η vs. radiative lifetime, and η vs. T.

Modeling results indicate that even at room temperature operation using the MQW approach, a cell with E_g in the range 1.1 - 1.2 eV can be achieved with fairly high values of η. Models of η as a function of operating temperature show that values in the high 90% can be achieved for temperatures above 400 °C - which can be an expected temperature for operation at high solar concentration. Modeling efforts will be reconciled with results from our growth efforts by modified MOCVD techniques such as molecular stream epitaxy (MSE) using the rotating susceptor approach.

Planned FY 2001 Activities: Efforts will continue in the development of $In_xGa_{1-x}As_yN_{1-y}$ bulk films ($y \leq 0.03$) and GaAsP/ $In_xGa_{1-x}As_yN_{1-y}$ based multi-quantum wells ($y \cong 0.01$) while maintaining the lattice matching condition to the GaAs substrate in all cases. MOCVD growth techniques at reduced to low temperature (500 °C < T_g < 600 °C) such as MSE, use of dimethylhydrazine (DMHy) as the column V precursor, and reduction of the V/III (As/Ga) gas phase ratio will be used to increase nitrogen incorporation in the grown films.

Efforts will also continue in the modeling of the proposed GaAsP/$In_xGa_{1-x}As_yN_{1-y}$ strained layer superlattices that have effective band gaps in the 1.2 to 1.1 eV range. We will build on our modeling results obtained in the past year (see Status/Accomplishments above) and will address issues such as: i) the behavior with temperature of parameters such as radiative lifetime, quantum efficiency (η), and thermionic emission characteristics of GaAsP/InGaAsN-SLS-based lower cells, ii) the effects and limitations of doping as related to the built-in field of GaAsP/InGaAsN SLSs, and iii) the potential advantages of adding B to this system.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

S. M. Bedair, J. C. Roberts, D. Jung, B. F. Moody, N. A. El-Masry, T. Katsuyama, "GaAsP/InGaAsN Strained Layer Superlattices for Solar Cell Applications", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

S. M. Bedair, J. C. Roberts D. Jung, B. F. Moody, N. A. El-Masry and T. Katsuyama, "Analysis of p^+-AlGaAs/n^+-InGaP tunnel junction for high solar concentration cascade solar cells" *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

S. M. Bedair, J. C. Roberts, and N. A. El-Masry, "GaAsP/InGaAsN Strained Layer Superlattices for Solar Cell Applications", Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, pp. 127-128 (2000).

Improved Transparent Conducting Oxides for PV

Contract #: AAD-9-18668-05	**Contract Period:** 5/12/99–7/11/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Northwestern University Department of Materials Science and Engineering Evanston, IL 60208-1110	
	Organization Type: CU	**Congressional District**: 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Thomas O. Mason **Phone:** 847-491-3198 **E-mail:** t-mason@nwu.edu	
Technical Monitor: Richard Matson **Phone**: 303-384-6431 **Fax:** 303-384-6604 **E-mail:** rick_matson@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: \$75,520 2000: \$89,592	**Cost Share Funding:**

Project Objective: This subcontract focuses on next generation transparent conducting oxides (TCOs) for improved photovoltaic performance. More specifically, there are two research foci—1) improved Sn-based, n-type TCOs aimed at enhanced CdTe PV cell performance, and 2) novel Cu-based, p-type TCOs applicable to a variety of existing and potential PV designs. The objective of the research under this subcontract is to identify, characterize, and optimize (e.g., by doping, annealing, etc.) novel compound transparent conducting oxides, both in bulk and in thin film form, for current and emerging photovoltaic technologies that can meet the long term goal of producing low-cost electricity from sunlight.

Approach/Background: Most current transparent conductors are primarily single-oxide host systems, e.g., based on In_2O_3, SnO_2 or ZnO. Our premise is that improvement in TCO behavior (higher conductivity, better optical transparency) will likely *not* be obtained in these already optimized materials. Our approach is to develop complex, compound oxide TCOs with improved TCO properties. Based upon well-known figures of merit for transparent conductivity, our approach is to develop high mobility, optically transparent materials. Several crystal-chemical strategies are being employed in this work—1) the development of layered TCO compounds, where doping takes place in carrier injection layers separate from the otherwise unperturbed conduction layers, 2) multi-site compounds, with separate sites involved in doping vs. conduction, and 3) electronic hybridization in multi-cation systems involving two or more TCO-active species (e.g., we are looking at ternary and higher combinations of d^{10} species like In, Sn, Zn, Cd, etc.). Cd_2SnO_4 is an excellent example of both multi-site and hybridization strategies and, as documented at NREL, possesses high carrier mobility. In addition, certain phases may form metastably in thin films which do not tend to form in the bulk. Again, Cd_2SnO_4 is an outstanding example. Our work (see below) shows that the orthorhombic form of Cd_2SnO_4 is stable in the bulk, whereas the high mobility spinel form can only be produced (and readily so) in films. Based on this and other similar observations, our approach calls for a combination of bulk and thin film methodologies to fully enable the development of novel TCO materials. In the p-type TCO area, we are investigating copper-based delafossites by bulk (including hydrothermal synthesis) and thin film methods.

Status/Accomplishments: In the synthesis and characterization of bulk materials, we have synthesized and made TCO property measurements on the promising solid solution between $CdIn_2O_4$ and Cd_2SnO_4. The solid solution does not extend all the way to Cd_2SnO_4, but terminates at x=0.7 in $(1\text{-}x)CdIn_2O_4\text{-}xCd_2SnO_4$. This result indicates that cubic Cd_2SnO_4, routinely obtained in thin films, is metastable. Bulk conductivities range from 2200 S/cm to 3500 S/cm, whereas optical band gap decreases from 3.0 to 2.8 eV, with increasing x. We have also characterized the Cd and Sn co-doped In_2O_3 solid solution, which is stable up to x=0.34 in $In_{2-2x}Cd_xSn_xO_3$. Electrical conductivity is not as high in this solution as in the spinel phase. The phase diagram of the In-Cd-Sn-O system is nearing completion, as is an analysis of potential underlying defect models for these TCO materials

It was thought that the cation distribution in the $CdIn_2O_4\text{-}Cd_2SnO_4$ spinel may play an important role in governing its TCO properties, i.e., the significant increase in conductivity and concomitant drop in band gap in the mid-range of the solid solution. Time-of-flight neutron diffraction experiments were carried out on $^{112}CdIn_2O_4$ at Argonne National Laboratory. In combination with X-ray diffraction data, combined Rietveld analysis showed the cation distribution to be close to normal. Analysis of intermediate compositions is ongoing, however TEM-ALCHEMI measurements showed that the distribution tended to randomize as x increased in $(1\text{-}x)CdIn_2O_4\text{-}xCd_2SnO_4$. A final report re: TCO properties vs. cation distribution is forthcoming.

Pursuant to the investigation of p-type TCO materials, phase-pure $CuAlO_2$ was prepared by standard ceramic synthesis in air at 1050°C. The equilibrium electrical properties were measured over the temperature range of 650-750°C under controlled atmospheres on bar-shaped specimens. The small positive pO_2 dependence of conductivity confirmed the p-type character, but was inconsistent with native defects controlling the defect chemistry. Rather, tramp impurities are believed to dominate. Attempts to acceptor-dope this material were unsuccessful. The undoped material has a temperature-independent thermopower (constant carrier content) and a thermally-activated conductivity, i.e., the mobility is activated (small polaron conduction). This fact underscores the low mobility of this material. As a result, other more promising delafossites (more susceptible to doping and/or with potentially higher mobilities) are under investigation.

One promising result re: $CuAlO_2$ is the ability to achieve much larger oxygen non-stoichiometries in hydrothermally synthesized powders, as evidenced by thermogravimetric analysis. These powders are black, consistent with a much higher level of doping. Work is currently underway to more fully characterize the TCO and related properties of hydrothermally synthesized $CuAlO_2$ and related delafossites.

Over the past year, highly promising thin films of Cd-based TCOs were produced by MOCVD and pulsed laser deposition (PLD). In support of the MOCVD effort, novel Sn and Cd precursors were developed, most notably $Sn(acac)_2$ and $CD(hfa)_2TMEDA$ (hfa=hexafluoroacetoneate, TMEDA=tetramethylethylenediamine). Using the Cd precursor, pure CdO films were grown with room temperature conductivities of ~3500 S/cm and mobilities of ~200 cm^2/Vs. With an indium doping of 5 at%, MOCVD films with conductivities as high as 16,000 S/cm and band gaps in excess of 3.1 eV were produced. Similar success was achieved in PLD CdO films grown at 700°C on $MgF_2(001)$ substrates; room temperature conductivities as high as 4000 S/cm were realized (μ~105 cm^2/Vs). In-doped CdO films grown by PLD on MgO(100) and $MgF_2(001)$ substrates at 500°C exhibited conductivities as high as 42,000 S/cm. The optical band gap increases with Sn doping, from 2.4 eV for undoped CdO to 2.8 eV for 6 at% doped films.

Cd_2SnO_4 films have been successfully grown by MOCVD using $Cd(hfa)_2TMEDA$ and $(Bu)_2Sn(O_2CCF_3)_2$ as precursors. Argon was used as the precursor carrier gas and H_2O-saturated O_2 as the oxidant gas. ICP-AES confirmed the 2:1 Cd-to-Sn stoichiometry within experimental error. Room temperature transport studies showed the conductivity, carrier content, and mobility to be 2170 S/cm, 6 x 10^{20} cm^{-3}, and 20 cm^2/Vs, respectively. Optical transparency was better than 80% over most of the visible range. The electrical properties are not as high as in rf-sputterd films, but have significant potential for further optimization.

Planned FY 2001 Activities: We plan to complete our bulk phase diagram and point defect analysis of phases in the In-Cd-Sn-O system, with special attention to the TCO spinel and bixbyite solid solutions. We will also wrap up our comprehensive analysis of cation distribution in the spinel phase, as detemined by a combination of various techniques—Rietveld analysis of combined time-of-flight neutron diffraction on 112Cd-enriched powders and X-ray diffraction, TEM-ALCHEMI, and Mössbauer (in collaboration with The Colorado School of Mines)—to resolve the issue of what role cation distribution plays in the TCO properties.

With respect to p-type TCOs, bulk work will extend from $CuAlO_2$ to other more promising delafossites involving larger host cations (e.g., Y, Sc, In) and the potential for acceptor doping and/or oxygen stoichiometry modifications. Both standard ceramic synthesis and hydrothermal synthesis (HTS) methods will be employed, especially given the propensity for HTS to yield metastable compositions and/or defect populations.

In the thin film area we will continue to optimize MOCDV and PLD for the deposition of high mobility Cd-based (CdO and spinel) n-type TCOs, with attention to choice of substrate and variation of deposition parameters. We are also initiating growth of p-type TCOs (e.g., copper-based delafossites) for comparison with the bulk results. It may be possible to achieve metastable compositions and/or defect populations in films grown under specific conditions.

Major Reports Published in FY 2000:

T. J. Coutts, T. O. Mason, J. D. Perkins, and D. S. Ginley, "Transparent Conducting Oxides: Status and Opportunities in Basic Research," in Photovoltaics for the 21st Century, V. K. Kapur, R. D. McConnell, D. Carlson, G. P. Ceasar, and A. Rohatgi, eds., Electrochem. Soc. Proc. 99-11 (1999) pp. 274-288.

T. O. Mason, "Transparent Conducting Oxides: New Materials," Proc. MRS Workshop on Transparent Conducting Oxides, Denver, CO, June 19-20, 2000 (Summary of Workshop Breakout Session).

Major Articles Published in FY 2000:

D. R. Kammler, D. E. Edwards, B. J. Ingram, T. O. Mason, G. B. Palmer, A. Ambrosini, and K. R. Poeppelmeier, "Novel Compound and Solid-Solution Transparent Conducting Oxides for Photovoltaics," in Photovoltaics for the 21st Century, Kapur, V. K., McConnell, R. D., Carlson, D., Ceasar, G. P., and Rohatgi, A., eds., Electrochem. Soc. Proc. 99-11 (1999) pp. 68-77.

D. R. Kammler, T. O. Mason, and K. R. Poeppelmeier, "Phase Relationships, Transparency, and Conductivity in the Cadmium Indate-Cadmium Stannate System, " *Chemistry of Materials*, 12 (7) 1954-1960 July (2000).

A. J. Freeman, K. R. Poeppelmeier, T. O. Mason, R. P. H. Chang, and T. J. Marks, "Chemical and Thin Film Strategies for New Transparent Conducting Oxides," *Mat. Res. Soc. Bull.*, 25 (8) 45-51 August (2000).

Chemical Reaction Modeling for Encapsulants in Photovoltaic Modules

Contract #: AAD-9-18668-16	**Contract Period:** 5/24/99–7/23/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
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<tr><td>Organization Type: CU</td><td>Congressional District: 5</td></tr>
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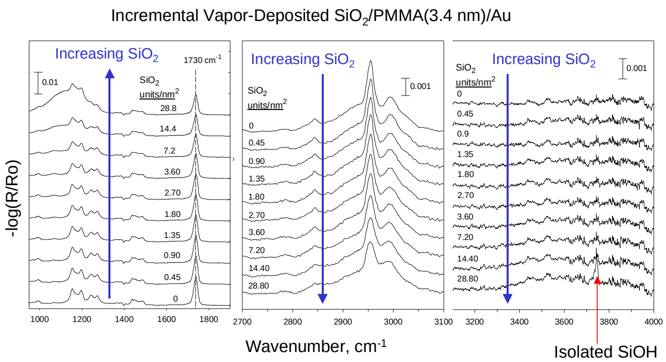
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $54,170
2000: $88,242</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this work is to develop a database of the fundamental processes that can occur at the interfaces between the inorganic oxides, SiO_2, Al_2O_3 and TiO_2, and an organic polymer which contains the types of organic functional groups (OFGs) that are present in the EVA pottant layer in a field-exposed PV device. The database is expected to cover the effects of temperature and humidity, the effects of acetic acid and associated reaction rates and parameters for those processes likely to be critical in PV field degradation.

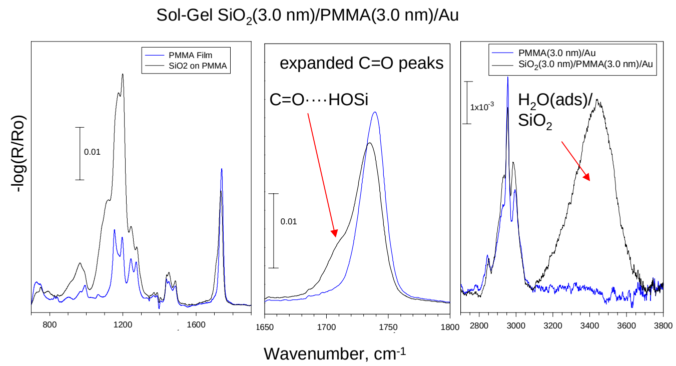
Approach/Background: The fundamental chemical processes that occur at model inorganic oxide(IOX)/OFG interfaces are to be explored experimentally through the use of model structures that incorporate essential features of actual PV structures. A comprehensive body of possible reactions will be tested for using two different types of basic structures: those made from self-assembled monolayers with specific OFGs and those made using polymer films. In the first structure, OFGs are to be reacted with vapor-deposited SiO_2, Al_2O_3 and TiO_2, with the emphasis on SiO_2. The effects of acetic acid (HOAc), T, and RH will be investigated with variations of T up to 85 °C. In the second structure polymer films will be formed on oxide substrates and the effects of HOAc, T, and RH studied. Once important processes are identified, ways will be developed to measure the reaction rates. The aim is develop reliable data that eventually can be used as input for predicting the long-term consequences of exposure of these interfaces to the environment.

Status/Accomplishments: This year's focus was on developing and evaluating each of the model interfacial structures for the oxide SiO_2. In addition, preliminary work was done to evaluate the possibility of direct studies of multicomponent sheet glass, particularly soda lime glass since it is the typical glass layer in an actual PV device. Each of these model structures is intended to provide information on the PV polymer-glass interface. The following abbreviations are used here: IOX = inorganic oxide, OFG = organic functional group (either self-assembled monolayers [SAMs]or polymer films). Vapor refers to vapor deposited and solution to solution deposited. Overall, we were successful in developing workable forms of all but one of the proposed polymer/oxide models for the case of SiO_2 oxide, SAMs and the model polymer PMMA [poly(methyl methacrylate)]. Further, we showed that quantitative IR analysis of the interfacial chemical reactions can be done. The effects of H_2O in these different interfaces was examined and a preliminary thermally-induced degradation run was done. The one model which proved difficult to develop was the SiO_2(sol-gel)/ester SAM/Au. High quality IOX(vapor)/OFG, IOX(solution)/OFG, OFG/IOX(solution) and OFG/IOX(sheet) structures were made successfully and shown to be viable for quantitative characterization by infrared reflection spectroscopy (IRS).
Figure 1 shows an example of an experiment on the SiO_2(vapor)/PMMA interface. PMMA contains ester groups and serves as an excellent analog to the more complex EVA polymer used in PV devices. This model structure will serve to study the effects of temperature, humidity, etc. on the polymer/silica interface.
Figure 2 shows IR spectra of the model structure of SiO_2(sol-gel)/PMMA. The spectra show that the ester C=O group is highly H-bonded by the SiOH groups present at the SiO_2 surface. Exposure to elevated temperature and humidity is expected to induce interfacial degradation. Preliminary results show that accelerated degradation of the PMMA interface occurs upon heating to ~115 °C for less than 10 minutes. The AFM image in the next figure demonstrates that the interface is very smooth as in a non-degraded PV module.

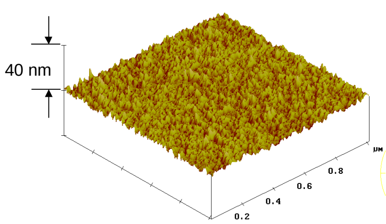
A more complex oxide would be the actual multicomponent glass, typically soda lime glass (SLG), that is used in the modules. We have investigated polymer/SLG structures for some of our planned kinetic studies and have had good preliminary success for the test case of a self-assembled monolayer of $C_{18}H_{37}SiO_X$. Figure 3 shows these interfaces can be directly analyzed by IRS based on the intrinsic optical function of the coating.
Finally, initial attempts were made to make the Al_2O_3 (vapor) and TiO_2 (vapor) structures. These experiments are underway and look to be successful.



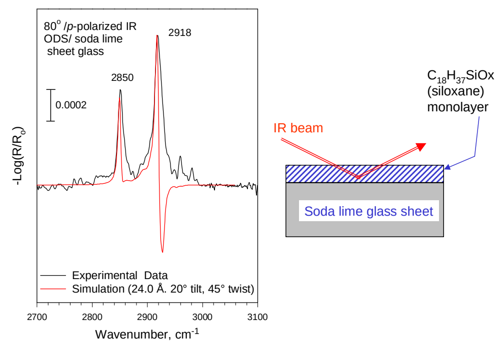
Successful Development of One Model IOX/Polymer Interface:
SiO_2 Vacuum Deposited onto Ultrathin PMMA Films
- No significant chemical interactions seen under the vacuum conditions
- Exposure to H_2O and heat will be checked for onset of interfacial degradation



Successful Development of A Second Model IOX/Polymer Interface: Sol-Gel-Deposited SiO_2 onto an Ultrathin PMMA/Au Film:
- IR shows strong H-bonding of the PMMA ester groups at the interface
- Comparison with the vac-deposited SiO_2 case shows interfacial interactions are induced by the presence of H_2O.



AFM image (1x1 μm^2) of SiO_2(sol-gel; 3 nm) / PMMA(3 nm) /Au. The Interfacial rms roughness is estimated to be 0.6-0.8 nm, similar to that of an optically polished sheet glass / polymer interface.



Preliminary result showing feasibility of quantitative IR studies of the polymer/soda lime glass interface

Planned FY 2001 Activities: The main focus of the coming year's work will be:

- All the SiO_2/Organic SAMs will be prepared, pre-characterized by IR and XPS and ellipsometry, then exposed to elevated temperatures ranging up to 80 °C. The exposure conditions will include inert gas, controlled humidity and acetic acid vapor. The samples will be removed at intervals and analyzed for interfacial degradation. The data will be analyzed for the kinetics of the degradation(s). The organic materials will include PMMA and the methylester-terminated SAM/Au. Model interfaces with poly(vinyl acetate) [PVA] will be made and tested. The acetate-terminated SAM will be made by self-assembling $HS(CH_2)_{16}OAc$ on Au and then used as with the other samples.
- Work will be done to start in-situ XPS characterization of the IOX(vapor)/Organic structures.
- Using the above model interfaces as analogs, new model structures will be made using Al_2O_3 instead of SiO_2 and then characterized. Initial exposure runs will be done.
- Followup work will be done to develop the multicomponent sheet glass/polymer interface structures. IRS and XPS characterization of these will be more difficult than the Au substrate based samples because of intrinsic electric field and charging effects, respectively, but efforts will be made to develop kinetics experiments.
- Initial work will be started incorporating EVA pottant polymers into the most well developed IOX/polymer structures.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Fundamental and Exploratory Research

Real Time Optics for the Growth of Textured Silicon Film Solar Cells

Contract #: AAD-9-18-668-09	**Contract Period:** 8/13/99–8/12/02

<table>
<tr><td>Sponsoring Office Code:</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>DOE Funding Allocation:
1999: $66,700
2000: $58,026</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The goal of this research project is to apply polarized-light probes both *ex situ* and *in situ* (i.e., in real time), including ellipsometric spectroscopy as well as the newly-developed Stokes vector and Mueller matrix spectroscopies, in order to better characterize and understand the fabrication of textured thin films used in photovoltaics technology. The specific objectives of this project are as follows: (i) to characterize thin film materials in their textured states as used in solar cell optimization and module production, (ii) to develop improved optical models for surface roughness and non-uniformity from microscopic to geometric scales, and (iii) to establish methods for measuring and controlling the evolution of roughness and texture in thin film silicon solar cells.

Approach/Background: Thin film solar cell designs based on silicon employ textured film surfaces and interfaces in order to scatter the incident solar radiation into oblique angles so that it can be captured and absorbed within the film more efficiently. In effect, the texturing serves to increase the optical path length of the weakly-absorbed, near-infrared rays within the silicon film, leading to an increase in overall absorptance, and hence an increase in solar cell efficiency. In spite of the importance of textured Si thin films, much of the basic research on materials and solar cells employs untextured (or specular) sample structures owing to the complexities introduced by light scattering. As a result of this emphasis, a basic understanding of the role of surface texturing has lagged behind other materials optimization issues. In this project, optical techniques are being developed and applied that are suitable for *ex situ* and real time analysis of textured surfaces before, during, and after solar cell fabrication. These techniques include ellipsometric, Stokes vector, and Mueller matrix spectroscopies in which incident light in varying polarization states is directed at the textured surface at an oblique angle, and full spectra (275-825 nm) in the reflected beam (i) irradiance, (ii) polarization tilt and ellipticity angles, and (iii) degree of polarization are all determined with a time resolution of 50 ms. With such a capability, it is expected that one can design textured silicon surfaces based on a deeper understanding, rather than on trial-and-error variation.

Status/Accomplishments:

A database of optical properties has been established for solar cell modeling.

Analytical formulas have been developed to describe the optical properties, i.e., index of refraction and extinction coefficient, for several thin film components of silicon-based solar cells. These components include: (i) doped SnO_2 used as the top contact in p-i-n solar cells, (ii) amorphous and protocrystalline silicon (a-Si:H) and its alloys (a-$Si_{1-x}Ge_x$:H and a-$Si_{1-x}C_x$:H) used as the active layers in multijunction solar cells, (iii) microcrystalline silicon (μc-Si:H:B and μc-Si:H:P) used as the doped layers in the solar cells, and (iv) aluminum used as a back-reflector. The optical properties of other material components of the solar cell have been measured, but their forms are too complicated to be parameterized with analytical formulas at present. These components include: (i) thick ZnO used as the back-reflector dielectric spacer or as a top contact in p-i-n solar cells, (ii) thin ZnO used as a protective layer on top of SnO_2, and (iii) silver used as a back reflector. These analytical formulas (or discrete data, for the latter case) are used as comprehensive inputs in optical modeling of solar cells. [Details are provided in Reference 1.]

An optical model for microscopic surface roughness has been reaffirmed.

A detailed assessment of microscopic surface roughness has been undertaken using real time spectroscopic ellipsometry as a probe of nucleating a-Si:H thin films on smooth substrates and continuously growing a-Si:H films on microscopically rough substrates. Microscopic roughness is defined as the surface modulations having in-plane spatial frequencies characterized by wavelengths L significantly less than the wavelength of the incident probe light (i.e., less than about 100 nm). Microscopic roughness is present at all surfaces and interfaces of the solar cell and must be taken into account in any realistic optical model of the cell. In this study, different effective medium theories of microscopic roughness were assessed in their ability to explain the experimental data. The totality of these data reveal that the optical response of rough surfaces and interfaces is best characterized in terms of an individual layer with a variable volume fraction of the overlying and underlying materials with optical properties determined from the Bruggeman effective medium theory. [Details are provided in Reference 2.]

Contract #: AAD-9-18-668-09

Status/Accomplishments (continued):

A computer program has been developed for optical analysis of specular solar cells.

A computer program has been developed that incorporates all the components necessary for a complete optical model for a-Si:H-based multijunction solar cells on specular substrates. This model includes the following components and capabilities. (i) Analytical expressions for the optical properties of a-Si:H-based active layers are provided that allow the user to incorporate active layer materials of any given optical gap, any given amount of disorder, and any given void volume fraction. (ii) Accurate optical properties of all other material components are incorporated, including doped contact layers, transparent conductors, and back-reflectors. (iii) Both incoherently transmitting layers (>10 µm) and coherently transmitting layers (<1 µm) can be incorporated with any sequence in the model. For example, this allows the modeler to incorporate the effects of the top glass in the p-i-n structure and to add any anti-reflection coatings on this glass surface. (iv) The capability of modeling rough surfaces and interfaces is included using the Bruggeman effective medium theory. Among the outputs provided by this program include: (i) spectroscopic transmission losses (if any -- usually none when a metallic back-reflector is incorporated), (ii) spectroscopic reflection losses, (iii) spectroscopic total absorption, (iv) spectroscopic absorption depth profiles, and (v) optical absorption quantum efficiency. The Penn State group is working closely with BP Solar to implement this program for the analysis of a-Si:H based solar cells for architectural applications.

The first multichannel Mueller matrix ellipsometer has been developed.

In the 1999 Annual Report for this project, the development of multichannel Stokes vector spectroscopy for the analysis of solar cell materials and structures was reported. In this experimental technique, an incident linearly polarized white-light beam is reflected from the structure and the spectrally-resolved polarization characteristics of the reflected beam are obtained as functions of the photon energy. These characteristics (defining the Stokes vector components) include (i) the irradiance (power per cross-sectional area), (ii) the polarization state tilt and ellipticity angles, and (iii) the degree of polarization. From this information and from the tilt angle of the incident linear polarization state, the characteristics of the sample can be deduced, including (i) the optical properties, (ii) the layer thicknesses and material volume fractions, and (iii) the surface and interface roughness layer thicknesses, including microscopic ($L < 100$ nm), macroscopic ($100 \text{ nm} < L < 10$ µm), and geometric components ($L > 10$ µm). In the Mueller matrix ellipsometer, information on possible anisotropy in the roughness components is determined by modulating the incident polarization state characterized by a variable Stokes vector, and thereby directly measuring the sample Mueller matrix. The Mueller matrix is a 4x4 real matrix that characterizes how the sample transforms an incident beam 1x4 real Stokes vector into a reflected beam 1x4 real Stokes vector. It provides information on how an isotropic sample with surface/interface roughness layers scatters/reflects incident linear polarization according to p→p, p→s, s→s, and s→p, where s and p designate the polarization directions parallel and perpendicular to the plane of incidence. In anisotropic systems such as µc-Si:H and polycrystalline silicon (poly-Si), the co-polarized (p→p, s→s) and cross-polarized (p→s, s→p) scattering occurs with different amplitudes. [Details are provided in Reference 3.]

Stokes vector spectroscopy has been applied to the analysis of textured solar cell structures.

[For details and figures, see Phase 1, Quarterly Reports for this project; see also Reference 4.]

Planned FY 2001 Activities:

Optical Modeling

- Continue efforts to make the optical simulation program user-friendly and available to BP Solar in their analysis of specular solar cells used in architectural applications.
- Assess the effect of different variables on the solar cell optical performance as determined from the specular reflection model; variables to be considered include: layer thicknesses, optical band gaps and interface roughness layer thicknesses.
- Incorporate texture into the optical modeling capability using angular dependence of scattering obtained from the literature; use the spectrally-resolved optical scattering loss function determined from real time Stokes vector spectroscopy.

Materials Fabrication and Real Time Analysis

- Develop deposition capability for high rate growth of µc-Si:H by very high frequency (vhf) plasma-enhanced chemical vapor deposition (CVD); design deposition capability for hot-filament CVD of silicon as a high rate process.
- Establish phase diagram for optimized fabrication of µc-Si:H versus of the H_2-dilution ratio and thickness using vhf-PECVD.
- Determine the evolution of optical properties, microstructure, and macrostructure during the growth of textured microcrystalline silicon films by the high rate process.

Major Reports Published in FY 2000:

P.I. Rovira, A.S. Ferlauto, R.J. Koval, C.R. Wronski, R.W. Collins, and G. Ganguly, "Real time optics of p-type microcrystalline silicon deposition on specular and textured ZnO-coated glass surfaces," National Center for Photovoltaics Program Review Proceedings, April 2000, p. 191.

R. J. Koval, A. S. Ferlauto, P. I. Rovira, X. Niu, J. Pearce, R. W. Collins, and C. R. Wronski, "Optimization of protocrystalline Si:H materials and fabrication of stable high-performance solar cells, National Center for Photovoltaics Program Review Proceedings, April 2000, p. 215.

Major Articles Published in FY 2000:

A.S. Ferlauto, J. Koh, P. I. Rovira, C. R. Wronski, and G. Ganguly, "Modeling the dielectric functions of silicon-based films in the amorphous, nanocrystalline and microcrystalline regimes," *Journal of Non-Crystalline Solids* **266**, 269-273 (2000).

H. Fujiwara, J. Koh, P. I. Rovira, and R.W. Collins "Assessment of effective medium theories in the analysis of nucleation and microscopic surface roughness evolution for semiconductor thin films," *Physical Review B* **61**, 10832-10844 (2000).

J. Lee, J. Koh, and R.W. Collins, "Multichannel Mueller matrix ellipsometer for real time spectroscopy of anisotropic surfaces and thin films," *Optics Letters* **25**, 1573-1575 (2000).

P. I. Rovira, A. S. Ferlauto, J. Koh, C. R. Wronski, and R. W. Collins, "Optics of textured amorphous silicon surfaces," *Journal of Non-Crystalline Solids* **266**, 279-283 (2000).

Fundamental and Exploratory Research

Synchrotron Radiation Studies of Photovoltaic Materials and Devices

Contract #: AAD-9-18668-14	**Contract Period:** 4/21/99–6/20/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: CU	**Congressional District**: 27
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Y. H. Kao **Phone:** 716-645-2576 **E-mail:** yhk@acsu.buffalo.edu	
Technical Monitor: Richard Matson **Phone**: 303-384-6431 **Fax:** 303-384-6604 **E-mail:** rick_matson@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $58,330 $2000: $87,295	**Cost Share Funding:**

Project Objective: To investigate atomic and nanoscale structure in thin film PV materials and to find correlations of photovoltaic (PV) characteristics with various microscopic structures, especially the morphology, stoichiometric stability, and intermixing of elements across the heterointerfaces.

Approach/Background: To pursue x-ray studies of various thin film PV materials using synchrotron radiation. As appropriate, grazing incidence x-ray scattering (GIXS), x-ray absorption fine structure (XAFS), angular dependence of x-ray fluorescence (ADXRF), x-ray diffraction (XRD), and anomalous x-ray scattering (AXS) experiments are performed; our previous results have already demonstrated that these techniques are well suited for probing the nanoscale structures, interfaces, and impurities in layer materials. Understanding of the interface is essential for the study of new materials needed to improve the sunlight conversion efficiency for next generation solar cell applications.

Status/Accomplishments: We have been continuing our successful ongoing experiments to study heterointerfaces in thin film PV materials. Several material problems closely related to actual performance of PV devices have been tackled on the basis of the nanoscale structure information obtained from our x-ray measurements. For the purpose of probing the short-range structures, the conventional x-ray diffraction method is not useful; on the other hand, advances in our development of XAFS and ADXRF techniques in conjunction with GIXS and AXS have established that it is now possible to obtain *element-specific* information about various types of thin film PV materials. Working principles of these methods and some results can be found in our previous reports.

In comparison with other existing method such as STEM most commonly used to investigate interfaces in layer materials, our x-ray techniques show many outstanding advantages, for example: (i) Nondestructive characterization of buried interfaces, (ii) Continuously variable probing depth of x-rays from about 3 nm to microns controlled by varying the incidence angle and wavelength of x-rays, allowing the possibility to examine deep buried layers even with high interfacial roughness, (iii) Capability of obtaining depth profile of specific atomic species in complex materials, particularly useful for the study of element distribution across the heterointerface.

Our main effort in the past year has been focused on studying the changes in spatial distribution of constituent atomic species as well as impurities in thin film PV materials as a result of various processing conditions, including: (i) Development of a new quantitative method for nondestructive characterization of the effects of surface roughness and atomic interdiffusion across a heterointerface, (ii) Application of this new method to a study of $Si_{1-x}Ge_x$/Si and CdTe/CdS heterojunctions, (iii) Investigations of other thin film systems CdS/CIS, CdS/CIGS, and Cu diffusion in CdTe.

One of the most important practical problems in thin film PV devices is the effect of heating or prolonged sunlight exposure on the stability of material properties that control the conversion efficiency. To understand the generic mechanisms responsible for the changes in the material properties, we have conducted detail studies of the interface morphology in CdTe/CdS heterojunctions processed under various heat treatment conditions. Our results indicate that the interfacial roughness varies by a factor of two or more with annealing temperature, and Te atoms can actually migrate from CdTe to CdS at relatively low temperatures accompanied by large stoichiometric changes, thereby resulting in significant variations in the PV properties.

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Following the same approach, similar measurements have also been made to investigate the heterojunctions formed between the common window material CdS and $CuInSe_2$ (CIS) or between CdS and Cd_2SnO_4, and also the effects of surface alternation of CIS polycrystalline thin films after chemical treatment. Some results have been presented at a recent International Conference on Ternary and Multinary Compounds (ICTMC-12) held in March 2000, and also NCPV Program Review Meeting in Denver, April 2000.

Another example of the rather unique application of our x-ray methods in PV studies can be found in our recent experiment for probing the distribution of dilute Cu impurities in CdTe. This project is closely related to the current widely discussed problem of Cu diffusion into CdTe/CdS solar cells through the Cu-containing back contacts. Our ADXRF and XAFS results reveal quantitatively the spatial distribution of Cu impurities in a single crystal of CdTe after heat treatment. This information should be useful for tracking the effects of Cu contamination on the changes in the performance of CdTe/CdS solar cells.

Although the GIXS and ADXRF techniques have generally been very useful for probing the interface in layer materials, in all the previous work there was a restrictive condition for data analysis due to an old model which requires that the surface roughness of samples under study must be sufficiently small (usually with a root-mean-square surface height fluctuations σ below about 5 nm) for these methods to work. This limitation has caused serious problems for analyzing the thin film PV materials like CIS, CIGS, and CdS made for actual device applications. To overcome this hurdle, we have recently reconstructed a new model capable of handling samples with high surface roughness even with σ larger than 100 nm and it also provides a global average of density fluctuations over the sample surface. This important progress is of general interest, and also makes it convenient to analyze new thin film materials for advanced PV applications.

Several ongoing research projects are carried out in collaboration with NREL research staffs. Some results have already been reported at professional conferences and also published in refereed conference proceedings and journals.

Planned FY 2001 Activities: To continue the ongoing experiments and analysis with the addition of new projects designed for investigating the interface morphology and intermixing of constituent elements in various types of thin film PV materials. More specifically, the PV materials to be investigated and experiments to be performed will emphasize on the following: (i) CdTe/CdS heterojunctions prepared under different heat treatment conditions, and a quantitative comparison of the heterojunction properties using polycrystalline CdTe samples with varying grain sizes, (ii) New junctions formed between CdS and Cd_2SnO_4 (CTO) as well as between CdS and Zn_2SnO_4 (ZTO) for a study of the interaction between the commonly used window material CdS with CTO and ZTO. This work will be useful for chemical control of the effective thickness of CdS in an effort to enhance the cell efficiency, (iv) A quantitative comparison of junctions formed between CdS and single crystal CIS with those formed between CdS and polycrystalline CIS or CIGS consisting of different phases, (v) Further x-ray studies of dilute impurity incorporation (especially Cu and Sb) in single crystal and polycrystalline CdTe and also the temperature effects on the local structure and distribution of the impurity atoms.

Major Reports Published in FY 2000: none.

Major Articles Published in FY 2000:

Y.L. Soo, S. Huang, Y.H. Kao, S.K. Deb, K. Ramanathan, and T. Takizawa, "Migration of Constituent Atoms and Interface Morphology in a Heterojunction Between CdS and $CuInSe_2$ Single Crystals", J. Appl. Phys. **86** (1999) 6052.

Y. L. Soo, S. Huang, S. Kim, G. Kioseoglou, Y. H. Kao, A. D. Compaan, D. Grecu, and D. Albin, "Effects of heat treatment on diffusion of Cu atoms into CdTe single crystals",Appl. Phys. Lett. **76**, 3729 (2000).

S. Kim, Y.L. Soo, G. Kioseoglou, S. Huang, Y.H. Kao, K. Ramanathan and S. Deb, **"**Nondestructive Characterization of Atomic Profiles in Layer-Structured Photovoltaic Materials Using the Method of Angular Dependence of X-ray Fluorescence (ADXRF)**",** Proceedings of NCPV 2000 Program Review Meeting, p.157 (2000).

S. Huang, Y.L. Soo, and A.D. Compaan), "Effects of Thermal Annealing on the Interface Morphology of CdTe/CdS Heterojunctions", J. Vac. Sci. Technol. (in press).

Y. L. Soo, S. Huang, Y. H. Kao, S.K. Deb, K. Ramanathan and T. Takizawa,"Probing the Interface and Microstructures in CdS/$CuInSe_2$ and InGaAsN/GaAs Heterojunctions by Synchrotron Radiation", Japanese J. Applied Physics (in press).

Yu-Han Cheng, Yun-Liang Soo, Shiwen Huang, George Kioseoglou, Soon-Seok Kim, Yi-Han Kao, Bae-Heng Tseng, Hsueh-Hsing Hung, Tang-Eh Dann, and Huey-Liang Hwang, "Comments on Surface Studies and Surface Alteration of $CuInSe_2$ Polycrystalline Thin Films", Japanese J. Applied Physics (in press).

Fundamental and Exploratory Research

Photovoltaic Devices Based on New Nanocrystal Composites

Contract #: XAD-9-18668-02	**Contract Period:** 7/19/99–9/19/02

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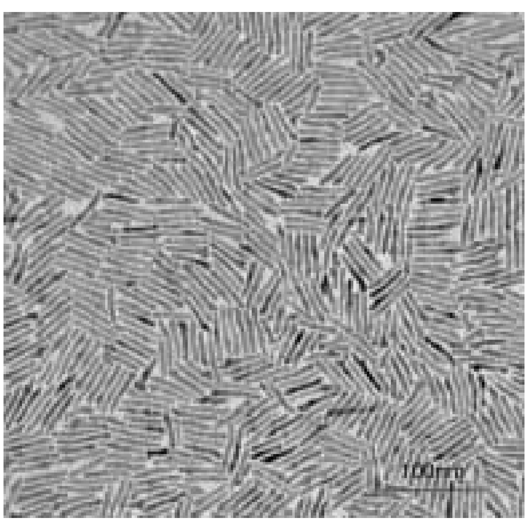
None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $68,680 2000: $60,520</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this proposal is to prepare novel photovoltaics based on nanocrystal/polymer composites.

Approach/Background: There is a great need for inexpensive routes to prepare advanced photovoltaics. Colloidal nanocrystals may be a building block for such materials, since they afford the possibility of inexpensively preparing samples that display quantum size effects. By tuning the size of the nanocrystal it is possible to adjust the band gap and oscillator strength of the absorbing medium. The nanocrystals can be mixed with polymers, yielding a photovoltaic composite. Variations in the polymer can allow us to control the pathways for electrical conductivity.

Status/Accomplishments: In our previous work funded under this contract, (Huynh WU, Peng XG, Alivisatos AP, "CdSe nanocrystal rods/poly(3-hexylthiophene) composite photovoltaic devices,". *Advanced Materials,* **11:** *923-+*, 1999), we showed that we could make basic photovoltaics using nanocrystal/polymer composites, and we identified the key areas of needed improvement. The earlier generation PVs consisted of a composite of randomly dispersed semiconductor particles inside a semiconductor polymer. These devices show reasonable charge separation at the nanocrystal/polymer interface, but it is difficult to collect all the separated charges, because of the complex path that they must follow to the electrodes. This is especially true for the electrons, which have to hop from one nanocrystal to the next, a process which is not terribly efficient. Accordingly, we set out to improve the geometry of the devices, and we are working on three major steps in that direction:



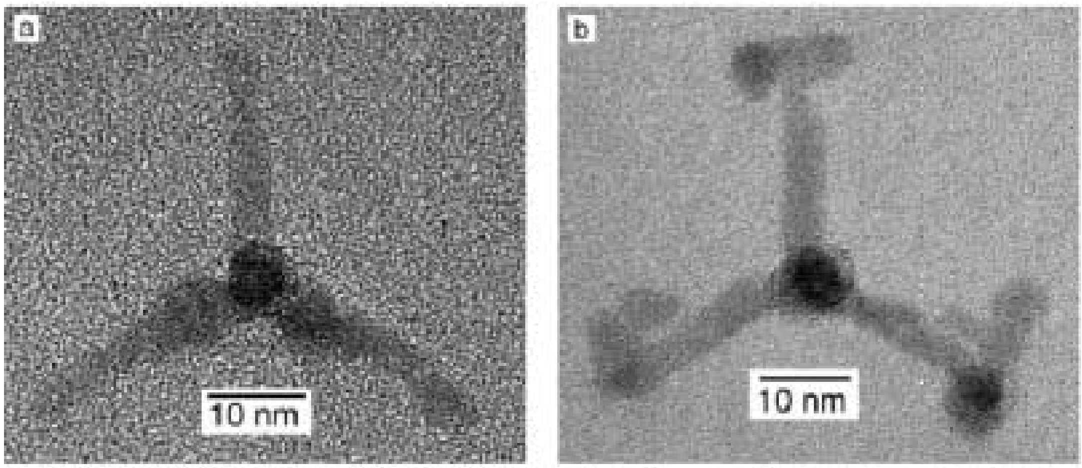
1. Preparation of nanorods. One-dimensional semiconductor nanorods are more suitable as the active components inside photovoltaics than nanocrystals. The reason is that once charge separation at the polymer/nanocrystal interface occurs, then the electron can move readily towards the proper electrode. We therefore developed a new method for the preparation of soluble and processable semiconductor nanorods (Peng XG, Manna L, Yang WD, Wickham J, Scher E, et al, "Shape control of CdSe nanocrystals,". *Nature,* **404:** *59-61*, 2000). CdSe is intrinsically a hexagonal material. Thus, different crystallographic faces can have different growth rates, leading to anisotropic shapes. We have shown that growth of the semiconductor in a binary surfactant mixture can be used to systematically vary the growth rates of the different faces, yielding highly anisotropic nanoparticles. One image of an array of such nanocrystals is shown at left. The rods are highly regular in shape and diameter, which is needed in order to control the optical and transport properties. We can tune the diameter between 2 and 6 nm and the lengths between 2 and 100 nm.

Contract #: XAD-9-18668-02

Status/Accomplishments (continued):

2. Dispersion of nanorods into polymers-electrically active surfactants.
A new issue we have now encountered is that the force between rods is much greater than that between dots. As a consequence, whereas it was relatively easy to simultaneously strip surfactant and disperse dots inside electrically active polymers, it is not so easy to do this with rods. The rods simply tend to macroscopically phase separate. We have initiated a new collaboration with the group of Professor Jean Frechet, here at Berkeley, to prepare organic surfactants that will simultaneously aid in the dispersal of the rods inside the polymers, while at the same time not preventing charge separation at the nanorod/polymer interface.

3. Tetrapods and Inorganic Dendrimers.



Quite unexpectedly, we have found that it is possible to reproducibly prepare "tetrapods," or four nanorods joined at the tetrahedral angle (Manna L, Scher EC, Alivisatos AP, " Synthesis of Soluble and Processable Rod, Arrow, Teardrop, and Tetrapod Shaped CdSe Nanocrystals.,". *Journal of the American Chemical Society,* **in press:** 2000). Images of such structures are shown above. Note that the fourth arm is pointing up out of the page. These structures spontaneously align on a surface and tend to aggregate much less than rods do (because they cannot easily get into close contact). As a consequence, these tetrapods can become the active semiconductor elements in photovoltaics, and we will now actively pursue this possibility as well.

Planned FY 2001 Activities:
In the next fiscal year, we plan the following activities:
- Incorporate nanorods into photovoltaics, and measure optical and electrical responses.
- Make both quantum dot and quantum rod based photovoltaics using electrically active surfactant to enhance charge transport at the interface.
- Make photovoltaics incorporating tetrapods. These will naturally have fully aligned transport paths

Major Articles Published in FY 2000:

Huynh WU, Peng XG, Alivisatos AP, "CdSe nanocrystal rods/poly(3-hexylthiophene) composite photovoltaic devices,". *Advanced Materials,* **11:** *923-+*, 1999.

Manna L, Scher EC, Alivisatos AP, " Synthesis of Soluble and Processable Rod, Arrow, Teardrop, and Tetrapod Shaped CdSe Nanocrystals.,". *Journal of the American Chemical Society,* **in press:** 2000.

Peng XG, Manna L, Yang WD, Wickham J, Scher E, et al, "Shape control of CdSe nanocrystals,". *Nature,* **404:** *59-61*, 2000.

Fundamental and Exploratory Research

GaInNAs Structures Grown by MBE for High-Efficiency Solar Cells

Contract #: AAD-9-18668-07	**Contract Period:** 6/25/99–8/24/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of California, San Diego Dept. of Electrical and Computer Engineering La Jolla, CA 92093-0407	
	Organization Type: CU	**Congressional District**: 22
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Charles W. Tu **Phone:** 858-534-4687 **Fax:** 858-822-3427 **E-mail**: ctu@ece.ucsd.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax**: 303-384-6481 **E-mail**: robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $66,030 2000: $72,027	**Cost Share Funding:**

Project Objective: To investigate novel materials for high-efficiency multi-junction solar cells (SC's).

Approach/Background: To increase the conversion efficiency, tandem SC's, consisting of semiconductor SC's with different band gaps, are realized in monolithic or mechanically stacked design. Monolithic GaInP/GaAs tandem SC's, where GaInP has a larger bandgap than GaAs, has achieved record-setting efficiencies of 26% under the AM0 spectrum, and 30% at 500 suns terrestrial. If a SC with a bandgap smaller than that of GaAs can also be fabricated, the efficiency can be increased further.

Recently we and others have demonstrated that a new material, GaInNAs, can be grown lattice-matched to GaAs substrates and has a range of lower bandgaps than GaAs, in particular, 1.0 eV. We grow GaInNAs by gas-source molecular beam epitaxy using elemental Ga and In, thermally cracked arsine, and a RF plasma nitrogen radical beam source. This approach is expected to result in less carbon contamination as compared to metal-organic chemical vapor deposition.

Status/Accomplishments:
1. *Short period $GaIn_{0.08}As/GaN_{0.03}As$ Superlattices [paper 6]:* Recently, the quaternary $Ga_{1-x}In_xN_yAs_{1-y}$ alloy system has attracted a great deal of attention due to its potential applications in next-generation ultra-high-efficiency multijunction solar cells. The extremely large bowing coefficient (b ~ -16eV) permits the $Ga_{1-x}In_xN_yAs_{1-y}$ quaternary alloy to have a wide range of tunable band gap energies smaller than the GaAs bandgap, while maintaining lattice match to GaAs when x~2.8y.
A problem with GaInNAs, however, is its low carrier mobility and short minority carrier lifetime due to alloy scattering and degradation of material quality with nitrogen incorporation. In order to improve the mobility, we have investigated short-period superlattices (SLs) of GaInAs/GaNAs as a digital alloy of GaInNAs and compare the two. The layers in the SLs are strain-compensated, i.e., GaNAs is under tension and GaInAs is under compression. Thus, thick $GaIn_{0.08}As/GaN_{0.03}As$ superlattices can be grown lattice-matched to GaAs substrates. Short-period SLs of GaInAs/GaNAs were grown by gas-source molecular beam epitaxy. Hall measurement shows electron mobility is improved by a factor of almost two (240 vs. 130 $cm^2/V \cdot s$). The SL miniband effective mass can be theoretically calculated and is about half of the GaInNAs effect mass. The improvement of electron mobility can be attributed to the smaller effective mass of the superlattice structure. The photoluminescence (PL) intensity is improved by rapid thermal annealing (RTA). The PL intensity of digital alloys is 2.5 to 3 times higher than that of the random alloy at room temperature, and the improvement is even greater at low temperature (10K) by a factor of about 12. The optimized RTA condition for short-period SLs is 700 °C and 10 sec in N_2 ambient. Photoconductive decay measurements show a longer carrier lifetime for the SL samples, 0.2 µsec vs. 0.1 µsec for the random alloy, which could be caused by charge separation due to the type-II band lineup of $GaIn_{0.08}As/GaN_{0.03}As$.
We have recently sent four annealed samples to Dr. R. K. Ahrenkiel of NREL and want to see the annealing effect on photoconductive decay time. We are waiting for the results.

2. *AlGaNP:* Incorporating a small amount of nitrogen (~0.5%) in GaP changes the indirect bandgap to direct bandgap, and thus GaNP exhibits a strong room-temperature photoluminescence (PL) at ~ 1.85 eV.[paper 11] Incorporating a small amount of Al into GaNP results in similar PL intensity at room temperature. With 30% Al, the PL spectrum peaks at about 1.55 eV. With only about 1% Al, the PL spectrum is very broad, with a full width at half maximum of about 550 meV. The range covers from 1.4 eV to 1.95 eV. At present we do not know the exact mechanism for the red shift of the PL peak with Al incorporation, which is contrary to expectation. Further characterization is still on going. In any case, the fact that the PL intensity is strong indicates that the minority carrier lifetime may not be short as in the case of GaInNAs. Since GaP is closely lattice-matched to Si, it may be possible that $Al_{0.01}Ga_{0.99}N_{0.01}P_{0.99}$ could be grown on a Si substrate with a GaP buffer layer for an AlGaNP/Si two-junction solar cell with high efficiency.

Contract #: AAD-9-18668-07

3. GaNAs grown by Migration Enhanced Epitaxy (MEE): We try to use Migration Enhanced Epitaxy (MEE) to improve the quality of Ga(In)NAs quality. Five GaAs/$GaN_{0.02}As$/GaAs QW samples were grown. In MEE, the group III and group V fluxes are supplied alternatingly. When the group V flux is absent, the surface migration length of the group III atoms can be increased, thus, achieving comparable material quality as that grown at higher growth temperature with continuous group V overpressure. Furthermore, when the group III flux is absent, the surface smoothness can recover somewhat. In our experiment, 50 Å $GaN_{0.02}As$ wells were grown by MEE with different kinds of shutter sequence. The interruption time per 2 monolayer of $GaN_{0.02}As$ growth varies from 2 seconds to 1 minute. Further characterization is on going.

4. System Maintenance: In the last quarter (July 1 to September 30, 2000), we had to open the growth chamber to fix a problem with the indium shutter and replace all source materials. We also replaced the beam flux gauge and the vacuum gauge in the growth chamber. The RHEED gun filament was replaced to improve performance. The manipulator was realigned to make sample transfer smoothly. Since some problems were complicated, we had to open the chamber 3 times, resulting in a long down time.

Planned FY 2000 Milestones:
- Continue the investigation of the Ga(In)NAs growth by MEE.
- Futher characterize AlGaNP to understand the origin of its broad, but strong, PL spectrum.
- Grow solar cell structures with such a digital alloy and make comparison with random alloys of GaInNAs.

The appendix lists the publications supported by this work. They deal mainly with the materials properties of Ga(In)NAs/GaAs and Ga(In)NP/GaP.

Appendix: Publications in FY2000

Buyanova, I.A.; Pozina, G.; Hai, P.N.; Thinh, N.Q.; Bergman, J.P.; Chen, W.M.; Xin, H.P.; Tu, C.W. Mechanism for rapid thermal annealing improvements in undoped GaN_xAs_{1-x}/GaAs structures grown by molecular beam epitaxy. Applied Physics Letters, vol.77, (no.15), 9 Oct. 2000. p.2325-7.

Xin, H.-P.; Tu, C.W. Photoluminescence properties of GaNP/GaP multiple quantum wells grown by gas source molecular beam epitaxy. Applied Physics Letters, vol.77, (no.14), 2 Oct. 2000. p.2180-2.

Xin, H.P.; Welty, R.J.; Tu, C.W. $GaN_{0.011}P_{0.989}$ red light-emitting diodes directly grown on GaP substrates. Applied Physics Letters, vol.77, (no.13), 25 Sept. 2000. p.1946-8.

Hai, P.N.; Chen, W.M.; Buyanova, I.A.; Xin, H.P.; Tu, C.W. Direct determination of electron effective mass in GaNAs/GaAs quantum wells. Applied Physics Letters, vol.77, (no.12), 18 Sept. 2000. p.1843-5.

Xin, H.P.; Welty, R.J.; Tu, C.W. $GaN_{0.011}P_{0.989}$-GaP double-heterostructure red light-emitting diodes directly grown on GaP substrates. IEEE Photonics Technology Letters, vol.12, (no.8), Aug. 2000. p.960-2.

Hong, Y.G.; Xin, H.P.; Tu, C.W. Improving properties of GaInNAs with a short-period GaInAs/GaNAs superlattice. Conference Proceedings. 2000 International Conference on Indium Phosphide and Related Materials, Williamsburg, Virginia, 18 May, 2000

Yong Zhang; Fluegel, B.; Mascarenhas, A.; Xin, H.P.; Tu, C.W. Optical transitions in the isoelectronically doped semiconductor GaP:N: An evolution from isolated centers, pairs, and clusters to an impurity band. Physical Review B (Condensed Matter), vol.62, (no.7), 15 Aug. 2000. p.4493-500.

Buyanova, I.A.; Chen, W.M.; Monemar, B.; Xin, H.P.; Tu, C.W. Photoluminescence characterization of GaNAs/GaAs structures grown by molecular beam epitaxy. Materials Science & Engineering B, vol.B75, (no.2-3), 1 June, 2000.

Xin, H.P.; Tu, C.W.; Geva, M. Effects of hydrogen on doping of GaInNAs grown by gas-source molecular beam epitaxy. Journal of Vacuum Science & Technology B (Microelectronics and Nanometer Structures), vol.18, (no.3), May 2000. p.1476-9.

Shan, W.; Walukiewicz, W.; Yu, K.M.; Wu, J.; Ager, J.W., III; Xin, H.P.; Tu, C.W. Nature of the fundamental band gap in GaN_xP_{1-x} alloys. Applied Physics Letters, vol.76, (no.22), 29 May 2000.p.3251-3.

Xin, H.P.; Tu, C.W. Effects of nitrogen on the band structure of GaN_xP_{1-x} alloys. Applied Physics Letters, vol.76, (no.10), 6 March 2000. p.1267-9.

Kozhevnikov, M.; Narayanamurti, V.; Reddy, C.V.; Xin, H.P.; Tu, C.W.; Mascarenhas, A.; Zhang, Y. Evolution of $GaAs_{1-x}N_x$ conduction states and giant Au/$GaAs_{1-x}N_x$ Schottky barrier reduction studied by ballistic electron emission spectroscopy. Physical Review B (Condensed Matter), vol.61, (no.12), 15 March 2000. p.R7861-4.

Zhang, Y.; Mascarenhas, A.; Xin, H.P.; Tu, C.W. Formation of an impurity band and its quantum confinement in heavily doped GaAs:N. Physical Review B (Condensed Matter), vol.61, (no.11), 15 March 2000. p.7479-82.

Yong Zhang; Mascarenhas, A.; Xin, H.P.; Tu, C.W. Valence-band splitting and shear deformation potential of dilute $GaAs_{1-x}N_x$ alloys. Physical Review B (Condensed Matter), vol

Fundamental and Exploratory Research

Growth and Characterization of GaInNAs for High-Efficiency Solar Cells

Contract #: AAD-9-18668-17	**Contract Period:** 7/29/99–9/28/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of California, Santa Barbara Materials Department Santa Barbara, CA 93106-2050 **Organization Type**: CU	**Congressional District:** 22
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J.S. Speck and S.P. DenBaars (UCSB) and V. Narayanamurti (Harvard) **Phone:** 805-893-8005 **Fax:** 805-893-8983 **E-mail**: speck@engineering.ucsb.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $54,170 2000: $63,323	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective:
UCSB:
Development of high quality (In,Ga)(As,N) by MOCVD and by MBE.

Harvard (subcontractor from UCSB):
Characterization of (In,Ga)(As,N) by STM and BEEM.

Approach/Background:
UCSB has carried out an extensive literature review of all previous work on GaNAs and InGaNAs. The reported properties, growth by MBE, CBE, and MOCVD, characterization and devices are being evaluated. Of particular interest in the early stages of our project are the MOCVD growth and device work – since our early focus will be on MOCVD growth. Many groups are using alternative precursors, particularly tertiarybutylarsine (TBA) and dimethylhydrazine (DMHy) for the group V sources due to their lower dissociated temperature, usually 500 – 600 C, which is advantageous as numerous studies have shown that higher growth temperatures result in lower N content of the films. Using N_2 as a carrier gas further enhances N incorporation into the films. It has also been shown that the N incorporation decreases with higher In concentrations in InGaNAs films. Again, however, using N_2 as the carrier gas helps with raising the N content. The optical quality of the films is greatly improved by post-growth rapid thermal annealing, as shown by many studies that shown an increase in PL intensity following this treatment.

At Harvard, Narayanamurti has collaborated quite closely with Prof. Charles Tu (UCSD) to make the first STM and BEEM measurements of MBE-grown GaNAs alloys for N concentrations ranging from 0.3% to 2.1%. The BEEM results clearly identify bands which vary markedly with N concentration. They show that N introduces significant band mixing between γ and L and that the impurity induced N resonant level is a smaller, pertubative effect. These measurements have shed a new light on the effects of N on the band structure which previously had relied solely on optical measurements, whose interpretation is controversial.

Status/Accomplishments:
Several 1000 Å undoped $GaAs_{1-X}N_X$ layers (x=0, 0.003, 0.005, 0.007, 0.012, 0.017, 0.021 and 0.025) grown on n^+ (001)-oriented GaAs substrates by gas source MBE were studied by STM and BEEM using a Au tip. To make the Schottky contacts, Au layers (65 Å thick) were deposited by thermal evaporation through a shadow mask at a background pressure of 2×10^{-7} torr. It was found that despite certain surface-related contrast in BEEM, BEEM images are rather uniform for all samples indicating on high uniformity of the Schottky barrier and current transmittance across the sample.

To acquire the BEEM spectra, the tip-to-base voltage was varied between 0.3 and 2.3 V while keeping a constant tunneling current of 4 nA. In an effort to better understand the effect of nitrogen incorporation, we analyzed the second voltage derivative (SD) of the BEEM spectra rather than the original BEEM spectra, since the SD-BEEM spectra approximately represent the heterostructure transmission coefficient, and, therefore, allow an explicit energetic partitioning of the transport channels. Two main features (peaks) observed in the SD-BEEM spectra we associate with the Γ-like and *L*-like conduction minima in GaAsN, originating from gradually moving apart the Γ and *L* peaks of GaAs. As the nitrogen concentration increases, the energetic separation between these peaks increases, with a relative decrease of the *L*-like band contribution to the BEEM current (by two thirds as the nitrogen concentration increases from 0.3% to 2.1%). While the Γ-like threshold decrease has a nearly linear compositional dependence up to x=2.1%, the *L*-like threshold position increases initially at $x \leq 1.2\%$ and then is almost constant. Since nitrogen substitution breaks the crystal symmetry and, as a consequence, splits the fourfold *L* valley into the $a_1(L_{1c})$ singlet and $t_2(L_{1c})$ triplet states, the *L*-like band in the BEEM experiments is mostly weighted on the $t_2(L_{1c})$ triplet state because its large density-of-states (DOS). The alternative *L*-like band identification as a localized resonant *N*-level is very unlikely because in this case one would expect a resonant *N*-level contribution to increase with the nitrogen concentration (larger DOS), whereas the experimentally observed high-energy peak amplitude decreases with the nitrogen concentration. Thus, BEEM results support the explanation that a high-energy state (E_+) in optical experiments derives from nitrogen-induced G-L mixing rather that from a nitrogen-induced resonant impurity state.

The SD-BEEM spectra of two GaAsN samples, x=1.2% and 1.7%, reveal an additional weaker peak (indicated by the arrow), located ~0.40 eV and ~0.43 eV above the Γ-like state, respectively. This peak might represent the contribution from the $a_1(L_{1c})$ singlet state. The weaker amplitude of this peak matches the expected small DOS due to the increasing Γ-character of the $a_1(L_{1c})$ state in the alloy limit.

Another prominent effect of the nitrogen incorporation is a giant decrease of the Au/GaAsN Schottky barrier, from ~0.92 eV at x=0 down to ~0.55 eV at x=0.021. The observed Schottky barrier reduction follows approximately the bandgap reduction. This result that is very important for device applications indicates that the effect of the nitrogen incorporation on the valence band is small.

Planned FY 2001 Activities:
We plan to conduct the STM/BEEM study of $GaAs_{1-x}N_x$ at ultra low nitrogen concentrations ($0.05 \leq x \leq 0.2\%$). This range of concentrations corresponds to the impurity-alloy transition in $GaAs_{1-x}N_x$, and anomalous changes in the band structure parameters are expected. In addition, we plan to study directly the $GaAs_{1-X}N_X$ valence band in the large range of nitrogen concentrations (up to 3%).

We also plan to extend our STM/BEEM experiments on dilute GaInAsN and GaPN, where the effect of nitrogen incorporation is of the same order as in GaAsN. In GaInAsN, substituting a small amount of indium for gallium compensates the strain effect caused by the addition of nitrogen and also further reduces the bandgap, making this system an ideal candidate for 1.3 μm lasers and high-efficiency multijunction solar cells. GaPN, in its turn, has a relatively high-critical concentration for the formation of the impurity band, which makes this material to be an attractive system for investigating the impurity band effects.

Major Reports Published in FY 2000:
V. Narayanamurti, M. Kozhevnikov, C.V. Reddy, H.P. Hin and C.W. Tu, "Ballistic Electron Emission Spectroscopy in Au/$GaAs_{1-x}N_x$" presented in PV Review, Denver Colorado, April, 2000.

Major Articles Published in FY 2000:
M. Kozhevnikov, V. Narayanamurti, C.V. Reddy, H.P. Hin, C.W. Tu, A. Mascarenhas and Y. Zhang, "Evolution of $GaAs_{1-X}N_X$ conduction states and giant Au/$GaAs_{1-X}N_X$ Schottky barrier reduction studied by ballistic electron emission spectroscopy," *Phys. Rev. B* 61, R7861 (2000).

V. Narayanamurti and M. Kozhevnikov, "The Role of BEEM for characterization of physical phenomena in semiconductors alloys and quantum structures," Invited Review Paper in the Selected Topics in Electronics and Systems, Vol. 17 "Frontiers in Electronics: From materials to Systems," eds. Y-S. Park, M.S. Shur, S. Luryi, J.M. Xu and A. Zaslavsky (2000). Journal variant: Int. J. High Speed Electronics and Systems 10, 55 (2000).

M. Kozhevnikov, V, Narayanamurti, C.V. Reddy, H.P. Hin and C.W. Tu "Ballistic Electron Emission Spectroscopy in Au/$GaAs_{1-X}N_X$," *MRS 2000 Spring Meeting*, San Francisco, CA, 24-28 April 2000.

Medium Range Order and Stability in Amorphous Silicon

Contract #: AAD-9-18668-04	**Contract Period:** 6/23/99–8/23/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $75,520 2000: $75,255</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This new contract is intended to resolve whether medium range structural order (MRO) is involved in the formation of metastable electronic defects in a-Si:H films used in solar cells. In order to understand the possible influence of MRO, we must (i) measure and model the existence of MRO in films deposited by various methods; (ii) determine how the order changes upon light soaking, and if reversibly; (iii) understand how the growth process, particularly the large flux of atomic H at the film surface, produces MRO in the microstructure; (iv) predict, through collaborations with solid-state theorists, the electronic structure associated with particular type and volume fraction of MRO in Si:H films; and (v) develop approaches to modify the MRO of a-Si:H films grown in industrial production, in order to reduce the Staebler-Wronski effect and increase solar cell efficiency.

Approach/Background: The MRO of amorphous materials can be represented by higher order correlation functions of atomic positions. We recently developed a new technique called variable coherence transmission electron microscopy (VC-TEM) and shown that it is highly sensitive to three- and four-body correlation functions. Essentially, one is probing the statistical fluctuations in a mesoscopic volume containing about 1000 atoms, which is exquisitely sensitive to medium-range ordering. At present, the most effective way of analyzing our data is based on model simulations. The models we have used are a continuous random network and a "paracrystalline" structure that may be thought of as the fine-grained limit of the nanocrystalline state.

a-Si:H films which are resistant to metastable defect formation can be deposited under carefully chosen conditions: H_2 diluted silane plasma CVD and hot wire CVD are the most feasible in terms of practical solar cell production. The properties of a-Si:H films grown by hot wire CVD at high substrate temperature are substantially different from those of conventional films, including excellent electronic quality at a bonded H concentration of only a few atomic percent, a lower susceptibility to metastable defect formation, and the lack of an internal friction signature characteristic of all other amorphous materials. We will set up a hot-wire CVD system for the growth of a-Si:H films, and analyze the surface and sub-surface H reactions using RIR.

The detailed mechanisms by which reactive growth species interact with a growing surface to produce a-Si:H or μc-Si:H are complex and not well understood, but it is known that the insertion and removal of H from Si–Si bonds plays a key role in the development of the Si microstructure. We have developed an optically enhanced mode of real-time IR reflectance (RIR) spectroscopy to quantify the evolution of Si–H bonding during thin film growth or modification through changes in vibrational mode absorptions. Variations in the intensity, position, line width, and polarization dependence of the IR absorptions correspond to the quantity, configuration, local environment, and orientation of the bonds, respectively.

We will also use real-time spectroscopic ellipsometry (SE) to provide information complementary to RIR. Our SE instrument provides information on the film nucleation, microstructure, crystallinity, bandgap and composition via the optical dielectric response.

Status/Accomplishments:

- Performed fluctuation microscopy on state-of-the-art a-Si:H samples grown by H_2-diluted PECVD (USSC), hot-wire CVD (NREL), and reactive magnetron sputtering (UIUC) [1,2]. These films all showed large and similar signatures (TEM dark-field image variance) of medium-range order (MRO) in the as-deposited state; but upon light-soaking, some films became **more** and others **less** ordered.

Contract #: AAD-9-18668-04

- Grew a-Si:H films by hot-wire CVD in our laboratory. We attempted to reproduce the optimized conditions in the NREL reactor, but obtained a growth rate 4× higher for the same silane pressure. This indicated that the rate of gas supply is a key variable. We therefore used mass spectrocopy to map out the silane depletion as a function of gas flow and pressure, and are now modeling the data in order to obtain reliable scaling relationships between these (or any two) growth chambers.
- Determined the independent effects of substrate temperature, hydrogen flux, and heavy (Ar^+) ion flux on the development of MRO in a-Si films [3,4,6]. Determined the extent to which MRO effects are also visible in Raman scattering and spectrocopic ellipsometry. We now possess an iniital map of the order-processing relationship which will be critically useful in optimizing a-Si:H to reduce the Staebler-Wronski effect.
- Created a working group of scientists, including theorists (Drabold, Zotov, Keblinski) who (i) derived models to explain the observed MRO based on the paracrystalline structure, and extracted the electronic and vibrational states of these models for comparison with experiment [7]; and (ii) recently derived an unhydrogenated paracrystalline Si model that has no defect states in its bandgap [8].
- Showed that the transition from the amorphous to nanocrystalline (microcrystalline) state is not sharp, as previously believed, but is a gradual transition mediated by increasing MRO in a-Si [4-6].
- Built a second hot-wire CVD filament assembly for our "optics" vacuum chamber, which will allow us to perform real-time IR absorption and spectroscopic ellipsometry measurements during growth.

Planned FY 2001 Activities:

- Obtain "standard" and "degradation-resistant" a-Si:H samples from a wide range of NREL team participants, and analyze the changes in MRO upon light-soaking and annealing.
- Grow degradation-resistant a-Si:H films by hot wire CVD, focusing on the use of hydrogen near to the nc-Si:H boundary.
- Use reflection IR spectroscopy to analyze the H-surface reactions during hot-wire CVD of a-Si:H, and formulate initial models.
- Create a molecular dynamics (MD) model of hydrogenated paracrystalline structure.
- Test our MD model for significant structural re-arrangements induced by light, and the relationship of those changes to metastable electronic defect formation.
- Based on the above, show the relationship of MRO to the use of hydrogen dilution and to the Staebler-Wronski effect.
- Deliver hot-wire CVD a-Si:H films grown at UIUC to NREL and to other team members for independent evaluation.
- Deposit a series of mixed phase (a-Si:H / nc-Si:H) materials and evaluate both the MRO and electronic properties.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

P. M. Voyles, M. M. J. Treacy, J. M. Gibson, H-C. Jin, and J. R. Abelson, "Experimental Methods and Data Analysis for Fluctuation Microscopy," Proc. MRS Symp. Q (Nov. 1999).

P. M. Voyles, M. M. J. Treacy H.-C. Jin, J. R. Abelson, J. M. Gibson, S. Guha, and R. S. Crandall, "Comparative Fluctuation Microscopy Study of Medium-Range Order in Hydrogenated Amorphous Silicon Deposited by Various Methods," Proc. MRS (Symp. A, April 2000).

J. E. Gerbi and J. R. Abelson, "Microstructural Control of Thin Film Si Using Low Energy, High Flux Ions in Reactive Magnetron Sputter Deposition," Proc. MRS (Symp. A, April 2000).

P. M. Voyles, J. E. Gerbi, M. M. J. Treacy, J. M. Gibson and J. R. Abelson, "Increased Medium-Range Order in Amorphous Silicon with Increased Substrate Temperature," Proc. National Conference on Microscopy (2000).

J. E. Gerbi and J. R. Abelson, "The Deposition of Microcrystalline Silicon: Direct Evidence for Hydrogen-Induced Surface Mobility of Si Adspecies," accepted by J. Appl. Phys. (2000).

P. M. Voyles, J. E. Gerbi, M. M. J. Treacy, J. M. Gibson and J. R. Abelson, "Absence of an Abrupt Phase Change from Polycrystalline to Amorphous in Silicon with Deposition Temperature," submitted to Phys. Rev. Lett. (2000).

P. M. Voyles, N. Zotov, S. M. Nakhmanson, D. A. Drabold, J. M. Gibson, M. M. J. Treacy, and P. Keblinski, "The Structure and Physical Properties of Paracrystalline Atomistic Models of Amorphous Silicon," submitted to J. Appl. Phys. (2000).

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Experimental Studies of Light-Induced Changes in Long-Ranged Disorder in Amorphous Silicon

Contract #: AAD-9-18668-13	**Contract Period:** 5/14/99–7/13/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	The University of Minnesota School of Physics and Astronomy Minneapolis, MN 55455 **Organization Type**: CU	**Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** James Kakalios **Phone:** 612-624-9856 **Fax:** 612-624-4578 **E-mail:** kakalios@physics.spa.umn.edu	
Technical Monitor: Richard Matson **Phone**: 303-384-6431 **Fax:** 303-384-6604 **E-mail:** rick_matson@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $42,920 2000: $57,114	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The principal objective of the proposed research is the experimental study and elucidation of the role that long ranged disorder plays in the light-induced metastable conductance changes in hydrogenated amorphous silicon (a-Si:H).

Approach/Background: Long range disorder (LRD) , due to compositional modulations or potential fluctuations on length scales of 100 – 1000 Angstroms, is believed to influence the current carrying states at and near the mobility edge in a-Si:H. Amorphous silicon films grown under varying deposition conditions, which have enhanced microstructure, have been synthesized. Experimental studies of the thermopower/conductivity activation energy difference, along with the non-Gaussian statistical properties of the conductance fluctuations, will be employed to quantify the long range disorder in these films, providing a connection between the structural and electronic disorder. Changes in the LRD with light soaking and annealing treatments will then be investigated.

Status/Accomplishments: Studies begun during the previous year, of the sensitivity of light induced defect creation (the Staebler-Wronski effect) on a series of hydrogenated amorphous silicon films (a-Si:H) for which the deposition temperature during film growth was varied from $25 < T < 250$ C have been continued with two new physics graduate students: T. Jim Belich and Jeremy Huston. Mr Huston, starting in my lab in June 2000, completed a research project on Q-function (involving a comparison of the temperature dependence of the dark conductivity and thermoelectric power, which is traditionally interpreted as reflecting long range disorder at the mobility edge) measurements on a series of amorphous silicon-sulfur alloys, grown by Prof. P. C. Taylor's group at the University of Utah. These materials display a Persistent Photoconductivity effect, basically an Inverse Staebler-Wronski effect, wherein light exposure results in an increase in the dark conductivity, which is reversible upon annealing. While the origin of this effect remains undetermined, one proposed model suggests that trapping of photoexcited charge carriers decreases the potential fluctuations at the mobility edge, in essence decreassing the long range disorder following illumination. Mr. Huston's research, however, completed and defended in September 2000, indicates that there is no corresponding change in long range disorder in the persistent photoconductivity effect in these films. However, a more thorough investigation, of a broader class of materials is warrented, based upon Mr. Huston's preliminary results.

Mr. Belich's studies have involved investigations of light induced changes in conductance fluctuations in amorphous silicon. Experimental measurements of the light soaking dependence of both the Q-function (a comparison of the conductivity and thermopower activation energies) and the spectral wandering of 1/f noise (characterizing the time dependence of the noise spectral density, which is a measure of the non-Gaussian statistical character of the fluctuations) in n-type doped a-Si:H have begun. There is a significant decrease in the spectral wandering of the non-Gaussian 1/f noise following light soaking of a device quality film, consistent with earlier studies of the Staebler-Wronski effect and 1/f noise in a-si:H by my laboratory, which suggests an increase in LRD. However, we find no corresponding change in the Q-function following illumination. For films deposited at lower temperatures (which thus contain more hydrogen microstructure) we also observe a shift in the spectral wandering after illumination, which is accompanied by a small change in the Q-function. By comparing the temperature dependence of the 1/f noise for films grown at varying substrate temperatures we find that the light-induced changes in the LRD appear to depend on the annealed state resistance value of the a-Si:H film, which, based upon these preliminary results, may be the key parameter which will enable us to detangle these results.

Contract #: AAD-9-18668-13

Planned FY 2001 Activities: The results described suggest that there is no change in the Q-function nor 1/f noise non-Gaussian statistics following extended light soaking in hydrogenated amorphous silicon films deposited under optimal conditions. These results are puzzling, in that they are in conflict with other experimental measurements which indicate a change in the medium or long range disorder in the Staebler-Wronski effect. Moreover, recent reports have claimed changing the medium range disorder in the material, through variations in the deposition process, such as in Hot Wire CVD or in PECVD under conditions close to those which promote microcrystalline formation, results in films which are resistant to light induced defect formation. In the coming year we intend to:

- Continue the studies of the Q-function and spectral wandering of the 1/f noise in glow discharge deposited a-Si:H films for which the disorder is deliberately increased, by varying the deposition conditions and post-deposition high temperature annealing treatments, in order to ascertain the role that excessive disorder plays in light induced defect creation.
- Institute a sample exchange program with Prof. John Abelson in the Materials Science Department of the Univesrity of Illinois at Urbana-Champaign. Using a modified sputtering technique, Prof. Abelson has produced amorphous silicon films which have controlled variations in their medium range order. These films have been structurally characterized by Abelson's group, but he lacks the capability to fully characterize the influence of the medium and long range order on the electronic properties. A cooperative effort between the Minnesota and Illinois groups can provide important information on the role of deposition conditions, structural disorder and electronic transport on the Staebler-Wronski effect.
- Explore the possibility of modifying my PECVD deposition chamber to grow amorphous silicon films using a silane plasma at low pressure and high hydrogen dilution, in order to promote nanocrystalline cluster formation and incorporation into the growing silicon matrix. In this way we may have an alternative technique for modifying the medium range order in the films and hence control the light induced defect kinetics.

Major Reports Published in FY 2000:
Jeremy Huston, "Long Range Disorder and Persistent Photoconductivity in Amorphous Silicon", Plan B Masters Project, University of Minnesota, June 2000.

Major Articles Published in FY 2000:
T. J. Belich, J. Huston and J. Kakalios, "The Staebler-Wronski Effect and 1/f Noise in Amorphous Silicon" (in preparation).

Fundamental and Exploratory Research

Novel Capacitance Measurements in Copper Indium Gallium Diselenide Alloys

Contract #: XAD-9-18668-15	**Contract Period:** 7/1/99-8/31/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of Oregon Department of Chemistry and Materials Science Institute Eugene, OR 97403-5219	
	Organization Type: CU	**Congressional District**: 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** David Johnson **Phone:** 541-346-4612 **E-mail** davej@oregon.uoregon.edu	
Technical Monitor: Richard Matson **Phone**: 303-384-6431 **Fax:** 303-384-6604 **E-mail:** rick_matson@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $41,670 2000: $55,391	**Cost Share Funding:**

Project Objective: The objective of this research is to measure the electronic properties of copper indium diselenide and copper indium/gallium diselenide alloys using several well-developed capacitance techniques appropriate for probing materials with a continuous distribution of electronic energy states in the gap. We will follow trends in the measured quantities as a function of different synthesis techniques and annealing conditions. Samples obtained through collaborations with related research teams at NREL will be compared with CIS and CIGS films grown at Oregon using elementally modulated reactants. The growth/suppression of particular defect levels and the importance of electronically active defects at grain boundaries will be probed. We will measure the valence band offset between copper indium diselenide and copper indium/gallium diselenide alloys using a heterostructure sample and optical pulsing experiment.

Approach/Background: The use of elementally modulated reactants has permitted the synthesis of many new compounds which are thermodynamically unstable with respect to disproportionation. In this synthesis approach, the ability to design reactants consisting of thin (10-100 Angstrom) elemental layers repeatedly deposited on a substrate gives control over the subsequent evolution of this reactant. Low temperature annealing results in an amorphous reaction intermediate. Nucleation controls what compound forms from this reaction intermediate, permitting thermodynamically stable reaction intermediates to be avoided. This approach is being used to prepare high quality samples of $CuIn_{1-x}Ga_xSe_2$ alloys. An advantage of this approach is the ability to grade composition and control the local concentration of defects and dopants. We are combining this new synthesis approach with sophisticated optical and capacitance techniques which will permit us to develop an understanding of the interaction between structure of the initial elementally modulated reactant, annealing conditions and defect levels in $CuIn_{1-x}Ga_xSe_2$ alloys. We intend to characterize optimized samples, both from our synthesis approach and from other related research teams at NREL, with the anticipation of following trends in the number of total defects, the growth and or suppression of particular defect levels, and the relative importance of defects at grain boundaries as a function of both synthesis approach and annealing conditions.

Status/Accomplishments: During the first part of this funding period, Mr. Thompson confirmed the cross deposition of selenium during Cu and In deposition and was able to eliminate this problem. During recalibration, outstanding low angle diffraction patterns of binary In-Se modulated elemental reactants were observed. Recalibrating the Cu-Se binary system we observed the formation of a kinetically stable amorphous phase near the composition Cu:Se 1:2. At the 1:1 composition, CuSe was observed to nucleate. If thick layers of Cu and Se were deposited (greater than 100Å repeats), CuSe was observed to nucleate at the reacting interfaces.

We have prepared films with a range of diffusion distances and repeat layer sequences including Cu-In-Se, Cu-In-Se-In and In-Se-Cu-Se-Cu-Se. We will continue to explore films made with this repeating structure and conduct annealing studies to understand the sequence of phase formation and the evolution of defect concentration and structure as a function of annealing temperature and time.

We have also calibrated the gallium source and have prepared films with a range of diffusion distances and repeat layer sequences. Gallium appears to interdiffuse slower with copper and selenium layers than does indium. Annealing these films produces $CuGaSe_2$ without any observable secondary phases directly from either a nanocrystalline or amorphous intermediate. We are beginning to prepare samples of $CuIn_{1-x}Ga_xSe_2$ alloys.

Contract #: XAD-9-18668-15

The transient photocapacitance method (TPC) has been used to measure the sub-bandgap defect states of working CIGS devices. TPC probes the occupation of sub-bandgap states after a voltage “filling” pulse. The TPC signal originates from trapped charge that is optically excited into mobile conduction and valence band states so that it can escape near the barrier region.

After a voltage “filling” pulse, the sample evolves back to its equilibrium carrier occupation through optical and thermal excitations. Since the depletion region will contract as positive charge is lost and the negative charge density increases, this change in gap state occupation can be measured as a transient capacitance signal. The sign of the capacitance transient indicates whether carrier motion is occurring predominantly in the conduction or valence band. In this case it is a predominately majority carrier process, ie. trapped holes being excited into the valence band.

The difference between the dark transient signal and that measured in the presence of sub-bandgap light gives the purely optical component of the release of trapped gap state charge. This difference signal, when intensity normalized and integrated over an appropriate time window, is identified as the TPC signal. We take care to operate in the low light intensity limit, where the TPC signal is intensity independent. Thus, the TPC spectrum reveals the distribution of allowable transitions for an electronic population of gap states not appreciably disturbed by the optical excitation, but rather determined by the application of the voltage pulse followed by whatever thermal evolution takes place before the transient is recorded

During this funding period, Ms. Heath assembled and calibrated her own TPC measurement system that will be dedicated to CIGS studies and began drive level capacitance profiling (DLCP) of CIGS samples. We have been attempting to determine the relationship between the deep defect transitions extending between 0.75 and 1.0 eV we observed in our TCP studies and the 0.3eV states observed in our DLCP studies. Additional experiments are needed to identify these deep defect states and relate them to these previously observed CIGS defect states. Observation of how the spectrum of deep defects varies with Ga content should lend insight into the identity of these defect states and the role of Ga in the CIGS material. These studies are currently underway on a series of samples provided to us by Bill Shafarman at the University of Delaware.

Planned FY 2001 Activities: Next year we will focus our synthetic efforts on preparing high quality samples of $CuIn_{1-x}Ga_xSe_2$ alloys. We will write up our results on our studies of how the initially deposited multilayer structure controls the low temperature solid-state reactions in the binary systems Cu-Se, In-Se, and Ga-Se. We will also write up our results demonstrating the effect of thickness and co-deposited layers on reaction progress and impurity phases in the ternary Cu-In-Se and Cu-Ga-Se systems. Optical and TPC measurements will be conducted as a function of annealing to follow the evolution of defect states, providing additional insight to optimize the annealing conditions. We will be expanding our TPC and DLCP measurements on samples from Energy Photovoltaics, the University of Delaware, and other NREL CIGS team members.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Fundamental and Exploratory Research

Porous Polycrystalline Silicon Thin Film Solar Cells

Contract #: AAD-9-18668-06	**Contract Period:** 5/25/99–7/24/02

Sponsoring Office Code: EE-11	**Performing Organization(s)** University of Rochester Department of Electrical Engineering Rochester, NY 14627-0231	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	**Organization Type**: CU	**Congressional District**: 28
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Philippe Fauchet **Phone:** 716-275-1487 **E-mail:** fauchet@ece.rochester.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $70,800 2000: $77,346	**Cost Share Funding:**

Project Objective: The goal of this work is to develop an efficient thin film photovoltaic device using porous polysilicon technology.

Approach/Background: The primary innovation incorporated into this project is the electrochemical etching of LPCVD polysilicon to form a porous polysilicon layer. This processing step provides three critical advantages that we believe will boost the efficiency of these solar cells. First, the porous surface is highly textured, leading to efficient collection of solar radiation with minimal reflection. Secondly, it is well known that the bandgap of porous silicon can be increased beyond that of crystalline silicon due to quantum confinement effects in the nanostructure of the porous material. This effect could be used to tune the bandgap of porous polysilicon toward the theoretical optimum bandgap of 1.5eV for maximal efficiency. Third, efficient photoluminescence of porous silicon could allow for the down conversion of higher energy (blue/UV) solar radiation into longer wavelength light (red/IR) which is absorbed more efficiently by bulk silicon.

The experimental approach is to first optimize our porous polysilicon photovoltaic device on a standard silicon wafer. Using a silicon wafer allows for simplified processing and an efficient back contact to the devices, while parameters such as doping concentrations, etching conditions, and top contact formation can be optimized. After optimal conditions are known, the Si wafer will be replaced with a glass substrate coated with a highly conducting ITO or silicide layer. The final device will then be optimized

Status/Accomplishments:
A collaboration with Evergreen Solar was initiated in which they provided our group with non-metallized string ribbon growth polysilicon solar cell substrates. We successfully incorporated a porous polysilicon layer onto the front surface of these substrates and demonstrated a 50% increase in the efficiency of these bare substrates with the incorporation of a porous layer. This increase in efficiency was accompanied by increases in short circuit current, open circuit voltage, and fill factor. Reflectivity was also decreased by a factor of two over the visible spectrum.

Our diagnostic and fabrication capabilities were improved with the fabrication of a light and dark current-voltage (IV) measurement setup and an improved metallization procedure. With two newly purchased multimeters, we can now take IV data within our lab, allowing for rapid characterization of our current samples and greater flexibility in future optimization experiments. Our metallization procedure had been problematic, limiting the performance of our devices. By incorporating tri-layer Ti/Pd/Ag front contacts to our devices, substantial improvement in efficiency and reproducibility have been realized relative to Al contacts. The previous metallization technique also involved the evaporation of metal over the entire sample, followed by selective etching to pattern the contacts. This procedure increased the reflectivity of the open porous polysilicon layer due to incomplete removal of the metal from the heavily textured surface. A liftoff procedure has since been optimized in which a layer of photoresist is first patterned on the surface. Following metallization, the photoresist is removed, taking the excess metal with it and leaving a patterned contact. Thus, only photoresist touches the open porous region, and is easily removed without damage.

Contract #: AAD-9-18668-06

All fabricated samples have been characterized with reflectivity and light IV analysis for a relative comparison of efficiency. Scanning Electron Microscopy of selected samples has also been conducted to determine the thickness and general morphology of the porous polysilicon layers.

Several LPCVD polysilicon samples have been fabricated at the Cornell Nanofabrication Facility (CNF) and at the Rochester Institute of Technology (RIT). Two students were trained to use the in-situ doped LPCVD at CNF and one set of p-i-n substrates were deposited. These samples could be etched uniformly and had low reflectivity, however their electrical characteristics were fairly poor. These non-optimal characteristics are likely due to an overly thick intrinsic polysilicon region. This structure will be improved in future depositions. Samples were fabricated at RIT to determine the optimal orientation of the p-n junction in our initial substrates. Due to the nature of the electrochemical etching process, p-type material tends to exhibit more favorable etching characteristics, however a junction with p-type material on the surface is in a reverse biased state during etching. Therefore two sets of RIT samples were fabricated using ion implantation to form opposite junction orientations. Samples with n-type emitters etched far more uniformly, and we will use this orientation in all our future devices.

Planned FY 2001 Activities:
Having demonstrated that thin porous polysilicon films can be formed that substantially reduce reflectivity while maintaining or improving the electrical characteristics of solar cell substrates, we plan to further improve these layer characteristics using addition variables in our electrochemical etching process. One area of particular interest that has not been widely studied involves gradient index antireflection layers. The electrochemical etching current provides direct control over the porosity at any instant during the etch. Therefore, the index of refraction (a function of porosity) can theoretically be varied continuously within the porous polysilicon layer, potentially leading to reduced reflectivity and wider AR bandwidth. Other variables such as etching solution and substrate geometry can also be studied to improve our layer design.

The collaboration with Evergreen Solar will continue, and further optimization of porous polysilicon layers to improve the performance of these photovoltaic substrates will be studied. Compatibility of porous polysilicon with their metallization and other processing steps should also be investigated.

Additional LPCVD depositions will be conducted at CNF and at RIT to improve the behavior of our thin film devices. As one of the goals of this project, our thin film work will continue and the optimization of our in-situ doped LPCVD process will be a priority. Work will continue to be conducted on Si wafer substrates due to contamination concerns within the LPCVD system when foreign substrates and used. Other potential substrates and deposition techniques will also be investigated.

Measurements of surface recombination velocity, efficiency, and light IV will be conducted at NREL to gain additional insight into the behavior of porous polysilicon in photovoltaic applications, and also to help us calibrate some of our experimental setups.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:
C.C. Striemer, F. Shi, S.P. Duttagupta, and P.M. Fauchet, "Porous Silicon Texturing of Polysilicon Substrates," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

C.C. Striemer, F. Shi, and P.M. Fauchet, "Porous Silicon Texturing of Polysilicon Substrates," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, pp. 169-170 (2000).

Biomimetic Photovoltaics Employing Semiconducting Nanocrystal Multicomposites

Contract #: AAD-9-18668-11	**Contract Period:** 5/24/99–7/23/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Vanderbilt University Department of Chemistry Nashville, TN 37235 **Organization Type**: CU	**Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** S. Rosenthal **Phone:** 615-322-2633 **Fax:** 615-343-1234 **E-mail**: sjr@femto.cas.vanderbilt.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: \$62,250 2000: \$61,518	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The project seeks to develop a molecular photovoltaic (PV) device whose performance exceeds that of existing PV technologies (crystalline and thin-film semiconductor systems) in terms of device efficiency, flexibility of applications, and cost of production. To achieve this there are three primary design goals: 1) Efficient absorption of light and conversion into charge carriers. 2) Efficient (low-loss) transport of both electrons and holes to the external electrodes. 3) A cheap, scalable manufacturing process with the potential for making large area devices at costs (in $/kWh energy produced) competitive with conventional energy technologies.

Approach/Background: The design philosophy employs a biomimetic approach borrowing concepts from both conventional PV technology and photosynthesis. The main points are the use of an efficient molecular light-harvesting compound for converting light into charge carriers, coupled with balanced charge transport to the external electrodes. The former is achieved with the use of cadmium selenide (CdSe) nanocrystals (nc's). These nanocrystals are a robust, direct bandgap material whose absorption peak can be tuned over most of the visible solar spectrum. Hole transport is accomplished using a semiconducting polymer. Proof of principles for both of these concepts have been demonstrated in the literature. In addition, we intend to incorporate an efficient electron transporter in the form of soluble fullerene derivatives. The completed device will be a sandwich layer device using in order, a metal electrode layer, the photoactive composite layer consisting of conducting polymer, nc's, and fullerenes, a transparent conducting oxide (TCO) layer as the top electrode. An important design goal is assembly of the device using mild conditions, i.e minimization of energy-intensive (expensive) processes involving high temperature or high-vacuum. Hence, solution-based, wet-chemical techniques are preferred wherever possible. For instance, the assembly of the composite layer is accomplished simply by spin-coating a solution containing the various components onto a TCO-coated glass substrate.

In practical terms, there are three main components to the project: 1) Syntheses of the materials used in the device. This includes the nc's as well as the polymer and fullerene derivatives. In the case of the polymers, there also exist commercially obtainable alternatives. Similarly TCO's are commercially available on glass substrates (e.g. ITO, SnO_2). 2) Assembly of the device: This involves functionalizing the various components such that they are compatible with each other and the processes employed in building up the various device layers. 3) Testing and characterization of both the materials and completed devices. Due to the novelty of the materials and device architecture this necessarily involves a significant amount of basic research into the behavior of individual components as well as their interfaces.

Status/Accomplishments:
Materials and characterization:
- We have synthesized soluble C60 derivatives and have incorporated them into the nanocomposite.
- ITO coated glass substrates have been purchased (Instead of $Sn0_2$).
- STEM-EELS investigations has been submitted for publication.
- The timescale for hole trapping in NC's has been determined by fluorescence upconversion spectroscopy.
- Transmission electron microscopy was used to investigate the effect of solution treatment before spin-coating on the film morphology. It was found that sonication of the sample prior to spin-coating had a beneficial effect both on the macroscopic uniformity of the film, as well as the composition on the nanometer scale.

- The density of the P3HT polymer as well as its absorption coefficient in the solid state has been determined for the first time.
- Impurities (Zinc and Bromine) were discovered in commercially available P3HT and have been quantified with RBS.

Device fabrication and characterization:

- Fabricated prototype devices using poly-3-hexylthiophene (P3HT) and CdSe nanocrystals as the active layer. Photovoltaic response in the range of 600 – 750 mV open circuit voltage and 2.5 μA short circuit current on CdSe/P3HT composite devices was obtained.
- Work is finished on the DUT (device under testing) apparatus, so we can now make full electrical measurements.
- Etching away half the ITO from the glass substrate before spin coating the composite has solved the shorting problem.
- A new testing rig was designed and built which incorporates a micrometer screw, this allows movement of the external leads up to the device in micron steps, therefore we can make contact without electrode punch-through.
- It was discovered that the thickness of the polymer composite film also plays apart in whether or not the devices short. If the polymer composite film thickness is beneath 50 nm the devices short, probably due to small pinholes in the polymer thin film. The polymer thin films need to be at least 80 – 100 nm thick to stop the device from shorting.
- Work has been begun on the full composite (P3HT/CdSe/C_{60}) devices.
- I-V curves for a device using the full composite consisting of 20% CdSe, 40% P3HT and 40% C_{60} have been obtained. The I-V curves showed that we are able to get diode type response from the devices, but the short circuit current obtained from the devices was in the 2 μA range.

Planned FY 2001 Activities:

- Our focus will be on device fabrication, characterization and optimization of the composite materials.
- We will make devices that use different sizes of nanocrystals and calculate the efficiency for each different size nanocrystals.
- Replace the C_{60} derivate with soluble TiO_2 because the $Ti0_2$ has a better band gap line up with the CdSe nanocrystals (C_{60} is more expensive as well). An n-type polymer could also be substituted.
- Synthesize and characterization of several oligothiophenes and use them to replace the P3HT in the devices.
- Obtain carrier mobilities for all materials.
- Ultrafast experiments to obtain the hole transfer rate from CdSe to P3HT in solution and the electron transfer rate from CdSe to C_{60} in solution.
- Begin investigation into ^{18}O and metal diffusion into polymer thin films and composites.

Major Articles Published in FY 2000:

A. Kadavanich, D. Underwood, M. Erwin, T. Kippeny, R. Ward, J. McBride, S. Pennycook, S. J. Rosenthal "Materials Issues For CdSe Nanocrystal Activated Polymer Photovoltaics" Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO (2000).

"Sublattice Resolution Structural and Chemical Analysis of Individual CdSe Nanocrystals Using Atomic Number Contrast Scanning Transmission Electron Microscopy and Electron Energy Loss Spectroscopy" A. V. Kadavanich, T. Kippeny, M. Erwin, S. J. Pennycook, and S. J. Rosenthal. J. Chem. Phys. B, In Press.

David F. Underwood, Tadd Kippeny, and Sandra J. Rosenthal, "Ultrafast Carrier Dynamics in CdSe Nanocrystals Determined by Femtosecond Fluorescence Upconversion Spectroscopy", *J. Chem. Phys. B*, In Press.

David F. Underwood, Tadd Kippeny, Rachel Ward, Andreas V. Kadavanich, Jason Taylor, and Sandra J. Rosenthal, "Size and Surface Dependence of Ultrafast Carrier Dynamics in CdSe Quantum Dots Determined by Fluorescence Upconversion Spectroscopy". *Springer Series in Chemical Physics, In Press.*

Fundamental and Exploratory Research

Novel Characterization Methods for Microcrystalline Silicon

Contract #: AAD-9-18668-01	**Contract Period:** 5/24/99–7/23/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 75,520 2000: $32,840</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this project is to develop a detailed understanding of the nature of the defect states and the relationship between these defect states and their effect on photo-excited carrier processes in microcrystalline silicon and related materials using a combination of novel positron beam and femtosecond optical techniques. In particular, we expect to develop an understanding of the defect states and carrier dynamics as they occur in the different phases of heterogeneous thin film silicon and in amorphous silicon, with an emphasis on how they are influenced by deposition and processing techniques, so as to optimize the photovoltaic properties of the materials.

Approach/Background: This work incorporates both positron beam measurements and femtosecond laser spectroscopic measurements to directly determine the relationship between the nature of the defect complexes and their effect on photo-excited carriers. Positron annihilation measurements provide detailed information about the defect complexes in the microcrystalline and amorphous materials, and can identify both the type and concentration of defect states. Femtosecond optical measurements reflect the evolution of photo-excited carriers which, in the materials of interest, can involve carrier interactions with the defect states, including the carrier trapping and recombination processes that are crucial to understand and, thereby, control in order to develop and optimize the materials for photovoltaic applications. The optical studies include measurements sensitive to interactions involving the band-tail states near the mobility edge, which are expected to strongly influence the electronic properties of these materials. Positron annihilation and femtosecond laser spectroscopic measurements are carried out on various series of samples of microcrystalline and amorphous semiconductor materials. These studies are designed both to understand important fundamental properties of the materials, and to evaluate the effects of deposition and processing conditions.

Status/Accomplishments: We have carried out femtosecond studies of both amorphous and nano-/micro-crystalline silicon materials in which we have made time-resolved measurements of the relaxation dynamics of photoexcited carriers using pump-probe techniques. We have made detailed measurements on a series of thin film silicon samples prepared by hot-wire chemical vapor deposition (HWCVD) by Dr. Qi Wang at NREL in which the H-dilution during deposition was systematically varied across the amorphous to nanocrystalline phase boundary. These samples were extensively characterized by x-ray diffraction, Raman, and optical spectroscopies, and showed increasing crystallite size and crystalline fraction with increasing H-dilution above the crystalline threshold. Of particular interest are “edge” materials, grown at the threshold of crystallinity, owing to their favorable electronic properties and resistance to photoinduced degradation. Femtosecond measurements revealed clear differences in the fast carrier relaxation dynamics in the nanocrystalline vs. amorphous materials, with a strong component associated with rapid carrier trapping in the nanocrystalline phase, providing direct evidence for this proposed mechanism for the enhanced stability of the crystalline material. For time scales beyond ~ 1 ps, the femtosecond measurements revealed bimolecular recombination dynamics in the full range of materials similar to those observed in our previous studies of amorphous films. We have also extended our earlier studies of HWCVD a-SiGe:H alloys prepared at NREL by Dr. Brent Nelson. In our new studies, we investigated a wider range of alloys compositions, including pure a-Si:H as well as additional alloy samples containing between 2 and 50 atomic percent Ge to carry out detailed measurements of the carrier response as a function of excitation energy relative to the band gap, and investigated the dynamics as a function of temperature. These studies have confirmed rapid relaxation processes associated with carrier distributions originating in band tail states, and also provided a basis for comparison for our studies of nc-Si and edge materials.

Contract #: AAD-9-18668-01

Status/Accomplishments (continued): Thin films of nano-/micro-crystalline Si grown on stainless steel substrates by HWCVD have been measured by Positron Annihilation Spectroscopy (PAS). The samples were prepared by Qi Wang at NREL. The hydrogen to silane dilution ratio R was changed in different samples and ranged from 1.2 to 8, while the temperature was kept constant at 250 C. Each sample was characterized by standard one-detector PAS technique because of its extremely high sensitivity to open volume defects. The S parameter measuring the positron annihilation with low momentum electrons was used to profile the defect distribution of the samples. From the S data we could give an estimate for the vacancy-like defects contained in the samples by extracting the positron diffusion length, which is directly related to the defect concentration. By assuming neutral vacancy-like defects distributed uniformly along the layer, our results indicate a defect concentration higher that 10^{19} cm^{-3} in all samples. The lowest dilution sample shows a concentration one order of magnitude higher than the other samples studied. A second set of device-quality layers 250 nm thick on stainless steel substrates were prepared at United Solar Systems Corp. Previous studies showed superior characteristics of these layers as solar cells when grown with dilution ratios near the onset of microcrystallinity. The PAS data are interpreted as a measure for the size and concentration of open volume defects acting as trapping sites for positrons. The positron properties in both H-diluted and non-H-diluted are the lowest ever measured attesting to the dense nature of the material, and has allowed us to for the first time measure the Stabler-Wronski (S-W) effect and its recovery. Following light soaking, a decrease in S is observed in both normal and H-diluted samples, suggesting a change in the defect associated with light soaking. Two hours annealing at 160 C in air restores the original S-parameter. This behavior may be interpreted as evidence of large scale metastable changes associated with the (S-W) effect.

Planned FY 2001 Activities: Owing to the success of measuring the Stabler-Wronski effect and its recovery with PAS, we plan to extend these studies to carefully examine the Staebler-Wronski effect during annealing to measure the energy necessary to recover this light associated defect. We also plan PAS studies to determine the chemical element type of atoms near the site of annihilation, and we hope to measure detailed 2D ACAR and compare the results to atomistic theory to allow for unambiguous structure analysis. We also plan to extend our femtosecond studies on photoexcited carrier dynamics in nc-Si, and in materials grown at the amorphous to nanocrystalline phase boundary. The planned studies include measurements on more detailed series of samples, with emphasis on varying degree of crystallinity near the phase boundary. We will directly investigate the role of photoinduced structural changes with studies on light-soaked and annealed samples designed to be correlated with the positron annihilation spectroscopy measurements. We also plan to begin the femtosecond far-infrared measurements to investigate the carrier dynamics in a new energy scale.

Major Articles Published in FY 2000:

S.L. Dexheimer, J.E. Young, and B.P. Nelson , "Ultrafast dynamics of photoexcited carriers in HWCVD a-Si:H and a-SiGe:H," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, p. 227-228 (2000).

J.E. Young, B.P. Nelson, and S.L. Dexheimer, "Ultrafast dynamics of photoexcitations in HWCVD hydrogenated amorphous silicon alloys," Materials Research Society Symposium Proceedings, Vol. 609: Amorphous and Heterogeneous Silicon Thin Films—2000, Materials Research Society Spring Meeting, April 24-28, 2000, San Francisco, CA (2000).

S.L. Dexheimer, J.E. Young, and B.P. Nelson, "Ultrafast dynamics of band tail carriers in hydrogenated amorphous silicon," Bulletin of the American Physical Society, Vol. 45, No. 1, p.398, APS March Meeting, March 20-24, 2000, Minneapolis, MN.

J.E. Young, B.P. Nelson, and S.L. Dexheimer, "Photoexcited carrier dynamics in the band tail states of hydrogenated amorphous silicon," to be submitted to Phys. Rev.

S.L. Dexheimer, K.E. Myers, J.E. Young, B.P. Nelson, and Q. Wang, "Ultrafast carrier dynamics through the transition from amorphous to microcrystalline silicon ," submitted to the Electrochemical Society 199th Meeting, March 25-30, 2001.

K.E. Myers, Q. Wang, and S.L. Dexheimer, "Femtosecond carrier dynamics in nanocrystalline silicon films: The effect of the degree of crystallinity," submitted to the Materials Research Society Spring Meeting, April 16-20, 2001.

K.E. Myers, Q. Wang, and S.L. Dexheimer, "Ultrafast carrier dynamics in nanocrystalline silicon through the amorphous to nanocrystalline phase transition," to be submitted to Appl. Phys. Lett.

S. Rassiga, K.G. Lynn, H. Mahan, B.P. Nelso, "Defect profiling of thin-film microcrystalline silicon using positron annihilation spectroscopy," NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO.

M.P. Petkov, C.M. Chen, H.A. Atwater, S. Rassiga and K.G. Lynn , "A Relation Between Surface Oxide and Oxygen-Defect Complexes in Solid-Phase Epitaxial Si Regrown from Ion-Beam-Amorphized Si Layers," Appl. Phys. Lett. Vol. 76, (2000).

S. Rassiga, K.G. Lynn, Q. Wang, B.P. Nelson, and R.S. Crandall, "Impurity and Defect Characterization in c-Si by Positron Beams," 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, CO, August 15, 2000.

C.M. Chen, S. Rassiga, M. Petkov, M.H. Weber, K.G. Lynn, H.A. Atwater, 'Study of Vacancy and Impurity Complexes in Si Solid-Phase Epitaxial Crystallization with Positron Annihilation Spectroscopy," MRS Symposium Proceedings, Vol. 609: Amorphous and Heterogeneous Silicon Thin Films—2000, MRS Spring Meeting, April 24-28, 2000, San Francisco, CA (2000).

Y.H. Kao, L. Kazmerski, K.G. Lynn, and A. Mascarenhas, "Photovoltaics Characterization: An Overview," in Proceedings of the Electrochemical Society, Photovoltaics for the 21st Century Symposium, pp. 289-300 (2000).

Nanostructure Arrays for Multijunction Solar Cells

Contract#: AAD-9-18668-10	**Contract Period:** 5/12/99–7/11/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	West Virginia University Department of Computer Science and Electrical Engineering Morgantown, WV 26506-6109 **Organization Type:** CU	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Biswajit Das **Phone:** 304-293-0405 x2525 **E-mail:** das@csee.wvu.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1999: $66,700 2000: $108,375	**Cost Share Information:** None. **Cost Share Funding:**

Project Objective: The objective of this project is to develop multijunction photovoltaic cells using stacked layers of semiconductor nanostructures. This will be accomplished by the fabrication and characterization of single junction PV cells using quantum wires, stacked single junction cells using quantum dots, and finally stacked multijunction cells using quantum dots.

Approach/Background: Nanostructure based PV cells have been previously proposed for their potential to provide a very high energy conversion efficiency due to quantum confinement effects. However, a major impediment to the development of this technology has been the inability to fabricate large arrays of semiconductor nanostructures with the required periodicity and size control at a low cost. To meet this challenge, we are currently using a template based nanostructure fabrication technique for developing high efficiency PV cells. The fabrication technique is based on electrochemical synthesis of semiconductor nanostructures on a template formed by the anodization of an aluminum thin film. This approach provides the ability to fabricate a variety of semiconductor materials on an arbitrary substrate with good control over the size, shape and periodicity of the nanostructures.

The above objective will be accomplished in three phases. First, n-type and p-type semiconductor quantum wire arrays will be fabricated and characterized. Then, these materials will be combined to form arrays of p-n junction quantum wires. Finally, stacked layers of uniform sized quantum dots will be fabricated and characterized. This will require innovation in the electrochemical fabrication of doped compound semiconductor nanostructures, the ability to fabricate abrupt interfaces between different materials using electrochemical synthesis, and an analysis of both the optical and electrical properties of doped semiconductor quantum wires.

Status/Accomplishments: This project is currently in Phase II with a primary objective of fabricating and characterizing semiconductor quantum wires and quantum dots. The principle accomplishments during FY 2000 have been to develop a model for the optical properties of the semiconductor nanostructure arrays, to develop a rapid template characterization technique, and to fabricate preliminary II-VI semiconductor nanostructures. These accomplishments have been achieved through the following specific tasks:

- A model has been developed to determine the absorption properties of the semiconductor nanostructure arrays. This model includes the effect of nanostructure dimensionality, size, shape, and composition. In addition, this model provides the ability to relate distributions in nanostructure size to observed optical properties.
- A capacitance-voltage characterization technique has been developed. This technique provides the ability to rapidly determine template thickness, template quality, and average pore size.
- CdTe quantum wires have been fabricated by electrochemical deposition into the template pores. Preliminary optical characterization of the material has been performed and has been used to verify the model of optical properties.
- A collaboration has been established with the Electrochemical Research Group at the University of Notre Dame to develop a theoretical model of the pore fomration process in aluminum thin films, and for electrochemical and electrophoretic deposition of semiconductor materials into these pores. The theoretical model developed as a result of this collaboration will provide increased pore size uniformity and material quality for the nanostructure arrays.
- We have developed a process for fabrication of nanostructure arrays on ITO-coated glass susbtrates. This provides flexibility in the choice of substrate material and the ability to fabricate transparent PV cells.

Contract#: AAD-9-18668-10

Status/Accomplishments (continued):

- We have developed a process for the fabrication of stacked nanostructure arrays. This process provides the ability to fabricate multijunction devices and increase the effective thickness of the active PV material.

Planned FY 2001 Activities: The primary goal for FY 2001 is to fabricate and characterize semiconductor nanostructure arrays with varying nanostructure size and chemical composition. The size and composition will be determined to provide an optimum match with the solar spectrum. The following specific tasks will be accomplished to meet this goal:

- An initial theoretical model for the pore formation and semiconductor synthesis process using aluminum thin films will be developed as a result of our collaboration with the University of Notre Dame. This model will allow us to improve control of pore size distribution and periodicity. In addition, we will be able to improve the pore filling factor and material quality of the synthesized semiconductor material.
- CdTe, CdS, and InAs nanostructure arrays with varying material composition and dimensionality will be fabricated and characterized. The variation of length, diameter and composition will allow us to optimize the absorption and transport properties of the arrays.
- The model of optical properties developed during FY 2000 will be extended to include transport properties, including contact issues. This will allow us to directly relate physical properties of the nanostructure arrays to photovoltaic performance.
- The optical, electrical, and structural properties of the fabricated nanostructure arrays will be characterized. The optical properties will be determined through absorption, reflection and PL measurements. The electrical properties will be investigated through the use of IV and CV measurements as a function of temperature and magnetic field. The structural properties will be evaluated through the use of FESEM microscopy and Scanning Auger techniques.
- A process for reliably contacting the semiconductor nanostructure arrays will be developed. This will entail determining the structural properties of the ITO/semiconductor interface as well as an experimental investigation of the I-V properties of the contacts as a function of temperature and magnetic field.

Major Articles Published in FY 2000:

B. Das, S. McGinnis, P. Sines, C. Garman, D. Grey, and W. Zhang, "Nanostructure Arrays for Multijunction Solar Cells," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver,CO, BK-520-28064 (2000).

C. Garman, P. Sines, S.P. McGinnis, and B. Das, "An improved automated anodization apparatus for fabricating nanostructure devices and porous silicon," Review of Scientific Instruments, **72**, 1 (2001).

HBCU PV Research Associates Program

Renewable Energy Technology & Technology Applications for Developing Countries

Contract#: XAK-8-18675-01	**Contract Period:** 3/29/99–3/28/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Central State University Office of Sponsored Research Wilberforce, Ohio 45384 **Organization Type:** CU	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Clark W. Fuller **Phone:** 937-376-6312 **Fax:** 937-376-6598 **E-mail**: cfuller@prodigy.net	
Technical Monitor: Fannie Posey Eddy **Phone**: 303-384- 6247 **Fax**: 303-384- 6877 **E-mail:** fannie-posey_eddy @nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1999: $ 21, 856 2000: $ 13,286	**Cost Share Information:** In –kind matching, Central State Univ. **Cost Share Funding:** 2000: $ 5,616

Program Objective: As sponsored by the National Renewable Energy Laboratory, Golden, Colorado, the Central State University HBCU Photovoltaic Research Associates Program provides undergraduate scholarship and program support funds for the pursuit of study and research in the field of renewable energy and photovoltaics at Historically Black Colleges and Universities (HBCUs). The aim is to attract qualified sciences, engineering and business students toward pursuing a career in these areas with emphasis in photovoltaic technology.

Approach/Background: Since the early 1990's, Central State University has utilized its experience and expertise with the "Northern Senegal Water Management Project" (NSWMP) to form the core in developing the foundation for student training and research under programs sponsored by NREL and NASA. The NSWMP is a natural resources project in Senegal, West Africa, and is designed to develop self-sufficiency among Senegalese villagers by providing them with the expertise and materiel to install and maintain their own renewable energy water pumping systems (wind and solar energy technology). While under the sponsorship of the NREL scholarship program, the undergraduate students who participate in the program not only learn the basics of wind and solar technology, but they also focus on research in ways in which photovoltaics can provide new and supplemental energy sources to address the critical shortage of water in many developing countries. Students have the opportunity to participate in hands-on research at many domestic locations and laboratories as well as participate in one or two overseas projects located in South Africa or Senegal.

Integration of Complementing Programs- The CARET/SORET Consortium: Central State University has sought ways in which to expand the opportunities for NREL student research associates by creating and participating in consortium programs that provide a variety of renewable energy program/research opportunities. The Consortium for Advancing Renewable Energy Technology (CARET) and the Student Outreach for Renewable Energy Technology consortium (SORET) are research and education programs involving five universities and the NASA Glenn Research Center. These five universities (Fisk, Wilberforce, Central State, Savannah State, and Kent State Universities) are working together with the NASA Glenn Research Center and several business entities toward four objectives, which are: (1. To develop programs which promote science, technology, and engineering disciplines to secondary school students using the theme of renewable energy; (2. To attract more science, technology, and engineering students to member institutions and encourage their continued education through participation in CARET/SORET programs and a pipeline mechanism which facilitates transitions to other member institutions; (3. To perform fundamental research in areas with the potential to advance the technology available for renewable energy systems, and; (4. To promote advances in the quantity and quality of utilization of renewable energy systems in our society.

The consortium has developed a pipeline mechanism which actively works with students interested in these areas to manage their educational opportunities within the consortium and works with students to develop educational programs for secondary school students. CARET/SORET is also addressing these objectives by encouraging retention by expanding the educational opportunities available to consortium students. In the course of pursuing these objectives, CARET/SORET has developed affiliations with several additional organizations interested in working with the consortia to achieve its goals. These organizations include the Florida Solar Energy Center, the Why Not Corporation, the Grand Traverse Band of Ottawa and Chippewa Indians, Bay Mills Community College, and Lac Courte Oreilles Ojibwa Community College.

Contract#: XAK-8-18675-01

Status/Accomplishments: From October 1, 1999 through September 30, 2000, four (4) Central State University students have benefited with partial scholarships under the program (Charlie Hurt [prime student] Senior, Water Resources Management; Jercoxia Curney [alternate student], Graduating Senior, Water Resources Management; Kishinna Foxie [alternate student], Graduating Senior, Water Resources Management; and Brad Sampson [alternate student], Junior, Manufacturing Engineering.

- All 4 research associate students were required to enroll in the Renewable Energy Laboratory Course, NS 450, for Winter and Spring Quarters, 2000. The course was taught at Wilberforce University and involved hands-on design and installation of renewable energy lighting systems that utilize photovoltaic technology. Four students successfully completed the Winter Quarter requirements and two students also completed the Spring Quarter requirements. (A complete course syllabus was provided in previous Quarterly Technical Reports).
- Each student was required to develop a work plan for Fall, Winter and Spring Quarters that incorporated renewable energy technology as a part of their major field of study (Manufacturing Engineering and Water Resources Management). The students received work-study pay as a part of their activities, including attending the renewable energy laboratory course above. (Student work plans were provided in a previous Quarterly Technical Report).
- The research associates were also required to interact with PV manufacturers, visit research and technology distribution sites, and become familiar with technology applications at various locations in the eastern and mid-western United States. These site visits and activities included (among others):
  1. Attend the Farm Science Review Fair, London, Ohio, September, 1999;
  2. Visit the office of the U.S. Geological Survey (USGS), Columbus, Ohio, October, 1999;
  3. Attend the National Environmental Career Conference, Hartford, CT., October, 1999;
  4. Prepare a Central State University renewable energy project/program briefing as part of the NASA/CSU presentation to the American Indian Science and Engineering Society (AISES) Conference, Minneapolis, MN, November, 1999;
  5. Tour renewable energy projects and facilities at Georgetown University, BP SOLAR Inc., and WINROCK International, Washington, D.C., December, 1999.
  6. Assist in the development and presentation of renewable energy outreach activities developed for at least five (5) regional high school programs, January-June, 2000;
  7. Continue technology familiarization objectives by visiting various PV module manufacturers and renewable energy technology installation sites throughout Ohio and Indiana (Solar Cells, Inc, Toledo, Ohio and Outdoor Wind Technology Demonstration Site and Museum, Hammond, Ind.), March, 2000.
  8. Attend and present research findings (poster session) at the National Center for Photovoltaics Program Review Meeting, Denver, Colorado, April, 2000;
  9. Participate in the NASA sponsored HBCU Research Review Conference, Ohio Aerospace Institute, April, 2000;
  10. Attend the Renewable Energy Technology Exposition, Madison, Wisconsin, June, 2000;
  11. Help plan and actively participate in a 6 day, on-campus CSU Summer 2000 Renewable Energy Summer Camp for High School Students, July, 2000;
  12. Conduct a six-week internship as part of the Renewable Energy Environmental Protection (REEP) Academy, Texas Southern University & South Africa, June-August, 2000;
  13. Attend and present research findings (Power Point presentation) at the Renewable Energy Academic Partnership Conference (REAP), National Renewable Energy Laboratory, Golden, Colorado, August, 2000.

All of the objectives for the research and research support activities as described above were accomplished. The student trip/activity reports for the above are included in a separate program report.

Planned FY 2001 Activities:
Fall Academic Quarter, 2000: Prime student (Charlie Hurt) will perform a major role in program orientation sessions for three newly appointed research associates (Mr. Waymond Smith, Junior, WRM; Ms. Niya Curry, Junior, WRM; and Mr. Anthony Williams, Sophomore, MFE). The orientation sessions include an introduction to renewable energy principles and technology as well as on-campus and off-campus requirements regarding previous renewable energy internship experiences.
Winter Academic Quarter, 2001: All four (4) students will enroll in an advanced course related to renewable energy technology.
Spring Academic Quarter, 2001: Student research associates will continue their energy course requirements while also participating in a six month internship program hosted by the NASA Lewis Research Center and the Cleveland area African American Museum. The internship program, entitled, "African Solar Village Research Intern Program", will provide students research opportunities in Cadium Sulfide solar cell development.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:
C. Fuller, G. Ndao, C. Hurt, W. Smith, "The Central State University Renewable Energy Research Associates Program," 2nd Annual Renewable Energy Academic Partnership (REAP) Review Meeting, NREL, Golden, CO, 9-11 August 2000, pp. 9-10.

C. Fuller, H. Evans, C. Hurt, "Marketing Renewable Energy Devices in Developing Countries," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064.

HBCU PV Research Associates Program

Undergraduate PV Research Projects

Contract #: XAX-5-15021-2	**Contract Period:** 9/21/95–5/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
Phone: 202-586-2455
Fax: 202-586-8148
E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Clark Atlanta University
James P. Brawley at Fair Street, SW
Atlanta, GA 30314</td></tr>
<tr><td>Organization Type: HB</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Gerald W. Grams
Phone: 404-880-6907 E-mail: ggrams@cau.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Robert McConnell
Phone: 303-384-6419
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E-mail: robert_mcconnell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
none</td></tr>
<tr><td>DOE Funding Allocation:
1997: $20,122 2000: $0
1998: $60,365
1999: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The Clark Atlanta University (CAU) Historically Black Colleges and Universities (HBCU) Photovoltaic Research Associates Program provides financial support and research opportunities for undergraduate students to enhance the student's knowledge in the field of photovoltaic research and to encourage them to pursue careers in photovoltaics.

Approach/Background: Research activities initiated by past collaborations between Clark Atlanta University and Vista University in Port Elizabeth, South Africa, are being continued. The primary goal of that work had been to determine the effects of atmospheric variability on the production of solar energy by photovoltaic devices. A combination of solar radiation measurements, meteorological observations, and computer modeling work is used to carry out an assessment of the efficiency of operation of photovoltaic modules under different atmospheric conditions. Another goal of this project is to promote the use of photovoltaic technology to provide electric power to remote areas in developing countries. We are also developing a collaborative project with Dr. Godfrey Augustine of the Northrup Grumman Science and Technology Center who has a background in modeling and design optimization of Indium Phosphide solar cells and who volunteered to mentor a student on such a project. One of our students is working with Dr. Augustine to optimize the design of current InP solar cells.

Status/Accomplishments: CAU's Earth Systems Science (ESS) program operates an Atmospheric Optics Observatory (AOO) on the roof of the Research Center for Science and Technology. The AOO provides a platform for operating instruments to monitor the amount of solar energy reaching Earth's surface throughout the day. A Brewer ultraviolet spectrometer measures the ground-level intensity of the attenuated incident solar radiation at five specific ultraviolet wavelengths. An Ascension Technology RSP (Rotating Shadowband Pyranometer) measures the global, direct, and diffuse radiation at the surface for visible wavelengths. In addition, a NOAA automated weather station operated at the AOO site provides simultaneous data on atmospheric pressure, temperature, humidity, wind speed, and wind direction. A combination of solar radiation measurements, meteorological observations, and computer modeling work is used to carry out an assessment of the efficiency of operation of photovoltaic modules under different atmospheric conditions. To improve our ability to interpret data obtained by the RSP and the meteorological instruments, we are developing a simple, inexpensive atmospheric haze sensor that uses an LED (light-emitting diode) as a narrow-band detector. Six different LED wavelengths are available, and data from such a device operated throughout the day at multiple wavelengths can be used to determine the fraction of incident solar energy that has been lost due to the presence of haze (aerosol particles) in the atmosphere. Successful operation of this device will improve our ability to model atmospheric effects on the solar resource. Work began on the development of the LED haze sensor during the summer of 1999 by Bryant Pierson and Akil Sutton (physics majors from Morehouse College). A working model was completed and preliminary measurements were obtained prior to the First REAP (Renewable Energy Academic Partnership) Conference sponsored by NREL and held at Southern University in Baton Rouge, LA, August 9 – 13, 1999. During the past year, additional efforts were carried out to optimize the performance of the LED haze sensors and to develop the computer software required for analysis of data. Our work on atmospheric effects on the production of solar energy was incorporated into a summer project for an NSF-sponsored undergraduate research program that was conducted at CAU during Summer 2000. This project involved an undergraduate student (Adwoa Gyekye, a CAU physics major) who carried out tests and routine observations with the new sensor to evaluate the operation and accuracy of the instrument. These results were reported by Mr. Pierson at the Second NREL/REAP conference during August 9-11, 2000.

Contract #: XAX-5-15021-2

Status/Accomplishments (continued): As discussed earlier, we also have a student working on modeling and design optimization of Indium Phosphide solar cells in a collaborative project with Dr. Godfrey Augustine of the Northrop Grumman Science and Technology Center. Mr. Robert Easley, a Physics and Mathematics major from Morehouse College began working with Dr. Augustine during the Fall 1999 semester. A research effort was initiated to carry out literature searches and to update an existing model for optimizing the design of InP solar cells for higher efficiency and greater radiation tolerance. We also purchased the PC1D computer program from the Photovoltaics Special Research Centre at the University of New South Wales in Sydney, Australia. This program solves the fully coupled nonlinear equations for the quasi-one-dimensional transport of electrons and holes in crystalline semiconductor devices, with emphasis on photovoltaic devices. The program has been installed on a computer in our laboratory, and Mr. Easley worked with the program under the guidance of Dr. Augustine. Mr. Easley continued this work while serving as an intern at NREL during Summer 2000, and results of his work on this project were described at NREL's Second REAP Conference during August 2000.

Planned FY 2001 Activities: Our students have completed a considerable amount of research in the past year and the enthusiasm that they acquired from obtaining their results has added a new feature to their activities – speaking and presenting posters describing their research projects to other students at other universities and organizations. A list of some of their activities is included below as *Oral and Poster Presentations for FY2000.* These activities serve to introduce students not directly supported by the PV Associates program to the field of photovoltaic research and thereby encourage those other undergraduate students to pursue careers in photovoltaics. The research projects described above will be continued. A Multi-Filter Rotating Shadowband Radiometer (MFRSR) has been purchased with funds from other projects. The instrument will soon be installed as part of CAU's rooftop AOO facility. Our plans are to incorporate data from the haze sensor and the MFRSR as additional input for computer models designed to carry out an assessment of the efficiency of operation of photovoltaic modules under different atmospheric conditions. As the work carried out by the students in our program continues, their research efforts are expected to attract the attention of other students who, in turn, may also be encouraged to pursue careers in photovoltaics.

Oral and Poster Presentations in FY 2000:

Easley, Robert L. Jr., "Modeling the Performance of Indium Phosphide Solar Cells," Poster Presentation, Howard University Third Annual Atmospheric Science Conference, March 20 – 22, 2000, Washington, D. C.

Easley, Robert L. Jr., "Modeling the Performance of InP Solar Cells," NREL Renewable Energy and Academic Partnerships (REAP) Conference, August 9 - 11, 2000, Golden, Colorado.

Easley, Robert L. Jr., "Modeling the Performance of Indium Phosphide Solar Cells," Poster Presentation, Morehouse College First Annual Science and Mathematics Research Exhibition, September 7, 2000, Atlanta, Georgia.

Easley, Robert L. Jr., "Modeling the Performance of Indium Phosphide Solar Cells," Poster Presentation, Tuskegee First Annual Science Research Exhibition, October 14, 2000, Tuskegee, Alabama. *This presentation received first prize in the Aerospace Engineering, Mechanical Engineering, and Physics Division at the Exhibition.*

Gyekye, Adwoa K., "Using the Sun Photometer to Determine Extinction due to Aerosols and Water Vapor," Poster Presentation, Research Experiences for Undergraduates in Earth System Science at Clark Atlanta University, July 28, 2000, Atlanta, Georgia.

Grams, G. W., K. B. Bota, and R. L. N. Mandock, "Historically Black Colleges and Universities (HBCU) Photovoltaic Research Associates Program", Poster Presentation, NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, Colorado.

Grams, G. W., K. B. Bota, and R. L. N. Mandock, "HBCU Photovoltaic Research Associates Program at Clark Atlanta University," NREL Renewable Energy and Academic Partnerships (REAP) Conference, August 9 - 11, 2000, Golden, Colorado.

Pierson, Bryant R., "The Development of a Sun Photometer for the Measurement of Haze," Poster Presentation, Howard University Third Annual Atmospheric Science Conference, March 20 – 22, 2000, Washington, D. C.

Pierson, Bryant R., "Atmospheric effects on production of solar energy," NREL Renewable Energy and Academic Partnerships (REAP) Conference, August 9 - 11, 2000, Golden, Colorado.

Major Reports Published in FY 2000:

NREL Photovoltaic Program FY1999 Annual Report, NREL/BK-210-27479 (2000)

Major Articles Published in FY 2000:

Grams, G. W., K. B. Bota, and R. L. N. Mandock, "The Historically Black Colleges and Universities Photovoltaic Research Associates Program at Clark Atlanta University", Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 53-54 (2000).

HBCU PV Research Associates Program

The Floating Theater: A Demonstration of Photovoltaic Technology in a Marine Architectural Context

Contract #: AAK-9-18675-07	**Contract Period:** 8/6/99–8/5/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Hampton University Department of Architecture Hampton, VA 23668	
	Organization Type: HB	**Congressional District:** 3
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Araya Asgedom **Phone:** 757-727-5021 **E-mail** araya.asegedom@hampton.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax**: 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $33,333 2000: $ 0	**Cost Share Funding:**

Project Objective: To demonstrate the applicability of photovoltaic and renewable energy technology to marine based architecture by studying, researching, designing, and simulating a Floating Theater which is a marine architectural structure. As a Department of Architecture located in the Hampton Roads region, a region of seven municipalities whose access to the ocean, rivers, waterways and coasts is vast, this project addresses the following:

- That the Theater uses a form of renewable energy, i.e. Photovoltaic technology.
- That the facility can be designed for educational, demonstration of energy technologies,
- That its mobility, its waterway access to many points along the Hampton Roads makes it an effective facility;
- That it can be designed to be a visitors' attraction;
- That it can serve as a conference/gathering facility; and
- That it could be a self-sufficient operation.

Approach/Background: Approaching the project objective by taking advantage of our design and simulation skills which is an integral part of our educational goals in our 5-year professional architecture program seems appropriate. We approached this design and simulation project as a design problem that will fit into the third year design studio sequence where students, under the supervision of the principal investigators will spend 4 weeks each in fall and spring semester designing the Floating Theater. These designs will be collected, analyzed, and compiled as responses and possibilities from that particular class towards the project objectives.

Status/Accomplishments:

September – December 1999 and January - May 2000

- Collected basic design data for understanding photovoltaic technology
- Conducted the first and second design studios producing two-and-three dimensional designs for Demonstration/Education, Theater, Conference, and Restaurant facilities.
- Selected and employed two student associates who helped coordinate design studio activities as well as the collection and editing of the production from the design studios.

Summer 2000

- One student associate attended summer internship at NREL headquarters in Denver, CO.

September - December 2000

- Continued with the third design studio for Demonstration/Education, Theater, Conference, and Restaurant facilities with particular emphasis on the analysis and study of light-weight architectural structures, which could have implications for our design, and simulation of the various proposals from the studio.
- Building a knowledge base and developing a design for a web site that would host the Floating Theater Project.
- Building a digital studio that would support the activities of the project and the Floating Theater web site.

Contract #: AAK-9-18675-07

Planned FY 2001 Activities:
January - May 2001
- To build and run a fully functioning web site by May 2001.
- To conduct the fourth design studio and develop two-and-three dimensional designs.
- To collect, analyze, improve, and document the best designs from the design studios.
- To digitize the designs and lay the foundation for the simulation of the various designs.
- To post on the web site the production of the classes.
- To present Project findings and status at NCPV Program Review Meeting by Principal Investigator.

Summer 2001
- To present Project findings and status at NREL Headquarters by Principal Investigator and Student Associates.

September - December 2001
- To continue with design studios and develop two-and-three dimensional designs.
- To collect, analyze, improve, and document the best designs from the design studios.
- To digitize and conduct simulation of the various designs.
- To post the production of the designs and simulation results on the web.

Major Reports Published in FY 2000:
Asgedom, Araya (2000) The Floating Theater Project: The First Year, National Renewable Energy Laboratory, Golden, CO.

HBCU PV Research Associates Program

Electronically Controlled Photovoltaic (PV) Power Using Artificial Neural Network

Contract #: DEAC36-98-GO10337 **Sub-contract #** AAK-9-18675-6	**Contract Period:** 4/99-4/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
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Washington, DC 20059</td></tr>
<tr><td>Organization Type: HB</td><td>Congressional District: At-large</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
James A. Momoh
Phone: 202-806-5350 Fax: 202-806-6588 Email: jm@scs.howard.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Fannie Posey Eddy
Phone: 303-384- 6247
Fax: 303-384- 6877
E-mail: fannie-posey_eddy @nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information: none</td></tr>
<tr><td>DOE Funding Allocation:
1999: $33,333
2000: $31,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objectives: The project is aimed at developing:

1. Engaging students and faculty in PV research activities and integration of PV technology into EE curriculum.
2. Development of research thrust area in systems engineering approach to improve the quality and reliability of PV technology, i.e.
   (a) Development of an intelligent system scheme such as ANN scheme to predict radiation effects on PV system under different times and temperatures.
   (b) For a given system of faulted PV modules under operation, a GA algorithm scheme is to be developed to track the optimal maximum power points.
   (c) Testing of a developed control scheme using an electronics and fuzzy logic controller to achieve a stable and quality PV system.
   (d) Engaging students in variety of hands on projects and thesis development in PV technology.
   (e) Generalizing the application of intelligent system approach to PV technology, power management, cell fault detection and controls.

Approach/Background:
New systems engineering technology is considered for improving the performance of PV System for real time operation. Their values allow us to determine the optimal operating point during different system states. Whenever the PV cells and battery state of discharge are studied on different fault, multiple maximum points are possible. The existing technique, from our literature review, cannot determine the optimal point due to multi-peaks problem. Because of the limitations of existing optimization techniques to handle multiple peak points, GA with evolutionary algorithm

Our research using integrated ANN-GAs employed to provide tracking of the PV under different uncertainties. The scheme is tested using NREL hourly synoptic data sets for Sterling, VA located at *"http://www.nrel.gov/solar/pubs"*. The ANN is derived from Back Propagation and GA employs search evolutionary algorithms. In addition, we have reviewed Intelligent System and Control Scheme (ISCS) for handling system instability during contingency. We have employed the fuzzy logic scheme to improve stability and ensure maximum power quality

We have reviewed different control options for system stability, two applicable methods of control can be used namely; power electronic and fuzzy logic. These schemes will be tested using state of the art tools and practical data from the industry. During the post summer additional hands-on work was designed to engage pre-college students in understanding and application of PV technology as a potential renewable energy source.

Contract #: DEAC36-98-GO10337 **Sub-contract #** AAK-9-18675-6

Status/Accomplishments:

During this year, ending by September 30th, 2000**,** our research team has performed the following to date:

- Completed literature review on PV power tracking and controls
- Evaluated different controls and optimizations technique such as Fuzzy Logic, Artificial Neural Network, Genetic Algorithm and Optimization techniques
- Engaged in pre-college Energy Expert System Institute (EESI) 2000 summer program: 12 students, implemented hands-on project that involved controlling the performance of the Hybrid PV system using Expert system.
- Attracted students and Research Associates interest to participate in system-based PV Research using emerging technology. Especially, we have:
  - Developed and tested GAs-based optimization program for detecting the optimal tracking points during a faulted PV system.
  - Developed and tested a robust ANN using back-propagation for predicting the solar radiation.
  - Tested Initial results for controlling PV stabilization process and power quality.
  - Tested the intelligent scheme using NREL hourly synoptic data sets for Sterling, VA located at *"http://www.nrel.gov/solar/pubs"*.
  - Tested "Intelligent System Control Scheme" for best PV tracking using genetic algorithm and artificial neural networks.
  - Developed Cost Benefit Analysis technique for evaluating different control option for stabilization.
  - Designed a fuzzy logic control scheme for enhancing PV stability and power quality.
  - Built a PV Power Management scenario for a model single family to expose pre-college students to PV technology

Planned FY 2001 Milestone: The research work planned involves:

- Design and implementation of a Fuzzy Logic Control scheme for increasing the PV system performance.
- Develop electronic control options such as:
  - Power condition (PC),
  - Minimum Power Tracking (MPT),
  - DC/DC Converter
  - Test the GA/ANN generalized system for cells / battery used in PV System,
  - Evaluate the potential of GA and Everett method for load curtailment during a low production PV system,
  - Develop a GUI-based simulation environment,
  - Publish reports/papers and attend conferences.

Major Reports and Papers Published This Year:

James A. Momoh and Sahar S. Kaddah "Optimal Tracker For A Faulted PV System Using ANN and Genetic Algorithm" proceeding of Large Engineering Systems Conference on Power Engineering (LESCOPE, 2000), Nova Scotia, Canada.

James A. Momoh, Joel Njoroge, "Power Mismatch Compensation for PV Systems using Genetic Algorithm", Proceeding of North American Power Symposium, California, October 1999.

James A. Momoh and Sahar S. Kaddah, "Managing Congestion in the New Deregulated Environment: An Implementation" 4th International Conference on Power Systems Operation and Planning (ICPSOP), Accra, Ghana, July 31 - Aug. 3, 2000, p.p. 95-101.

James A. Momoh, Sahar S. Kaddah, and Hassan Greene, "Tracking Optimal Operating Point For A Faulted PV System Using ANN and Genetic Algorithm", paper and presentation at the National Center Photovoltaics Program Review Meeting, Denver, Colorado, 16-19 April 2000.

Reports to National Renewable Energy Laboratory:

Presentation for the "National Center Photovoltaics program Review Meeting", Denver, Colorado, 16-19 April 2000,

James A. Momoh and Sahar S. Kaddah, "Optimal Tracker for A Faulted PV System Using ANN and Genetic Algorithm", presented at the Renewable Energy Academic Partnership (REAP) Symposium in Golden, Colorado, 8-12 August 2000.

Second Quarter report ending January 15th, 2000 for NREL,

Third Quarter report ending April 15th, 2000 for NREL, and

Fourth Quarter report ending September 30, 2000 for NREL.

HBCU PV Research Associates Program

Solar Radiation Measurements

Contract #: XAX-5-15021-06	**Contract Period:** 10/6/95–10/5/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
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E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Mississippi Valley State University
Natural Sciences Dept.
Itta Bena, MS 38941</td></tr>
<tr><td>Organization Type: HB</td><td>Congressional District: 2</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
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Phone: 662-254-3740 or 6737 E-mail: trifour@netdoor.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
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E-mail: fannie-posey_eddy @nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1994: $40,000 1998: $33,708
1995: $0 1999: $0
1996: $42,400 2000: $0
1997: $11,236</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This report will constitute a summary of the current activities associated with the photovoltaic undergraduate research program at Mississippi Valley State University. Our program's primary objective is to familiarize our students with various aspects of energy related research, particularly those associated with the developing photovoltaic industry.

We began FY00 by performing a comprehensive review of the studies we have done to date. There were long term studies about the solar energy signature at the earth surface. One set of experiments were carried out using radiation sensors that probed the various aspects of the radiation profile. Another involved power measurements using standard solar panels. We also carried out studies in reclaiming active metals from spent salts. These metals are the active components in most batteries and several types of fuel cells.

Approach/Background: Our approach, to understanding the nature of the solar radiation profile was to collect data for the three aspects of the profile (direct, diffuse, and global) as a function of season and cloud cover. We want to quantitate the average effect of cloud cover, and planetary motion on the various aspects of the solar radiation profile. This should lead to an estimate of the average available power for a region. Second we want to be able to store solar energy as chemical energy. In our case we are researching how solar energy can be stored as active metals. We have been carrying out experiments on reclaiming active metal from spent salt slurries. Our ultimate goal is to design a fuel cell element that can be regenerated by renewable energy systems. These active metals can then be used as precursors for hydrogen generation. A third aspect of our research is centered on alternative energy generation using active metals in various electrochemical systems. While not directly related to photovoltaic systems, electrochemical systems maybe instrumental in developing a demand for solar generated energy.

Status/Accomplishments: We have completed an analysis of solar radiation data collected over a two year period. This analysis has provided several significant insights into the nature of the radiation profile. This analysis has indicated that optimum power levels can be reached using an arrangement that eliminates the diffuse component of the radiation profile since it seems to reduce the absorption efficiency of the active surface. We have related these effects to the behavior of the Einstein absorption coefficients.

We have carried out experiments with solar panels that have indicated that significant power can be obtained from solar cells in the winter contrary to some beliefs. In fact we observed the maximum power of the panels in mid winter not in mid summer as might be expected. How ever the fact that in summer one has more hours of daylight means that the integrated or accumulated solar power is greater in mid summer. However with a rotating platform to maintain optimum orientation can produce upto 80% as much solar energy in mid winter as a similar system in mid summer.

We have completed a set of preliminary experiments that have shown that we can collect several kinds of the most used active metals like zinc, aluminum, and even magnesium from salt slurries using a relatively inexpensive setup. These metal are those most used in batteries and some fuel cells.

Contract #: XAX-5-15021-06

Planned FY 2001 Activities: For the coming year we want to continue studying the radiation profile using the abilities of the TCOM software to create a precise data base. We also want to built a rotating platform solar array and use it to reclaim active metals from salt slurries. We want to continue our work with batteries and fuel cells.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

T. Pierre and W. Mahone, "Renewable energy and fuel cells," 3rd *MAS Mississippi Academy of Sciences Conference, Beloxi MS* Feburary 2000.

B. Adams and W. Mahone, "Aspects of The Regional Solar Radiation Profile," 3rd *MAS Mississippi Academy of Sciences Conference, Beloxi MS* Feburary 2000.

HBCU PV Research Associates Program

Investigation of Photovoltaic and Thermophotovoltaic Semiconductors

Contract #: AAK-9-18675-03	**Contract Period:** 1/12/99–1/11/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	North Carolina Central University Department of Physics Durham, NC 27707	
	Organization Type: HB	**Congressional District**: 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Joe Dutta **Phone:** 919-560-5105 **E-mail:** jmd@sci.nccu.edu	
Technical Monitor: Fannie Posey Eddy **Phone**: 303-384- 6247 **Fax**: 303-384- 6877 **E-mail:** fannie-posey_eddy @nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $49,959 2000: $63,000	**Cost Share Funding:**

Project Objective: Our research objective is to establish several methods to study low temperature structural modification and characterization of photovoltaic and thermophotovoltaic semiconductors. Part of the objective is to identify electro-optical properties critical to the performance of these samples semiconductors and establish an adequate explanation of the observed variable behaviors of some of the selected solar cells. One of the principal aims of the task is to employ Free Electron Laser (FEL) capabilities in electron and vibrational excitations for Raman and high-resolution photoluminescence (PL) spectroscopy for characterization of thin films, as well as bulk samples.

Structural properties of a-$Si_{1-x}C_x$:H film are analyzed by SAXS (Small Angle X-ray Scattering) and IR spectroscopy, as a function of carbon concentration.
Chemical ordering of polyphase alloys is investigated by combining vibrational and nuclear methods on a-$Si_{1-x}C_x$:H.

Surface morphology of various solar samples are investigated by Scanning Probe Microscopes (SPM), such as the Atomic Force Microscope (AFM) and the Scanning Tunneling Microscopes (STM).

Three PV Research Associates with outstanding academic background (GPAs greater than 3.5 on a 4.0 scale) are trained to perform a variety of measurements and characterization of silicon based solar cells. Project provides full support to each participating Associates during the academic year and make arrangement for additional support for full time research participation during summer months. Associates are encouraged to present their research results in various scientific meetings.

Approach/Background: We are exploring specific FEL capabilities, such as, its tunability over a wide range of excitation energies (from infrared to ultra violet), brightness of the source (several orders of magnitude larger than that of conventional sources), and the superior control of the beam intensity, for modification and, as well as, characterizations of solar cells materials and devices.

Impurities in solar cell materials are usually consequences of the preparation method and in most cases cannot be removed in cost effective way. In some cases, impurities, like carbon and oxygen in silicon, build different kind of agglomerates and become electrically inactive. Conventional annealing procedure involves subjecting the sample at high temperature for an extended period of time. Here by direct transfer of energy to the certain defect by choosing specific wavelength of FEL source, kinds of problems, which may arise due to the presence of impurities and thus effect the performance of the solar cells, can be treated much more efficiently, at relatively low temperature. Low temperature crystallization and annealing is especially important for thin film devices, due to prevention of unintentional interdiffusion, chemical reactions, or deformation caused by excessive heating. Successful applications of these procedures can provide a scope to realize the manufacture of low cost solar cells with high efficiency.

Wavelength tunability of the FEL source provides an excellent scope to perform resonance Raman spectroscopy, which can enhance the resolution of the measurements, in some cases by orders of magnitudes.

Contract #: AAK-9-18675-03

Status/Accomplishments: During this reporting period, our studies have been primarily on silicon-based materials and devices.

- Materials Modifications: Hydrogen is crucial for improving the electrical and optical properties of a-Si:H. It not only saturates dangling bonds and decreases the density of defects states in the gap, but it also reduces the structural disorder. In order to study the possibility of influencing the phase containing predominantly Si-H bonds, with as low as possible influence on remaining material, samples of a-Si were exposed to Duke-FEL Mark III radiation. The wavelength of radiation was selected to fit the maximum absorption of stretching vibrations of Si-H bonds. By varying the wavelength between 4.8 and 5 μm, the illumination time and the power density, different type and degree of structural ordering, monitored by Raman spectroscopy, regarding Si-H bonds and Si-Si bonds was obtained. Using 5 μm at 10 kW/cm^2 leads to increase in structural disordering. However, increasing power to 60 kW/cm^2 improves both short and intermediate order in a-Si:H. Further, increasing power density by an order of magnitude results in crystallization of the sample (Publication 1).
- Chemical Ordering: One of the important characteristics of multi-composite materials is the degree of chemical ordering. It reveals the mutual positions of constituent atoms, which is turn determines the physical and chemical properties of the material. Thin amorphous hydrogenated silicon-carbon films, a-$Si_{1-x}C_x$:H were deposited by magnetron sputtering on glass and mono-crystalline substrate with carbon content from x = 0.2 to x = 1, wide variation of hydrogen concentration and different degrees of structural ordering. The obtained films were investigated by FTIR spectroscopy, Raman spectroscopy, RBS (Rutherford Backscattering) and ERDA (Elastic Recoil Detection Analysis). The results of the quantitative analyses obtained by the above-mentioned techniques were compared. It has been concluded that the applied vibrational methods can be used as quantitative, which enables estimation of the degree of chemical ordering in the analysed samples (Publication 2)

Planned FY 2001 Activities: Annealing and Crystallization Study: In a follow-up effort, two main FEL characteristics, wavelength tunability and ultrashort-pulse operation (~10 ps) with intense peak power (~MW), will be utilized to perform additional bond breaking experiments on doped amorphous silicon samples. By proper selection of the wavelength of the FEL radiation to fit the maximum absorption of the stretching vibration of the silicon bond under study, types and degree of structural ordering will be monitored by Raman spectroscopy.

- Materials Characterization: Internal photoemission (IPE) technique using FEL will be applied to study heterojunctions and metal-semiconductor devices. The conduction and valance band discontinuities at the interfaces buried deep into bulk can be directly measured by the FEL-IPE technique. This technique will be particularly useful to study the relation between the material and the junction quality of CdS/CdTe devices, performance characteristics of which are yet to be fully realized.
- Experimental methods applying conventional, as well as, FEL techniques, which are complementary to each other, will continue to be utilized in various experimental procedures. Such an overlap between conventional and FEL techniques will provide a desirable control on the merit of using FEL.
- Train about four undergraduates in the field of photovoltaic technology.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000

Dutta, J. M., Gracin, D., Bogdanovic, I., Borjanovic, V., Jaksic, M., and Vlahovic, B., "Selective bond breaking in amorphous hydrogenated silicon by using Duke FEL," to be published in Nuclear Instruments and Methods.

Gracin, D., Bogdanovic, I., Borjanovic, V., Jaksic, M., Dutta, J. M., and Vlahovic, B., "Quantitative Analysis of a-$Si_{1-x}C_x$:H thin films by Vibrational Spectroscopy and Nuclear Methods," to be published in Vacuum.

Gracin, D., et al., "Structural properties of a-$Si_{1-x}C_x$:H by SAXS and IR spectroscopy," Fizika A 8 (1999) 131.

Gracin, D., Dutta, J. M., Bogdanovic, I., Borjanovic, V., Jaksic, M.,., and Vlahovic, B., "Quantitative Analysis of a-$Si_{1-x}C_x$:H thin films by Vibrational Spectroscopy and Nuclear Methods," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 225-226 (2000).

Unpublished Contributed Presentations by PV Associates at the National Meetings:

A. Sunda-Meya " CRYSTALLIZATION OF a-Si:H THIN FILMS BY LASER ANNEALING," National Conference on Undergraduate Research, 27-29 April, 2000, Missoula, Montana.

Dana Maurice Warren," ATOMIC FORCE MICROSCOPY TO INVESTIGATE SURFACE MORPHOLOGY OF SEMICONDUCTORS," National Conference on Undergraduate Research, 27-29 April, 2000, Missoula, Montana.

HBCU PV Research Associates Program

Thin Film Electrodes and Electrolytes for Photoelectrochemical Cells

Contract #: AAK-9-18675-02	**Contract Period:** 1/27/99–1/26/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Southern University A&M College Surface Science, Spectroscopy, and Solid State Ionics Laboratory Department of Physics Baton Rouge, LA 70813	
	Organization Type: HB	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Rambabu Bobba **Phone:** 225-771-4130 **E-mail:** rambabu@grant.phys.subr.edu	
Technical Monitor: Fannie Posey Eddy **Phone**: 303-384- 6247 **Fax**: 303-384- 6877 **E-mail:** fannie-posey_eddy @nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $36,060 2000: $42,060	**Cost Share Funding:**

Project Objective: The objective of this project is to train and create interest in photovoltaics among the selected African American students at Southern University and A&M College, Baton Rouge. We aim at teaching the principles, concepts, research methods and advantages of renewable energies over the conventional fossil fuels and motivate them for careers in alternative energy technologies. These efforts involve a broad spectrum of advanced technologies in areas of , photovoltaic (PV) technologies (solar cells), small fuel cells, rechargeable solid state batteries, solid state sensors and thermoelectric devices. In this project, we are focusing on preparation and characterization of semiconducting oxide and sol gels immersed in strong electrolytes for photoelectrochemical cells (PECs) applications.

Approach/Background: The PECs will provide viable alternative to solid state PVs since they may be easier to manufacture and may have greater efficiencies due to sensitizing techniques. PECs have the advantage over the conventional PVs in six main areas: 1) By tailoring the electrolyte solution, the band bending of the semiconductor can be varied. 2) There are no solid to solid junctions which need to be created, so it is easy to fabricate a cell. 3) There is no need for antireflective coatings 4) the differential expansion is not a problem for PEC system and 5) the conventional fuels (hydrogen) can be produced directly with heterogeneous systems. PECs depend upon the irradiation of an electrode or an electrolyte to produce change in the open circuit potential or the current in the closed circuit system The construction of PECs are similar to the construction of electrochemical cells (batteries) in which one of the metal electrodes of a conventional electrochemical cell is replaced by a semiconductor electrode, PECs utilize the input optical energy to drive electrochemical reactions. Dye sensitized solar cells based on nanocrystalline porous films of TiO_2 are promising new kind of a PV cell. Technological interest in these cells stems from their demonstrated solar efficiencies of 10% -11% stability of the semiconducting material, potentially inexpensive manufacturing material cost, use of environmentally friendly components and potential unique applications (transparent various possible colored dyes). The most extensively studied cell consists of monolayer of a Ru- bipridyl based charge transfer dye adsorbed on to the surface of a thin nanocrystalline TiO2 film supported on transparent SnO_2 conducting glass. Although most work on dye sensitized nanocrystalline metal oxide solar cells has focused on anatase phase form of TiO_2 rutile TiO_2 is potentially cheaper to produce and superior light characteristics, which is a beneficial property from the perspective of effective light harvesting. In this project, we have initiated a work to deposit nanocrystalline rutile films onto the transparent tin oxide back contact from the hydrolysis of $TiCl_4$. In this reporting period, we have investigated TiO_2, SnO_2, CeO_2, Ag_2O - SiO_2 , Li_2O –SiO_2 gels and explored their utility as electrode materials for PECs, Fuel Cells, Batteries, and sensor applications.

Status/Accomplishments: During 1999-2000, NREL -HBCU- PV associates at SUBR were involved in the preparation and characterization of the following materials and devices: (1) TiO_2 based dye sensitized Photo Electrochemical Cells (PECs), (2) X-ray absorption spectroscopy and a.c. impedance measurements of new Nafion type polymer electrolyte for Direct Oxidation of Methanol Fuel Cells (DMFCs), (3) Scanning Tunneling Microscopy (STM) instrumentation and measurements on some selected metal and graphite systems, (4) Growth of $PbSO_4$ crystals in Lead Acid Batteries, and (5) Nanostructured Thin Films and Superlattices by Pulsed Laser Deposition (PLD) method.

(1) Nanostructured TiO_2: Calculated amount of high purity titanium (IV) isopropoxide (99.9%, Aldrich) was hydrolysed using doubly distilled water under constant stirring. The precipitate was filtered, washed with distilled water several times and dried in air at 100°C. The thermal characteristics of the as-prepared powder were studied by Differential thermal analysis (DTA) and Thermogravimetric analysis (TGA). As TiO_2 exhibits three different crystallographic phases namely anatase, rutile and brookite, temperature dependence of crystallographic phase analysis have been carried out by Powder X-ray diffraction method. The XRD patterns of samples heated at 450°C, 550°C, 600°C, 650°C & 700°C .. Sample heated at 300°C showed a broad pattern and are highly amorphous giving features of a gel-like material as the water removal was not completed. The sample heated at 450°C, gives spectrum corresponding to brookite phase of TiO_2. On increasing the calcination temperature to 550°C, XRD pattern of the sample gives a pure anatase TiO_2. Samples heated at 600°C and 650°C

are bi-phasic mixture of both anatase and rutile TiO_2 with the fraction of rutile phase increases with increasing calcination temperature. XRD pattern of sample heated at 700^{o}C gives lines corresponding to only rutile phase. The particle size analysis was performed by scherrer method for the most intense peak of anatase phase. An average particle size of 20.37 nm was obtained for TiO_2 powders heated at 550^{o}C which increases with increasing calcination temperature. The average particle size of TiO_2 heated at 600^{o}C is about 40.37 nm.

(2) Pulsed Laser Abalation Method: 10 gms of TiO_2 (purity 99.99%, Aldrich make) were ground and made in the form of pellets. These pellets were sintered in air at 1000 ^{0}C for about 24 hours. The XRD of the pellets reveal the lines corresponding to the rutile phase of TiO_2. These pellets were used as targets for preparation of thin films of TiO_2. A Lumonics pulsed excimer laser (KrF; lambda=248 nm) operating at 10 Hz was used to deposit films on polished <100> $LaAlO_3$ and glass substrates. Deposition parameters such as substrate temperature, laser pulse energy and target-substrate distance were varied. The optimized in-situ conditions are; fluence-3J/cm^2; substrate-target distance- 4.5 cm; temperature - 300 to 500 ^{0}C and oxygen partial pressure-200 mtorr.. Phase purity of the samples was checked by powder X-ray diffraction technique (XRD).

(3*) XANES spectra of rare earth dopants in CeO_2:* We have measured the Ce- L_{111} edge and the L_{111} edge XANES of the trivalent rare earth dopants (lanthanide series) in ceria and compared with the a.c impedance data obtained earlier in this project. The structural parameters for the solid solutions obtained from the best fit were then compared with various defect models and the structures of the next nearest neighbors (cation -cation pairs) are analyzed. So, the objective of this present study is to verify the local structure and short range order around a defect or dopant in order to explain the variations in conductivities. The cations of different ionic radie (over sized and under sized) than that of Ce^{4+} were chosen for XANES study and compared with the ac impedance measurements

(4) Nanostructured SnO_2 thin films: Nanocrystalline materials offer greatly reduced grain size, so that the depletion layer has similar dimensions to the particle radius. Under these conditions, oxygen adsorption will result in SnO_2 grains that are fully depleted of conduction band electrons. Thin film gas sensors based on nanocrystalline SnO_2 doped with Pt, Pd, or Ag prepared by PLD and gas phase condensation route yielded enhanced sensitivity compared with materials prepared by conventional methods. We have prepared SnO_2 powders and films in our laboratory. XRD, and TEM data revealed, particles are of the size 20 nm. .

Planned FY 2001 Activities: We will continue to synthesize nanostructured thin films and superlattices of semiconducting oxides, chalcopyrites and solid electrolyte materials for miniaturized thin film solar cells, multilayered ceramic fuel cells, lithium ion batteries and thin film gas sensors. Thin film solar cells have number of attractive features namely: light weight, high durability in the field, high radiation tolerance, flexible substrates, scalability to large areas, and generally low costs. The highly oriented chalcopyrite films prepared by PLD will be used in the design of tandem structures, optimization of the bandgap profile within a single-junction cell, and design of diodes where the electronic junction is spatially separate from the interface between these layers. In Fall 2001, we will attempt to prepare and characterize the following systems: (1) semiconducting oxides (ZrO_2, and TiO_2) for thin film gas sensors, (2) ternary and quaternary chalcopyrite semiconductors (ABX_2 (where A = Ag, Cd, Cu and Cd, B = Ge, Ga, In and X = P, Se and Te), and superlattices on GaAs, GaP, InAs, CdSe substrates for thin film solar cells, and (3) doped and undoped $LiMnO_2$ and $LiNiO_2$ on $LaAlO_3$ single crystal and sapphire substrate for Li – ion microbatteries. By combining EXAFS, surface probes and impedance spectroscopy studies, we should be in a position to provide an atomic level understanding of the processes taking place in the electrode surfaces and electrode-electrolyte interfaces.

Major Reports Published in FY 2000

A study of methanol electro-oxidation reactions in carbon membrane electrodes and structural properties of Pt alloy electro-catalysts by EXAFS, Tameka Page, Ronda Johnson, J. Hormes, S. Noding, B. Rambabu, Journal of Electroanalytical Chemistry 485 (2000) 34-4.

Sol Gel synthesis and characterization of Ag_2O-SiO_2 systems, N. Satya, N. Xie, and B. Rambabu, Materials Science and Engineering B72 (2000) 7-12.

Effect of Low Temperature Synthesis on Structural Properties of Lithium Silicate Dried Gels, N. Satyanarayana, Xie, Charles Wayne, and B. Rambabu, Journal of Solid State Ionics (SSI-12), 135, p 235, 2000. Ed. C. Vayenas.

X-ray Absorption Near Edge Structure (XANES) and Ionic Conductivity studies of trivalent cations in CeO_2. J. Hormes, Bryan Blazas, and B. Rambabu, Journal of Solid State Ionics (SSI –12), 136, p 1-10, 2000. Ed. C. Vayenas.

Nanostructured thin films and superlattices by pulsed laser deposition, G.K.Immanuel and B. Rambabu, 2nd Annual NREL- REAP conference, August 8-11, 2000.

Major Articles Published in FY 2000: none

HBCU PV Research Associates Program

Design, Analysis, and Testing of PV Stand-Alone and Grid-Connected Systems and the Development of an Education Study Guide

Contract #: AAK-9-18675-05	**Contract Period**:12/28/98–12/27/01

Sponsoring Office Code: EE-11	**Performing Organization**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Texas Southern University School of Technology Houston, TX 77004	
	Organization Type: HB	**Congressional District:** 18
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator:** Joshua Hill **Phone:** 713-313-7007 **Fax:** 713-313-1853 **E-mail:** tchajxhill@tsu.edu	
Technical Monitor: Fannie Posey Eddy **Phone**: 303-384-6247 **Fax**: 303-384-6877 **E-mail:** fannie-posey_eddy @nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1999 - $50,000 2000: $63,000	**Cost Share Funding:**

Project Objective: Provide undergraduate students support for photovoltaic energy research and education at HBCUs, with the aim of attracting qualified science, engineering, and business students toward pursuing a career in these areas with emphasis in photovoltaic technology. The objective is to also strengthen the PV research capabilities of HBCUs and to continue achieving the goals of the DOE/NREL PV Program within these schools.

Approach/Background: With the use of renewable energy technology, Texas Southern University School of Technology is committed to channeling more HBCU students and faculty into photovoltaic research and applications. TSU has three (3) Research Associates. The approaches for this program during 1999 were as follows: One PV Research Associate is conducting a literature search to review and report on photovoltaic and renewable energy study guide for teachers, including any developed by TSU faculty for the TSU's Renewable Energy and Environmental Protection (REEP) Academy. Two PV Research Associates are receiving in-depth training in the design and installation, testing, and analysis of PV systems in order to perform system load-data analysis of stand-alone systems and one Associate will establish a method for evaluating a grid-connected PV system.

Status/Accomplishments:

PV Research Associate Chien-Kai Chang

I continued my internship, this summer at NASA with GB TECH where I shared in preparation of a solar refrigerator for South Africa while also writing a user's manual. Additionally I started developing and testing the full size refrigerator and solar heat pump systems. I'm very excited at having this opportunity because it gave me a chance to work with very sophisticated PV applications and the latest technology. Significant time was spent developing and testing, because this unit is for REEP to install in South. Testing included two external data acquisition units for recording the temperature inside and outside of the refrigerator. We also made a plastic glass insulation tank for testing and modifying the phase change material freezing point then using that to adjust the electronic control device. In addition, we have done performance testing. We put 60 bottles of 150-degree coke into the refrigerator for cooling. Then we added 60 bottles more to see how much time elapsed before the temperature dropped to the expected point. Also, we continued to develop the solar heat pump system. As with the refrigerator, we wanted the best performance from heat pump. We insulated all of the pipes for better water temperature transfer. In addition, we changed the hot water loop pipes in an effort to raise water temperature from 150 degrees to 250 degrees. This job presented an excellent opportunity and experience. In addition, a major part of the job was setting up data acquisition systems and collecting data on the performance of the systems.

In addition to my internship at NASA with GB TECH I have also been assigned to designing the REEP website. The address to the site is http://technology.tsu.edu/REEP/default.htm. The information on the website includes the general information and REEP 1999 filed trips. Currently, the site is being updated to include the REEP 2000 data.

PV Research Associate Rahsaan Arscott

I participated in the battery-free solar refrigerator installation in the Transkei Region of the Republic of South Africa. Although the installation took place in South Africa, preparation for the installation began at Texas Southern. Several mock installations took place in the PV lab in order to get the actual installation to run as smoothly as possible. By doing these mock runs of the installation, we were able to come up with a list of obstacles we would possibly encounter. We were also able to compile a list of tools and safety equipment we would need for the actual installation. In case of any problems, we came up with a troubleshooting list for the South Africa installation. Although we went through months of preparation, a few problems were encountered once we arrived in South Africa. The frame we requested was supposed to be aluminum, instead, when we got there they had a steel frame. The steel frame was to heavy for the pole we had so we tried to place the frame on the roof. It was later determined that the roof could not support the steel frame either. We then had to design a wooden frame, which would be attached to the roof, but this presented another problem. Since we were in the Southern Hemisphere we had to face the panels north for optimization, but the North facing side of the roof was heavily shaded. We then had to determine the next best location for the panel to receive the most power throughout the daylight hours. Once the panels were in place, the wire was run into the house and to the battery-free refrigerator for power. A data logger was placed on the back of the refrigerator to monitor the temperature. The data will be taken periodically by technical staff from Eastern Cape Technikon. An analog thermometer was also placed in the refrigerator to aid the family in keeping the refrigerator's temperature within its operation range.

In the PV lab I am modifying an AC/DC Multi Function Emergency Lantern (MFEL) to operate solely on a 6-volt solar panel or a 6-volt rechargeable battery. The MFEL includes an AM/FM radio, a siren, an incandescent flashlight, a fan, and a fluorescent lamp. The MFEL is being modified to better suit rural off-grid areas; therefore the AC transformer and wall outlet have been removed from the device. A 6-volt charge controller will be installed in the device to keep the battery form being overcharged by the PV panel. When all modifications are complete the data loggers, donated by NREL, will be used to record data from the MFEL during its testing stage.

PV Research Associate Collaborative Activities

PV Research Associates Chien-Kai Chang, Reginald McCreary, and Rahsaan Arscott assisted with workshop preparation. Preparation included taking inventory of materials in the solar lab, purchasing solar lab supplies for the REEP program, routine maintenance in the PV Lab, and performing tests on the solar lab PV system. In the workshops, the Research Associates, under the supervision of Mr. Oral LaFleur assisted the students with wiring and testing solar panels. The first workshop was basically to familiarize the students with equipment that is used in the lab, such as the digital multi-meter, wire strippers and clippers and the soldering iron. Once the students became familiar with the equipment they got the chance to use it in an exercise where they were shown the difference between series, parallel, and series-parallel connections and how to make the connection. After the wiring workshop the students were taken outside to measure the shaded and unshaded voltage and current of the solar panels. This information was then compared with the actual voltage and current as listed on the back of the Panels. After the workshops were completed the Research Associates provided examples of when each type of wiring procedure would best fit the application. The Students were then given a verbal quiz on which wiring style would go with which PV application. In another workshop, PV Research Associates Chien-Kai Chang and Rahsaan Arscott assisted Mr. Mike Comer in helping the REEP students build solar ovens. They worked with students step-by-step in the construction of these solar devices.

In the PV lab we constructed a frame for two BP Solar 60-watt panels for testing the battery-free solar refrigerator at Texas Southern. The unit at TSU has the same configuration as the unit that was installed in South Africa. In the solar lab, we are testing the unit empty, and then with 10, 20, and 30 bottles of water. After that we disconnected the power and observed how long the temperature maintained itself, then we connected the power to repeat the test from the beginning. This testing is done in an effort to monitor and have comparisons for the unit in South Africa.

In August 2000 we attended the second Renewable Energy Academic Partnerships conference. The REAP staff chose to host the conference at NREL headquarters in Denver, Colorado which was an excellent decision. There we gave presentations on our research at Texas Southern University. Although we enjoyed giving our presentations, the real highlight was having the opportunity to see what the other PV research associates are doing at their universities. At the NREL headquarters we had the opportunity to learn about some of the latest renewable energy technology while on tour of the PV Center and Wind Facility.

Planned FY 2001 Activities: Activities for the 2001 Fiscal Year include, small appliance testing using solar power sources, continuation of the battery-free solar refrigerator testing, retrofitting an on-campus garage apartment with solar energy sources, and testing of small scale PV/Wind hybrid systems.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

Dr. J. Hill, O. LaFleur, and Chien-Kai Chang, "TSU Battery-Free Solar Refrigerator Project," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 51-52 (2000).

Dr. J. Hill, O. LaFleur, and R. Arscott, "PV Technology Transfer to Remote Areas in South Africa," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 49-50, (2000).

Measurements and Characterization

Analytical Microscopy

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/99-9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** M. Al-Jassim **Phone:** 303-384-6602 **Fax:** 303-384-6604	
Technical Monitor: P. Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E-mail**: pete_sheldon@nrel.gov	**B&R Code:** EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $1,172,000 2000: $1,310,650	**Cost Share Funding:**

Project Objective:
The Analytical Microscopy task provides measurement support, carries out collaborative research, and develops new measurement techniques for the advancement of Laboratory, subcontractor, and industry driven PV R&D. The main objective is to advance the development of PV devices via:

- Providing short-term support (routine analysis) of PV samples with quick turn-around time
- Providing long-term characterization research on key problems/issues facing PV materials and devices
- Developing new characterization techniques to tackle material problems that cannot be addressed by our current capabilities

Approach/Background:
The Analytical Microscopy Task has provided extensive support for both our in-house and subcontract groups. A wide variety of techniques are utilized to characterize PV materials and devices. Compositional measurements are performed by electron probe microanalysis (EPMA) using either energy dispersive or wavelength dispersive X-ray analysis. Structural and defect analyses are carried out by transmission electron microscopy (TEM). A project for the development of image analysis capabilities for the TEM was completed during FY00 enabling us to analyze high resolution images and diffraction patterns from areas as small as 300Å. Additionally, scanning electron microscopy (SEM) in its various modes, such as secondary electron imaging, cathodoluminescence (CL) and EBIC imaging, is providing support for measuring the topographical, luminescent and microelectrical properties of PV materials and devices.

In addition to the above-mentioned capabilities, this task has provided extensive support to the PV program in the nano-scale characterization area. AFM examination has been used to study the morphology and surface structure of a wide variety of materials and devices. Examples of these are: SnO_2, CdS, CdTe, Si, CIGS and III-V films.

All of the research activities carried out by this task are planned through other in-house tasks, National Teams, and our subcontractors.

Status/Accomplishments:
Over 6000 analyses were performed in support of our in-house teams and NREL's subcontractors. This includes measuring the composition, topography, structure, and the microelectrical properties. The following are a few highlights of some of the collaborative research projects we carried out in FY00:

The low-temperature CdTe project, in collaboration with NREL's CdTe Team, was continued. CdTe thin films, deposited by close-spaced sublimation at approximately 450 °C, were studied by compositional analysis and electro-optical measurement techniques. This process produced films with photoluminescence lifetimes above 2000 ps, which are among the best lifetimes measured in our laboratory for CdTe thin films. CdTe/CdS solar cells fabricated with these films also had superior efficiency to comparable cells produced using standard CSS CdTe. These results show the potential of this new process in the fabrication of high-efficiency devices.

Contract #: DE-AC36-99GO10337

The microstructure of SnO_2 and Cd_2SnO_4 transparent conducting oxide films was studied using high resolution TEM. In Cd_2SnO_4 films no defects were found inside most of the grains, whereas in SnO_2 films, high density of planar defects, mainly twins and stacking faults, were found. This significant difference explains the superiority of Cd_2SnO_4 as a front contact to CdTe cells.

The defect structure of CSS-deposited CdTe was studied. The structure is dominated by a high density of planar faults. The atomic structure of these faults was determined by high resolution TEM. Additionally, the chemical properties of the CdS/CdTe interface were studied by x-ray analysis in the TEM. Considerable amount of S diffusion into CdTe was observed in samples deposited at high temperatures. A mechanism for the S diffusion in CdTe was proposed.

In support of NREL's High Efficiency Concepts Team, $Ga_xIn_{1-x}As_yN_{1-y}$, $B_xGa_{1-x-y}In_yAs$ and $(GaAs)_{1-x}(Ge_2)_x$ alloy layers were characterized by TEM for the possible use as 1.00-eV cells in three-junction devices. Epitaxial growth of zinc-blende $B_xGa_{1-x-y}In_yAs$ layers with up to 5% boron has been demonstrated at low growth temperatures (520–600°C). Attempts to incorporate higher boron concentrations resulted in polycrystalline or amorphous material. Similar behavior occurred when high nitrogen concentration $Ga_xIn_{1-x}As_yN_{1-y}$ alloys were grown. It may be possible to kinetically stabilize $(GaAs)_{1-x}(Ge_2)_x$ alloys against phase separation by growing at low temperatures and high rates.

We have applied cross-sectional AFM to the study of semiconductor thin films. We have demonstrated the feasibility of this technique and compared our results with scanning electron microscopy. In particular we studied cross sections of thin-films of CdTe and CIGS, which presented completely different fracture mechanisms. We also combined cross-section AFM with electrostatic force microscopy (EFM) to study the distribution of the electric potential in CdTe/CdS solar cells.

Planned FY 2001 Milestones:

- Complete AFM development, including electrostatic force microscopy and scanning capacitance microscopy, and apply to at least one PV material system.
- Understand the chemical and structural difference between CBD and CSS CdS films and propose a model to explain the difference in device performance (publication).
- Carry out experimental and theoretical investigation of p-type doping of at least one TCO system (publication and/or patent)
- Investigate the microstructure and composition of the surface layer in high-efficiency CIGS absorber films (publication)
- Provide characterization support for the PV program

Selected Major Articles Published in FY 2000:

“Comparison of hydrazine, dimethylhydrazine and tertiarybutylamine nitrogen sources for OMVPE growth of GaInNAs for solar cells”, D.J. Friedman, A.G. Norman, J.F. Geisz, and S.R. Kurtz, J. Crystal Growth **208**, 11 (2000).

“Alternative procedure for the fabrication of close-spaced sublimated CdTe solar cells”, H.R. Moutinho, R.G. Dhere, C. Ballif, M.M. Al-Jassim, and L.L. Kazmerski, J. Vac. Sci. Technol. A **18**, 1599 (2000).

“Cross-sectional Electrostatic force microscopy of thin-film solar cells”, C. Ballif, H.R. Moutinho, and M.M. Al-Jassim, , J. Appl. Phys. (in press).

“Cross-sectional atomic force microscopy imaging of polycrystalline thin films”, C. Ballif, H.R. Moutinho, F.S. Hasoon, R.G. Dhere, and M.M. Al-Jassim, Ultramicroscopy **85**, 61 (2000).

“Observation and first-principles calculation of buried wurtzite phases in zinc-blende CdTe thin films”, Y. Yan, M.M. Al-Jassim, K.M. Jones, S.-H. Wei, and S.B. Zhang, Appl. Phys. Lett., 77, 1461 (2000).

“Do grain boundaries assist S diffusion in polycrystalline CdS/CdTe heterojunctions?”, Y. Yan, D. Albin, and M.M. Al-Jassim, Appl. Phys. Lett., (in press).

"TEM, AFM, and cathodoluminescence characterization of CdTe thin films", M.M. Al-Jassim, Y. Yan, H.R. Moutinho, M.J., Romero, R.D. Dhere, and K.M. Jones, Presented at the European Mater. Res. Soc. Spring Meeting (Strasbourg, France, June 2000). Thin Solid Films (in press).

Measurements and Characterization

Electro-optical Characterization

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401 **Organization Type**: FF	**Congressional District:** 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Richard Ahrenkiel **Phone:** 303-384-6670 **Fax:** 303-384-6604 **E-mail:** richard_ahrenkiel@nrel.gov	
Technical Monitor: P. Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E-mail**: pete_sheldon@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $1,164,900 2000: $1,524,735	**Cost Share Information**: **Cost Share Funding:**

Project Objective:
The overall objective of the electrooptical characterization task is to develop and provide electrical and optical measurement support for both in-house and subcontract PV device research, so as to accelerate commercialization of the respective technologies.

Approach/Background:
We are using measuring techniques that have been developed in our laboratory to analyze samples submitted from the above sources. These are used for both routine characterization and collaborative research with the various materials groups.

- We are developing new measuring techniques that will enhance to the characterization and parameterization of the various materials and devices that have been developed by the PV program.
- We are doing collaborative research with the various materials groups to better understand and improve their technologies. This includes active participation in the various Teams to lend our expertise to improving materials and devices.

Status/Accomplishments:

- Developed and constructed a Current-voltage-temperature (JVT) system for in-plane electrical characterization. This will be operational when the software interface is completed.
- Variable Angle Spectral Ellipsometry has been applied to CTO/ZTO/CdS/CdTe PV devices, GaAsN alloys, CIGS thin films, and InAsP alloys.
- Supported a-Si team with transmittance data and peak fitting analyses of a-SiNH. Continued to generate absorbance coefficient and H concentration data for a-Si team as well as United Solar Systems.
- Provided the TCO team with reflectance data for finding the plasma edge of zinc stannate.
- Led process integration and diagnostic development efforts resulting in the creation of a searchable Technique Database, initiation of a Characterization Needs Seminar Series, and participation in meetings resulting in a Process Integration Concept.
- Technique development efforts were initiated that will result in two new capabilities: a high resolution PL/Raman system and a near-infrared lifetime system.
- Designed and built a compact UHFPCD lifetime system that will be the basis for an R&D 100 submission.
- Designed and tested a dielectric resonator antenna UHFPCD system having a high quality factor for increased sensitivity.
- Constructed and tested a TEM horn antenna that can resolve the minority-carrier lifetimes of approximately 2 to 4 ns with less transient ringing than the previous large bandwidth UHFPCD designs.
- Continued extensive work with the in-house high efficiency Team to characterize the transport properties of GaAsN that lead to understanding device performance.
- Continued work on collabortive project with AstroPower to identify the principal impurities, such as oxygen precipitates, in the single crystal wafers that lead to poor device performance. Work led to a new proprietary anneal process at AstroPower that removes the latter from single crystal wafers.
- Redesign and fabricated AstroPower PVSCAN
- Wrote a PVSCAN Manual and sent completed draft to AstroPower.
- Upgraded Georgia Tech PVSCAN and trained two operators
- Started fabrication of USF PVSCAN.
- Developed an improved defect etching procedure (using Sopori etch) for ribbons —demonstrated this process for ASE Americas and Evergreen Solar ribbons. This is a very significant improvement that has prompted ribbon companies interest in purchasing PVSCAN.

- Improved PV Reflectometer (submitted for R&D100): reduced the measurement time to <1s (milestone met) and designed a reflectance attachment (for ribbon cells) that will make the reflectometer an “absolute” instrument.
- Developed a preliminary optical design for the Fiber Optic Solar Simulator that can meet the requirements of the III-V and Device Performance Teams.

Planned FY 2001 Activities:

- Provide Measurements and Characterization support for the PV program: increase PV Program participant interactions (Industry, University, and in-house).
- Continue support of the NCPV-facilitated National research Teams for the PV program (a-Si, CdTe, CIS, and others).
- Complete a comprehensive analysis of polycrystalline and single crystalline Si feedstock material by correlating FTIR impurity analysis with UHFPCD lifetime in order to identify the lifetime “killing” impurities. Expand collaborations with the Si PV industry (e.g., AstroPower, Evergreen Solar, ASE, BP Solar, Siemens, etc.).
- Develop at least one collaboration with an in-house team to tackle a scientifically important materials problem using the variable angle spectroscopic ellipsometer (contingent on capital equipment funding).
- Increase the number of peer reviewed publications and conference presentations.
- Develop and implement an electro-optical-based diagnostic technique compatible with photovoltaic module manufacturing environment.
- Assist University of South Florida in completing construction of a PVSCAN characterization tool.
- Design and build a compact, low cost UHFPCD system dedicated to crystalline silicon lifetime evaluation. Analyze wafers provided by at least one in-house or subcontract research group. Apply for an R&D-100 award nomination.
- Design and construct a second-generation, table-top version of the PV Reflectometer with improved performance and operating features (measurement time <1 s, 6” x 6” sample size, PV Optics software-based surface roughness or texture height measurement capability).
- Construct NIR-PMT based TRPL system and obtain lifetime data on at least one thin film, 1.0 eV bandgap material.
- Complete construction of high resolution PL system and apply technique to impurity identification in at least one silicon based photovoltaic system.
- Develop an in-house Variable Angle Spectroscopic Ellipsometry (VASE) characterization capability, capable of both variable angle ex-situ analysis and fixed angle in-situ analysis (contingent on capital equipment funding).
- Complete design and bread-board fabrication of the new Fiber Optic Solar Simulator (FOSS) for multijunction solar cell testing.

Selected Major Articles Published in FY 2000:

R. K. Ahrenkiel, W. W. Johnston, L. Gedvilas, and J. Webb, and J. Bisaillion, “Role of Oxygen Precipitates on the Performance of Crystalline Silicon-based Photovoltaic Devices”, Proc. Of PVSC-2000 (in press).

Balcioglu, R. K. Ahrenkiel, and F. Hasoon, “Deep-Level Impurities in CdTe/CdS Thin-Film Solar Cells”, J. Appl. Phys. **89**, 1 (2001).
R. K. Ahrenkiel, S. W. Johnston, B. M. Keyes, and D. J. Friedman and S. M. Vernon, “Transport Properties of $GaAs_{1-x}N_x$ Thin FilmsGrown by Metal-Organic Chemical Vapor Deposition”, Appl. Phys. Lett. (in press).

R. K. Ahrenkiel. S. W. Johnston, J. D. Webb, L. M. Gedvilas, J. J.Carapella, and M.W. Wanlass, “RECOMBINATION LIFETIMES IN UNDOPED, LOW-BANDGAP $InAs_yP_{1-y}/In_xGa_{1-x}As$ DOUBLE HETEROSTRUCTURES GROWN ON InP SUBSTRATES, Appl. Phys. Lett. (in press).

R. K. Ahrenkiel, R. Ellingson, and W. Metzger, D. I. Lubyshev and W. K. Liu, “Auger Recombination in Heavily Carbon-Doped GaAs”, Appl. Phys. Lett. (in press).

R. K. Ahrenkiel,. A. Mascarenhas, S. W. Johnston Y. Zhang, D. J. Friedman, and S. M. Vernon, “Photoconductive Properties of $GaAs_{1-x}N_x$ Double Heterostructures as a Function of Excitation Wavelength”, Mat. Res. Soc. Symp Proc 607, pp. 265-271, (2000).

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Measurements and Characterization

Solar Cell and Module Characterization

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Keith Emery **Phone:** 303-384-6632 **Fax:** 303-384-6604 **E-mail**: keith_emery@nrel.gov	
Technical Monitor: P. Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E-mail**: pete_sheldon@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $920,800 2000: $1,056,570	**Cost Share Funding:**

Project Objective: The performance of photovoltaic devices of all sizes and technologies are evaluated within this activity. This team supports the entire photovoltaic community by providing: secondary calibrations of photovoltaic modules and cells, efficiency measurements with respect to a given set of standard reporting conditions, efficiency verification of contract deliverables, current versus voltage (I-V) measurements under varying temperature, spectral irradiance and total irradiance. Support is provided for in-house programs in device fabrication, module stability, module reliability, PV systems, and alternative rating methods by performing baseline testing, specialized measurements and other assistance when required. This activity also supports the entire PV community by providing information on PV measurement equipment and systems that are appropriate for the end user, I-V measurement procedures, and uncertainty analysis. Included in the uncertainty analysis are the determination of potential artifacts in the I-V results because of equipment or procedures, and realistic estimates of the elemental error sources. This activity is committed to obtaining the lowest possible uncertainty in the measurement of the standardized PV performance of single- and multi-junction cells and modules.

Approach/Background: The photovoltaic current versus voltage characteristics are measured with respect to standard terrestrial reporting conditions (25°C temperature, 1000 Wm^{-2} total irradiance and ASTM E892 global reference spectrum). The intensity of the Spectrolab X-25 solar simulator (30 cm square beam) is adjusted until the measured short-circuit current of a reference cell is equal to it's calibration value corrected for spectral mismatch. The current versus voltage characteristics are then measured using 4-terminal Kelvin connections to the PV device with a custom data acquisition system designed to give a random error of less than ±0.1% and a non random error of less than ±1%. The uncertainty in efficiency measurements with respect to standard reference conditions is ±2-5% depending on the sample size, geometry and number of junctions. These procedures have been shown to be valid for any given tabular reference spectrum including AM0 and the ASTM direct normal reference spectrum. The system is also used for dark I-V and tunnel diode measurements. For two-terminal multi-junction devices the spectrum of the Spectrolab model X25 solar simulator is adjusted, using a special filter plate developed at NREL, until each junction is producing the correct photo-current. The I-V system is also used for examining the effects of pre-measurement conditions, bias rate, maximum power versus illumination time, V_{oc} *vs*. time, and I_{sc} *vs*. time on the PV performance.

The filter spectral response system uses periodic monochromatic light directed through one of 68 10-nm bandwidth interference filters covering the spectral range from 280 to 1900 nm. The system is capable of providing steady-state light bias levels up to 200 mA and voltage bias levels from ±1 mV to ±40V. The uncertainty in the relative spectral response as a function of wavelength is less than ±5%. The grating monochrometer based system has a wavelength range from 300-3200 nm with a 1-nm wavelength resolution and a 1-5 nm selectable bandwidth. The grating system was designed for accurate absolute spectral response measurements by illuminating a small 1-mm by 3-mm rectangular area and measuring the power of the entire beam. The system uses all reflective optics so chromatic aberrations and beam wander with wavelength are not present. The system is capable of broadband or filtered light bias for multi-junction or nonlinear devices. Both systems rely on accurate pyroelectric detectors or NIST calibrated semiconductor detectors for the measurement of the light power.

The efficiency versus concentration measurements are measured with a Spectrolab High Intensity Pulsed Solar Simulator (HIPSS). This system has been used to measure the performance as a function of concentration for GaAs, GaInP/GaAs, tandem, and GaInP/GaAs/Ge triple junction concentrator cells. The concentrator lamp housing allows measurement from 1 to 2000 suns. The cell performance as a function of concentration can also be measured using an unfiltered 1000W Xe-arc continuous light source that is focused to a small area. The primary reference cell calibration procedure involves measuring the short-circuit current, the total irradiance with an absolute cavity radiometer, and the spectral irradiance at the same time outdoors with the same 5° field of view. Since the measured spectral irradiance does not encompass the limits of the reference spectrum, the measured spectrum is extended using a computer model developed by the group to encompass the range of the reference spectrum (300-4000 nm). This procedure has been shown to have a total uncertainty of less than ±1% by rigorous uncertainty analysis, intercomparison with the World Photovoltaic Scale, primary AM0 standards and other intercomparisons. In addition to recalibrating NREL's primary reference cells this system was used to recalibrate 15 WPVS reference cells and calibrate 6 new WPVS candidate cells.

Contract #: DE-AC36-98-GO10337

The I-V characteristics of modules are routinely evaluated using the Spire 240A, Spectrolab model X200 Large-Area Continuous Solar Simulator and outdoors under clear sky conditions.

Status/Accomplishments: During FY00 the team performed 4381 I-V and QE measurements on 1898 cells and modules (I-V under standard reporting conditions). The team continued its hardware and software support of the I-V and QE systems in the user facility. Numerous email and phone consultations on I-V and QE measurement procedures, equipment and calibration strategies were discussed with members of the PV community.

Procedures for accurately determining the performance of multi-junction high-efficiency concentrator cells were documented and refined during this period. These procedures were compared with procedures in place at Sandia and the Fraunhofer Institute in Freiburg Germany. ASTM and international standards, and module energy rating methods were further refined and developed.

Planned FY 2001 Activities: Goals and objectives

- Provide standardized PV cell and module measurements and independent efficiency verification service to in-house groups and contractors in a timely manner.
- Continue to improve hardware, software, and procedures to minimize the uncertainty in PV I-V measurements.
- Continue to provide the U.S. PV industry with a calibration traceability path for efficiency measurements.
- Continue performing standard I-V measurements for all groups involved in terrestrial PV
- Continue ongoing measurements in support of module performance and reliability.
- Continue working with other teams specialized I-V measurement needs.
- Continue to disseminate PV performance measurement technology through tours, phone-conversations and visits.
- Continue to participate in PV standards activities.
- Continue to perform routine radiometric measurements under natural and simulated sunlight for the activities needs.
- Develop hardware, software and procedures to accommodate new cell and module technologies.

Major Reports Published in FY 2000:

Keith Emery, "The Results of the First World Photovoltaic Scale Recalibration," NREL tech. Rep. NREL/TP-520-27942, (March 2000).

C.R. Osterwald, J. Pruett, S. Rummel, A. Anderberg, and L. Ottoson, "Forward-Biased Thermal Cycling: A new Module Qualification Test," *Proc. NCPV Program Review Meeting 2000,* Denver, CO, April 16-19, 2000, pp. 65-66.

T. Moriarty and K. Emery, "Procedures at NREL for Evaluating Multijunction Concentrator Cells," *Proc. NCPV Program Review Meeting 2000,* Denver, CO, April 16-19, 2000, pp. 71-72.

H.L. Cotal, D.R. Lillington, J.H. Ermer, R.R. King, N.H. Karamm, S.R. Kurtz, D.J. Friedman, J.M. Olson, S. Ward, A. Duda, K.A. Emery, and T. Moriarty, "Highly Efficient 32.3% Monolithic GaInP/GaAs/Ge Triple Junction Concentrator Solar Cells," *Proc. NCPV Program Review Meeting 2000,* Denver, CO, April 16-19, 2000, pp. 111-112.

Major Articles Published in FY 2000:

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D.R. Myers, S.R. Kurtz, K. Emery, C. Whitaker, and T. Townsend, "Outdoor Meteorological Broadband and Spectral Conditions for Evaluating Photovoltaic Module", *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, AL, Sept. 15-22, 2000, IEEE, New York, 2000.

D.J. Friedman, J.M. Olson, S. Ward, T. Moriarty, K. Emery, Sarah R. Kurtz, "Ge Concentrator Cells for III-V Multi-junction Devices", *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, AL, Sept. 15-22, 2000, IEEE, New York, 2000.

H.L. Cotal, D.R. Lillington, J.H. Ermer, R.R. King, N.H. Karam, S.R. Kurtz, D.J. Friedman, J.M. Olson, J.S. Ward, A. Duda, K.A. Emery, and T. Moriarty, "Triple-Junction Solar Cell Efficiencies Above 32%: The Promise and Challenges of Their Application in High-Concentration-Ratio PV Systems," *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, AL, Sept. 15-22, 2000, IEEE, New York, 2000.

K. Emery, M. Meusel, R. Beckert, F. Dimroth, A. Bett and W. Warta, "Procedures for Evaluating Multijunction Concentrators," *Proc. 28th IEEE Photovoltaic Specialists Conf.*, Anchorage, AL, Sept. 15-22, 2000, IEEE, New York, 2000.

R.N. Byhattacharya, W. Batchelor, K. Ramanathan, M.A. Contreras, and T. Moriarty, "The Performance of $CuIn_{1-x}Ga_xSe_2$-based Photovoltaic cells prepared from Low-Cost Precursor Films," Solar Energy materials and Solar cells, vol. 63, pp. 367-374, 2000.

Measurements and Characterization

Surface Analysis

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	**Organization Type**: FF	**Congressional District**: 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** S. Asher **Phone:** 303-384-6450 **Fax:** 303-384-6604 **E-mail:** sally_asher@nrel.gov	
Technical Monitor: P. Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E-mail**: pete_sheldon@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $767,400 2000: $1,020,490 1998: $841,400 1999: $916,700	**Cost Share Funding:**

Project Objective:

- To advance the understanding of photovoltaic materials and devices by using surface analytical techniques to investigate surface and interfacial properties.
- To advance the utility and understanding of surface analytical measurements by improving analytical methodology and instrument development.
- To support research activities planned through the work of other in-house and subcontracted researchers for all areas of the National PV program.
- To disseminate research results through publications, presentations, and regular interactions with researchers in the surface analysis and photovoltaic disciplines.

Approach/Background: Surfaces and interfaces are the boundaries between different phases and different types of materials. Interactions in these regions often determine the properties of PV materials and devices. The Surface Analysis Team uses a sophisticated array of techniques for the chemical and compositional analysis of surface, near surface, and interfacial regions of materials. The techniques utilized include scanning Auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS), ultra-violet photoelectron spectroscopy (UPS), and dynamic and static secondary ion mass spectrometry (SIMS). XPS and AES spectroscopies are related techniques for determining the composition and chemistry of surfaces. Dynamic SIMS is used to perform trace element analyses for contaminants and dopants. Static SIMS provides trace elemental and molecular information from the top surface monolayers. Team members are Sally Asher (team leader), David E. King (10/99-08/00), Robert C. Reedy, Amy Swartzlander-Guest, and Matthew Young.

Status/Accomplishments: During FY00 the Surface Analysis team collaborated with researchers in all areas of the National PV program, internal, university and industrial. A summary of the highlights is presented here

- We have completed the first in a series of standards for SIMS analysis of polycrystalline thin film materials. Copper was ion implanted into CdTe, CdS, SnO_2 and other matrices. This work has allowed us to reach one of the first quantitative assessments of Cu distribution throughout CdTe/CdS devices.

- We have used SIMS to study the distribution of Cu throughout CdTe/CdS devices before and after exposure to stress conditions (V_{oc} in light and at 100°C). We have used the Cu standard discussed above to provide the first conclusive evidence to show that Cu is accumulating in the CdS layer of CdTe/CdS devices. The analysis with standards shows that there is a real increase in the Cu level in the CdS. These measurements have shown that actions at the back contact which might be expected to increase Cu diffusion (i.e. increase in deposition or processing temperature, length of stress time or increase in stress temperature) do appreciably raise the Cu level in the CdS.

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Status/Accomplishments (continued):

- We have used AES to provide significant support in CIGS materials research to both internal and subcontracted parts of the PV Program. The majority of this work has been to determine compositional profiles through the CIGS films.

- We continue to use SIMS, XPS, and AES to study bulk composition in the new low band-gap alloys. We have developed a set of standards for B-alloyed materials that allow for the accurate determination of the B content in a wide range of materials including GaAs, GaInAs, InAs, InP, GaP and GaInP. SIMS has been used to study light element contamination in these materials leading to better understanding of the MOCVD growth conditions and in the identification of source impurities.

- We have studied impurities and dopants in a broad range of Si materials during FY00. In this work we have been able to identify contaminants that were present in localized inclusions as well as those that were uniformly distributed by using a combination of depth profile analysis and secondary ion elemental mapping. The NREL SIMS laboratory has confirmed that Crystal Systems met a milestone concerning dopant and transition metal concentrations in their metallurgical grade silicon. This work has led to improved understanding of material growth parameters and enhanced material quality for NCPV subcontractors.

- We have performed bulk element analysis by SIMS on as-received metallurgical-grade silicon, cast metallurgical-grade silicon, and polycrystalline samples grown by iodine vapor transport deposited from these sources in order to study the possible purification effect

- SIMS was used to study dopant diffusion, hydrogen levels, and contaminant distribution in α-Si:H hot-wire n-i-p solar cells. Experiments were devised to determine the affects of substrate roughness on the apparent dopant diffusion as indicated by SIMS depth profiles. A sample grown on a polished substrate appeared to have ~20% less phosphorous and contaminants diffusing into the i-layer. There is a large amount of boron contamination in n-layer, approximately 1E19, which may be explained by the same chamber being used for n and p-layer deposition. This work has been used to understand diffusion during hot-wire growth.

Planned FY 2001 Activities:

- Investigate the use of the ultra-microtome for the preparation of thin film materials for study by Surface Analysis techniques
- Continue investigations of Cu in CdTe/CdS devices with emphasis on understanding whether Cu is entirely contained within grain boundaries of the material.
- Investigate the surface composition of CIGS films and its relationship to device performance.
- We will continue to assist ongoing collaborative research efforts in other PV program areas.

Major Articles Published in FY 2000:

Reedy, R. C.; Wang, Q.; Moutinho, H.; Iwaniczko, E.; Mahan, A. H. (2000). SIMS Characterization of Amorphous Silicon Solar Cells Grown by Hot-Wire Chemical Vapor Deposition on Stainless Steel. Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, Colorado.. Golden, CO: pp. 217-218; NICH Report No BK-520-28064

Asher, S. E.; Reedy, R. C.; Dhere, R.; Gessert, T. A.; Young, M. R. (2000). Determination of Cu Concentrations in CdTe/CdS Devices by High Mass Resolution Secondary Ion Mass Spectrometry. Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, Colorado. pp. 275-276; NICH Report No. BK-520-28064.

Geisz, J. F.; Friedman, D. J.; Olson, J. M.; Kurtz, S. J.; Reedy, R. C.; Swartzlander, A. B.; Keyes, B. M.; Norman, A. G (2000). BGaInAs Alloys Lattice Matched to GaAs. Applied Physics Letters. Vol. 76(11), 13 March 2000; pp. 1443-1445; NICH Report No. JA-520-27585.

Nelson, B. P.; Xu, Y.; Webb, J. D.; Mason, A.; Reedy, R. C.; Gedvilas, L. M.; Lanford, W. A. Techniques for Measuring the Composition of Hydrogenated Amorphous Silicon-Germanium Alloys. Journal of Non-Crystalline Solids 266-269 (2000) 680-684.

M. A. Contreras, B. Egaas, D. King, A. Swartzlander, T. Dullweber, (2000) Texture Manipulation of CIS Thin-Films, Thin Sol. Films, Vol. 361-362, 2000, p. 167.

Low Cost Glass and Glass-Ceramics Substrates for Thin Film Silicon Solar Cells

Contract #: XAF-8-17607-06	**Contract Period:** 3/25/98–3/24/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Cornell University Materials Science and Engineering Ithaca, NY 14853 **Organization Type**: CU	**Congressional District**: 26
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dieter G. Ast **Phone:** 607-255-4140 **Fax:** 607-255-2365 **E-mail:** dast@ccmr.cornell.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Corning Incorporated, Corning, NY 14831
	DOE Funding Allocation: 1998: $105,000 2000: $ 151,208 1999: $135,000	**Cost Share Funding:** 1998: $127,050 1999: $ 53,420

Project Objective: The objective of this project is to develop a transparent, high temperature substrate to enable the economical and rapid fabrication of thin film silicon solar cells. Transparency is required, since a transparent substrate can serve, 'flipped over', as the cell cover, lowering cost ('superstrate'). The substrate also should tolerate temperatures > 900 ^{o}C during cell fabrication since the rate at which thin film silicon can be deposited increases exponentially with temperature. The resulting high throughput lowers cell fabrication cost. Finally, deposition at high temperatures increases the cell conversion efficiency since the thin silicon film formed contains fewer crystalline defects. To date, the most heat resistant glass substrates can tolerate only about 600 ^{o}C. This temperature is too low to achieve either rapid deposition or a low density of crystalline defects.

The goals of the project are i) to develop a new, transparent substrate that uses low cost ingredients, possesses a strain point in excess of 950 ºC, matches the thermal expansion of Si , and has an optical transmissions of greater than 90% and ii), to fabricate experimental solar cells and other test structures on this substrate to demonstrate its suitability to mass produce thin film solar cells.

The substrate chosen is a glass-ceramic. As illustrated by their use as stovetops on electric ranges, glass-ceramics can withstand high temperatures and are chemically extremely durable. However, they are generally non-transparent, and do not match the thermal expansion of silicon. Thus, a new glass ceramic had to be developed. In addition, glass ceramics are low cost materials and their purity is not as high as that of fused quartz wafers, or the silicon wafers used in integrated circuit. Many of the impurities present in a glass ceramic are likely to migrate during high temperature processing from the substrate into the solar cell material, decreasing both the conversion efficiency and contaminating the processing equipment. An important third goal of the project, therefore, was to develop a low cost substrate coating ('diffusion barrier') technology to prevent the out-migration of impurities at high temperatures.

Approach/Background: This project is a joint effort between Corning Incorporated and Cornell University. The development of the substrate material is carried out at Corning without government support. The research encompasses four major technical components which are: i) developing a suitable glass ceramic, ii) developing and evaluating, by analytical techniques such as SIMS, a barrier system that stops the out-diffusion of substrate impurities, iii) testing the barrier layer by fabricating electronic test devices on substrates coated with varies barrier layers, and comparing their performance to devices made on fused quartz and oxidized silicon wafers, iv) understanding the relationship between the barrier layer morphology and the electronic properties of the deposited polysilicon films. This relationship needs to be understood to further improve device performance, see below.

Status/Accomplishments: A suitable glass-ceramic, meeting all above requirements, was developed. The material consists of 10-15 nm-sized spinel crystals dispersed uniformly in a siliceous glass matrix. The chemical composition (in wt%) is 59.3% SiO_2;19.1% Al_2O_3;9.0% ZnO;2.5%MgO;5.0%TiO_2;3.0%ZrO_2;2.1%BaO . The uncorrected transparency is > 95% matching that of glass. The strain point is > 900 ºC. The thermal expansion coefficient of $38 \cdot 10^{-7}$ /ºC matches that of silicon at higher temperatures.

The glass-ceramic wafers made at Corning had a higher surface roughness than conventional oxidized silicon and fused silica substrates. The glass ceramic wafers were therefore further chemically mechanically polished (CMP) at Cornell to reduce their surface roughness to a comparable level. Because of the different hardness of the spinel crystals and the amorphous matrix, the local polishing rate is different. Thus, the glass-ceramic, even when polished, has a higher surface roughness (0.7 nm rms) than the fused silica or the oxidized silicon wafers (0.3 nm rms) which we use as reference substrates.

Contract #: XAF-8-17607-06

Status/Accomplishments (continued):
After experimenting with different barriers, some of which contained up to 6 layers, we developed a two barrier layer system, consisting of 100 nm of SiN_x and 100 nm of SiO_2, both deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD). SIMS analysis of barrier coated substrates annealed at 900 ºC for 8 hours showed that none of the substrate elements penetrated this layer.

Since SIMS can detect impurities only when their concentration exceeds ≥ ~0.0001%, whereas electronic performance can be impacted at much lower concentration, we further evaluated the barrier layer by fabricating test devices. The first series of these test devices were n- and p- channel thin film transistors (TFTs) because an analysis of their performance yields quantitative information on the density of states (DOS) in the bandgap. The DOS is zero in crystalline silicon, and increases when structural defects or chemical impurities are present. TFTs were fabricated on barrier layer coated glass-ceramic substrates, and, as a control, on CMP polished fused silica, barrier layer coated fused silica, and oxidized silicon wafers. The polysilicon used was deposited as a 100 nm thick amorphous silicon film by LPCVD at 550 ºC and then recrystallized by a 900 ºC, 4 hour anneal. This procedure yielded a polycrystalline silicon film with a low structural defect density and a grain sizes about 1 micron. The temperature dependence of the TFT transfer characteristics was analyzed to derive the DOS. No differences were found for different substrates. However, when the films were hydrogenated (a procedure that lowers the density of states originating from structural defects), significant differences emerged. These differences were traced to differences in the surface roughness of substrates used. Polysilicon films deposited on oxidized silicon wafers and on CMP polished fused silica wafers (both of which have a surface roughness < 0.3 nm rms) had the lowest DOS ($\sim 10^{17}$ $cm^{-3}eV^{-1}$). Polysilicon films deposited on barrier layer coated glass-ceramics and barrier coated fused silica substrates (surface roughness 1.1 – 1.2 nm rms) had an order of magnitude higher DOS. TEM analysis showed that polysilicon films deposited on coated substrates had a 'subgrain' defect structure on the scale of 30 nm. The pattern of this subgrain structure matched that seen in AFM pictures of 'bare' barrier layers. The similarity indicates that surface morphology, translated into substructure, rather than chemical differences are responsible for the different DOS measured on different substrates.

Our next test devices were p-i-n diodes deposited on glass ceramic and oxidized silicon substrates. The p-i-n 'triple' poly-Si stack is the basic building block of the high efficiency, poly-silicon, thin film solar cell proposed by Martin Green. Multiple stacking of these layers permits to reach the necessary optical absorption to efficiently convert light.

The p-i-n triple layers were deposited at 620 ºC in a LPCVD tube using silane and then annealed at 900 ºC in nitrogen. The films were processed into vertical p-i-n diodes using photolithography and RIE etching. The thickness of the intrinsic (i-) layer was systematically varied from 0 to 1900 nm. The dark I-V characteristic of all diodes fabricated was measured and analyzed. To characterize the quality of the junction, we picked, arbitrarily, the ratio R of the forward and reverse current at 0.6 V. It was found that R reaches its maximum value when the i-layer is about 1000 nm thick. Diodes fabricated on different substrates (oxidized silicon versus glass-ceramics) behaved identically. This indicates that in vertical p-i-n devices, surface roughness (higher on barrier coated glass ceramics) does not play a role, a conclusion that needs to be confirmed independently. It also suggests, again, that no impurities from the glass ceramics substrate reach the poly-Si film, i.e. it confirms that the barrier layer developed is effective.

Planned FY 2001 Activities:
- Optimize the electrical characteristics of p-i-n diodes
- Collaborate with Prof. Neudeck's group at Purdue University to test p-i-n stack using thicker layers. Professor Neudeck's diclorosilane (DCS), cold-wall, atmospheric pressure, chemical vapor deposition (APCVD) system can deposit much thicker films than the hot-wall silane reactor at Cornell.
- Fabricate prototype p-i-n solar cells and send these cells to NREL for evaluation

Major Reports Published in FY 2000:
Annual progress report, Photovoltaic Program, FY 1999

Major Articles Published in FY 2000:
N.Nemchuk, S.Krasulya, D.Ast, J.Couillard "Barrier layers for high-temperature glass-ceramic substrates"// 197th Meeting of the Electrochemical Society, May 14-18, 2000, Toronto, Canada.

S.Krasulya, N.Nemchuk, D.Ast, J.Couillard "Fabrication of High performance POly-Si Thin Film Transistors" // 197th Meeting of the Electrochemical Society, May 14-18, 2000, Toronto, Canada.

N.Nemchuk, S.Krasulya, J.Couillard, D.Ast, F.Fehlner, L.Pinckney. "Novel Glass-Ceramic Substrates for Thin Film Polycrcrystalline SiliconSolar Cells"//NCPV Program Review Meeting, April 16-19, 2000, Denver, Colorado p.161.

N.Nemchuk, S.Krasulya, D.Ast, J.Couillard, F.Fehlner, L.Pinckney. "Substrate Roughness and Density of States of Poly-Si films Deposited on Glass-Ceramics" 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, August 13-16, Colorado.

S. Krasulya, N. Nemchuk, D. Ast, G. Couillard "Transparent Glass-Ceramic Substrates for Poly-Si Thin Film Electronics" Presented at 198th Meeting of Electrochemical Society, October 22-27, Phoenix, Arizona.

Investigation of Gettering Mechanisms in Crystalline Silicon

Contract #: XAF-7-17607-01	**Contract Period:** 7/21/97–4/20/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Duke University Department of Mechanical Engineering and Materials Science Durham, NC 27708-0300	
	Organization Type: CU	**Congressional District**: 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. Tan **Phone:** 919-660-5323 **Fax:** 919-660-8963 E-mail**:** ttan@acpub.duke.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $145,000 2000: $133,000 1998: $ 30,000 1999: $148,500	**Cost Share Funding:**

Project Objective:
The objective of this work is to model gettering processes in single- and multi-crystalline Si so as to predict gettering performance and design optimum gettering processes. Physically correct mechanisms and numerically accurate simulation results are sought after. It is necessary to perform experiments to verify the models and improve accuracy of the modeling parameters as well as to demonstrate practical application of the insights obtained from modeling.

Approach/Background:
The role of metallic impurities as efficiency limiting factors in solar cells fabricated using crystalline Si substrates is well established. In multi-crystalline Si, a large fraction of the impurities is in the form of precipitates and large numbers of dislocations and grain boundaries also exist. Various processes, including precipitate formation and dissolution, impurity atom diffusion, native point defect diffusion, clustering and dissociation of defects and dislocations etc., can affect the gettering of impurities and the minority carrier diffusion length. For complete understanding and control of the gettering process, it is necessary to have physically sound models of all the involved processes and accurate values of the modeling parameters. It is also necessary to evaluate the electrical performance of solar cells as a result of gettering. The numerical simulation of gettering process as well as solar cell operation as a device is the primary means to obtain the results.

Status/Accomplishments:
In order to evaluate theoretically the efficiency of a solar cell built on a multicrystalline substrate and to predict how it is affected by the impurity gettering process, it is necessary to know how the presence of metallic precipitates in Si affects the minority carrier lifetime. Previously, no quantitative model of the electrical activity of impurity precipitates was available. We have developed a physical and computational model of minority carrier recombination on metallic precipitates. It is based on the Schottky barrier nature of the interface between Si matrix and metallic precipitates and takes into account carrier diffusion, drift, recombination, and penetration into the precipitate according to the thermionic emission mechanism. This model explains the high minority carrier capture cross-section of metallic precipitates observed in experiments and shows a good agreement with experimental data. It allows us to predict the electrical activity of metallic precipitates in Si based on the substrate and precipitate materials parameters.

Modeling of Al gettering of Au in Si - Earlier experiments had consisted of deliberately contaminating single crystal Si by indiffusion of Au followed by Al gettering of the Au in Si. Characterization by Spreading Resistance Profiling (SRP) had shown that the gettering of Au proceeded from both wafer surfaces to progressively greater depths even though the Al layer was present only on one surface. The SRP profiles were converted to Au profiles by accounting for the increase in resistance due to the compensation of the dopant shallow level by the Au deep levels. It is well known that indiffusion of Au in Si is dominated by the kickout (KO) mechanism involving Si self-interstitials. However, we have found that modeling of the Al gettering process using the kickout(KO) mechanism for Au diffusion yield a rate of removal of gold that was too slow. Instead, if the Frank-Turnbull(FT) mechanism involving Si vacancies was invoked for Au diffusion, the rate of removal of gold was found to be satisfactory. A kinetic model is developed to explain the alternate dominance of Si self-interstitials and vacancies respectively under the Au indiffusion and gettering conditions.

Contract #: XAF-7-17607-01

Planned FY 2001 Activities:
We are planning to continue our efforts on modeling of Al treatment processing steps in solar cell fabrication and their effect on the cell efficiency. The following aspects will be considered:

- gettering of impurities other than Fe, e.g. Cu, Ni, Cr,
- optimization of temperature regime for simultaneous gettering of multiple impurities,
- effect of B indiffusion for BSF formation on cell efficiency,
- effect of gettering and BSF on efficiency of thin solar cells,
- effect of variable temperature gettering on formation of BSF.

Major Reports Published in FY 2000:
Tan, T.Y., Gosele, U.M., et al. (2000) “Investigation of Gettering Mechanism in Crystalline Silicon,” Third Annual Report, 31 pp. Available from Duke University, Durham, NC 27708-0300.

Major Articles Published in FY 2000:
S. Joshi, U. Gosele, T. Tan, “Modeling of Au outdiffusion from Si due to Al gettering,” Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 147-148 (2000).

P.S. Plekhanov, T.Y. Tan, “Modeling of electrical activity of metallic precipitates in silicon based on Schottky effect,” Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 149-150 (2000).

P. S. Plekhanov, T. Y. Tan, “Minority carrier recombination properties of metallic precipitates in silicon,” 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, 2000, (NREL, Golden, Colorado, 2000), p. 54-59.

S. Joshi, U. Gosele, T. Tan, “Modeling of Au outdiffusion from Si due to Al gettering,” 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, 2000, (NREL, Golden, Colorado, 2000), p. 204-207.

P. S. Plekhanov, T. Y. Tan, “Schottky effect model of electrical activity of metallic precipitates in silicon,” *Appl. Phys. Lett.*, **76**, 3777-3779 (2000).

S. M. Joshi, U. M. Gösele, and T. Y. Tan "Extended high temperature Al gettering for improvement and homogenization of minority carrier diffusion lengths in multicrystalline Si," *Solar Energy Materials and Solar Cells* (accepted for publication, 11/00).

S. M. Joshi, “Aluminum gettering of crystalline silicon for improvement of minority carrier diffusion length and for studies of fundamental diffusion mechanisms,” Ph.D. dissertation, Duke University, 2000.

Crystalline Silicon Research Center of Excellence

Contract #: AO-6162	Contract Period: 6/11/92–10/31/00

Sponsoring Office Code: EE-11	Performing Organization(s)	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Georgia Institute of Technology Atlanta, GA 30332-0250	
	Organization Type: CU	**Congressional District:** 5
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** A. Rohatgi **Phone**: 404-894-7692 **Fax**: 404-853-9882 **E-mail:** ajeet.rohatgi@ece.gatech.edu	
Technical Monitor: Douglas S. Ruby **Phone**: 505-844-0317 **Fax**: 505-844-6541 **E-mail:** dsruby@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1995: $525,000; 1996: $500,000; 1997: $548,000; 1998: $567,000; 1999: $599,000; 2000: $375,000	**Cost Share Funding:**

Project Objective: Improve the state of the art in crystalline-silicon solar cells through research on high-efficiency, one-sun, single- and multicrystalline silicon solar cells; improve fundamental understanding of efficiency-limiting defects and mechanisms; develop low-cost manufacturable processes; train future professionals in photovoltaic technology; and transfer new technology to industry through collaborative research.

Approach/Background: Conduct collaborative research with students from other universities and industry. Develop high-efficiency float-zone (FZ) and multicrystalline silicon solar cells in order to demonstrate new device concepts. Develop new processes for fabricating solar cells, including Rapid Thermal Processing (RTP). Develop characterization and modeling tools for high efficiency silicon solar cells.

Status/Accomplishments:
- Fabricated record high 18.6% planar multicrystalline CFP/PL Si solar cell
- Fabricated record high 16% EFG sheet Si CFP/PL cell
- Fabricated 4cm^2 record high 16.2% string ribbon CFP/PL cell
- Fabricated 20% efficient FZ and 19.1% efficient CZ “STAR” cell
- Fabricated record high 19.3% rapidly processed RTP/PL FZ Si cells, and 18.5%-19% CZ and MCZ cells
- Fabricated 4cm^2 record high 17.3% dendritic web RTP/PL cell
- Fabricated 4cm^2 record high 17.6% low-cost screen printed planar Si solar cells
- Fabricated screen printed bifacial cells with record high rear illumination efficiency of 11-13%
- Fabricated ~17% 4cm^2 monocrystalline silicon cells by a low-cost manufacturable process using screen printing, beltline diffusion and PECVD SiN
- Fabricated 4cm^2 14.9% efficient belt-line screen printed manufacturable cell on string ribbon silicon
- Pioneered the field of RTP which reduces the cell processing time from 16 hours to 2 hours
- Developed a novel “STAR” technology for simultaneous front and back diffusion and oxidation in a single furnace step
- Developed a novel and very effective RTO/SiN stack for passivating silicon surfaces which reduces the surface recombination velocity to less than 20 cm/s, and can also withstand screen printing firing
- Maintained and monitored 342 kW rooftop grid-connected PV system on the Georgia Tech Aquatic Center roof, which has so far produced more than one billion watt hours of electrical energy
- Graduated ten phD students and trained 10 more
- Awarded 4 U.S. patents

Contract #: AA-1638 and AO-6162

Planned FY 2001 Activities: Contract ended in FY00. New research contract from DOE/Golden began in July 2000 to continue research.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

S. Venkataraman, et al. "A Study of the Effect of Ultraviolet (UV) and Vacuum Ultra Violet (VUV) Photons on the Minority Carrier Lifetime of Single Crystal Silicon Processed by Rapid Thermal and Rapid Photothermal Processing," J. Electronic Materials, Volume 28, No. 12, pp. 1394-1398, December, 1999.

A.Rohatgi, et al. "Rapid Thermal Processing of Next Generation Silicon Solar Cells," Progress in Photovoltaics: Research and Applications, January 2000.

V.Yelundur, et al. "Al-enhanced PECVD SiN_x induced Hydrogen Passivation in String Ribbon Silicon," J. Electronic Materials, February 2000.

A.Ebong, et al. "Optimization of Front Metal Contact Firing Scheme to Achieve High Fill Factors on Screen Printed Silicon Solar Cells," Solar Energy Materials & Solar Cells, February 2000.

J.Jeong, et al. "Hydrogenation of Defects in Edge-Defined Film-Fed Grown Aluminum-Enhanced Plasma Enhanced Chemical Vapor Deposited Silicon Nitride Multicrystalline Silicon," J. Applied Physics, Vol. 87, No. 10, pp. 7551-7557, May 2000.

T.Saitoih, et al. "Suppression of Light-Induced Degradation of Minority-Carrier Lifetimes in Low-Resistivity CZ Silicon Wafers and Solar Cells, Proceedings of the 16th European Photovoltaic Solar Energy Conference and Exhibition, Glasgow, United Kingdom, May 1-5, 2000.

A.Rohatgi, et al. "Rapid Thermal Processing of Next Generation Silicon Solar Cells," Proceedings of the 10th International Workskhop on the Physics of Semiconductor Devices, New Delhi, India, December 14-18, 1999.

A.Ebong, et al. "Rapid Photo-Assisted Forming Gas Anneal (FGA) for High Quality Screen-Printed Contacts for Silicon Solar Cells," Proceedings of the 18th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

M. Begovic, et al. "Four-Year Performance Assessment of the 342 kW PV System at Georgia Tech," Proceedings of the 28th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

A.Rohatgi, et al. "Aluminum Enhanced PECVD SiN_x Hydrogenation in Silicon Ribbons," Proceedings of the 16th European Photovoltaic Solar Energy Conference and Exhibition, Glasgow, United Kingdom, May 1-5, 2000.

V. Yelundur, et al. "PECVD SiN_x Induced Defect Passivation in String Ribbon," Proceedings of the 18th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

High Efficiency Solar Cell Fabrication on Commercial Si Substrates

Contract #: XAF-8-17607-05	**Contract Period:** 2/4/98–2/3/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail:** Jeffrey.Mazer@ee.doe.gov	Georgia Institute of Technology Atlanta, GA 30332	
	Organization Type: CU	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Ajeet Rohatgi **Phone:** 404-894-7692 **Fax:** 404-894-5934 **E-mail** ajeet.rohatgi@ece.gatech.edu	
Technical Monitor: Robert McConnell **Phone:** 303-384-6419 **Fax:** 303-384-6481 **E-mail:** robert_mcconnell@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1998: $105,000 1999: $126,300 2000: $180,367	**Cost Share Funding:**

Project Objective: The project objective is two-fold: (a) minimize electrical activity of performance limiting defects in promising low-cost Si materials through fundamental understanding and optimization of low-cost gettering and passivation techniques, and (b) develop cell process sequences to incorporate the best gettering and passivation techniques to fabricate record high efficiency cells on low-cost materials.

Approach/Background: Silicon material accounts for about 40% of the cost of current Si photovoltaic modules. In an attempt to reduce cost, most cell manufacturers use low-cost defective Si materials. Unfortunately, this comes at the expense of cell efficiency because low-cost materials contain defects and defect clusters involving carbon, oxygen, transition metals, grain boundaries and dislocations which severely degrade bulk lifetime. The goal of this project is to minimize the harmful effects of the above defects by implementing appropriate combination and sequence of gettering and passivation techniques. This will lead to high-efficiency cells on low-cost materials and a significant cost reduction of Si photovoltaic modules.

The approach to realize the above objective is outlined below.

- Characterize and identify lifetime limiting defects and defect clusters in low-cost materials
- Optimize and enhance the synergistic effect of gettering and passivation techniques such as phosphorus and Al gettering and SiN and forming gas induced hydrogenation of defects
- Implement RTP to enhance gettering and passivation of defects and defect clusters
- Integrate gettering and passivation techniques in proper order to achieve record high efficiency cells on low-cost materials

Status/Accomplishments:

- Fabricated record high 19.3% rapidly processed RTP/PL FZ Si cells, and 18.5%-19% CZ and MCZ cells
- Fabricated 4 cm^2 14.3% manufacturable n-type phostop, and 14.2% p-type BLP/PECVD/SP cells on dendritic web silicon
- Fabricated 100 cm^2, 15.1% efficient belt-line/RTP/SP cell on EFG Si
- Developed SP process to achieve 0.76-0.77 FF on mc-Si cells
- Developed and optimized manufacturable gettering and passivation techniques, including Al-enhanced hydrogen passivation, to achieve >25 µs lifetime in most commercial substrates
- Demonstrated that Al enhanced PECVD-SiN induced hydrogenation
- Demonstrated that faster cooling rate after the hydrogenation is critical to retain hydrogen at the defects
- Proposed and validated a three step model for PECVD SiN induced hydrogenation in the presence of Al

Contract #: XAF-8-17607-05

Planned FY 2001 Activities:

- Will form a basis using PCD measurements for the understanding process-induced quality enhancement in low-cost silicon.
- P and Al gettering will be performed individually and in combination to enhance the gettering efficiency on various promising PV materials.
- Will control the H content, refractive index, and induced surface damage of SiN films by selecting appropriate deposition parameters.
- Low-cost manufacturable process sequences will be developed by integrating several techniques in one step to achieve the program goal of 18% efficiency large-area cells.
- RTP will be used to enhance gettering and passivation of defects

Major Articles Published in FY 2000:

A. Rohatgi, A. Ebong, V. Yelundur and A. Ristow, "Rapid Thermal Processing of Next Generation Silicon Solar Cells," Progress in Photovoltaics Research and Applications, vol. 8, pp. 515-527, July, 2000.

A. Ebong, M. Hillali and A. Rohatgi, "Rapid Photo-Assisted Forming Gas Anneal (FGA) for High Quality Screen-Printed Contacts for Silicon Solar Cells," Proceedings of the 28th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

A. Rohatgi, V. Yelundur, J. Jeong, A. Ebong, D. Meier, A.M. Gabor, and M. Rosenblum, "Aluminum Enhanced PECVD SiN_x Hydrogenation in Silicon Ribbons," Proceedings of the 16th European Photovoltaic Solar Energy Conference and Exhibition, Glasgow, United Kingdom, May 1-5, 2000.

A. Rohatgi, V. Yelundur, J. Jeong, A. Ristow, and A. Ebong, "Advances in Low-Cost Multicrystalline Silicon Solar Cell Processing in the Last Decade," 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, August 13-15, 2000.

B Damiani, A. Ristow, A. Ebong, and A. Rohatgi, "Reduction of Light Induced Degradation in Czochralski Silicon Solar Cells," 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, August 13-15, 2000.

V. Yelundur, J. Jeong, A. Rohatgi, M. Rosenblum and R. Wallace, "Understanding and Optimization of Al-Enhanced SiN_x, Induced Defect Passivation in Ribbon Silicon, 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, August 13-15, 2000.

A. Ebong, M. Hilali, A. Rohatgi, D. Meier and D. Ruby, "Belt Furnace Gettering and Passivation of n-Web Silicon for High Efficiency Screen-Printed Front Surface Field Solar Cells," , 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, August 13-15, 2000.

Crystalline Silicon

University Photovoltaic Research, Education and Collaboration

Agreement #: DE-FC36-00GO10600	**Contract Period:** 7/1/00-6/30/05

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Georgia Tech Research Corporation Georgia Institute of Technology Centennial Research Building Atlanta, GA 30332-0420	
	Organization Type: IN	**Congressional District:**
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dr. Ajeet Rohatgi **Phone:** 404-894-7692 **Fax:** 404-894-5934 **E-mail:** ajeet.rohatgi@ece.gatech.edu	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E:mail**: lizana_pierce@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Georgia Tech Research Corporation
	DOE Funding Allocation: 2000: $125,000	**Cost Share Funding:** 2000: $34,370

Project Objective: In support of the DOE five-year plan, Georgia Institute of Technology's 60-month program, entitled "University Photovoltaic Research, Education and Collaboration" has the overall goal of advancing the current state of crysta-lline silicon solar cell technology in order to make it more competitive with the conventional energy sources. Under the program, Georgia Institute of Technology will fabricate large area (~100 cm^2) solar cells on commercial substrates, using commercially compatible high throughout processes, with target efficiencies of 18-19%. The program will emphasize fundamental and applied research appropriate for education and advanced degrees, while performing industry relevant research that would lead to low-cost high-efficiency silicon solar cells. Industry collaboration will play an important role in developing commercial technologies that will be eventually transferred to industry to reduce the cost of silicon photovoltaics.

The specific objectives of the program are to: 1) improve the quality of commercial silicon substrates during cell processing through fundamental understanding and removal of performance limiting defects and mechanisms; 2) develop advanced concepts and cell designs that can produce high efficiency cells on thin commercial substrates; 3) develop industry relevant low-cost high-throughput processes that can result in advanced cell structures with high performance; 4) fabricate statistically significant quality of low-cost high-efficiency silicon solar cells to verify and to demonstrate the benefit of cell design and technology advances; 5) test and analyze finished devices using characterization and simulation tools to explain the improved performance and predict the performance of new and improved cell designs and processes; 6) collaborate with U.S. manufacturers of crystalline silicon solar cells to improve performance and reduce the cost of their products; 7) enrich the educational experience of undergraduate and graduate students through classroom teaching as well as hands-on training; and 8) support university-level education programs in solar cells through the operation of a silicon solar cell fabrication laboratory.

Approach/Background: Georgia Tech Research Corporation was awarded a five-year Cooperative Agreement to for University Photovoltaic Research, Education and Collaboration under Supplemental Announcement 05 to the FY2000 Broad Based Solicitation (DE-PS36-00GO10482) for Submission of Financial Assistance Applications Involving Research, Development and Demonstration for the Office of Energy Efficiency and Renewable Energy. This activity continues the silicon solar cell research Georgia Tech has been involved in since 1985. Georgia Tech was awarded a University Center of Excellence by the DOE in 1992 for the sustained contributions to the science and technology of silicon photovoltaics. Current research activities at Georgia Tech focus on the development of rapid thermal technologies for low-cost high-efficiency silicon cells by a combination of material characterization, device modeling and cell design, technology development, cell fabrication, and testing and analysis of silicon solar cells.

Agreement #: DE-FC36-00GO10600

Status/Accomplishments:
- Developed a process for screen printed self aligned selective emitter
- Initiated experiments on screen printed IBC cells
- Fabricated record high 19.3% rapidly processed RTP/PL FZ Si cells, and 18.5%-19% CZ and MCZ cells
- Fabricated 4 cm^2 14.3% manufacturable n-type phostop, and 14.2% p-type BLP/PECVD/SP cells on dendritic web silicon
- Fabricated 100 cm^2, 15.1% efficient belt-line/RTP/SP cell on EFG Si
- Developed SP process to achieve 0.76-0.77 FF on mc-Si cells

Planned FY 2001 Activities: The activities included under the University Research, Education and Collaboration program include: 1) Task 1: High-Efficiency Cells on Commercial Silicon Substrates; 2) Task 2: Development of High Throughput Cell Technologies; 3) Task 3: Development of Low-Cost and High-Performance Screen Printed Metallization for Silicon Solar Cells; 4) Task 4: Fabrication of High-Efficiency Advanced Cell Structures by Simplified Low-Cost Rapid Technologies; 5) Task 5: Collaborative Research and Development; 6) Task 6: Educational Support Program; and 7) Task 7: Reporting and Documentation.

Under Task 1, High-Efficiency Cells on Commercial Silicon Substrates, Georgia Tech will fabricate 4cm^2 untextured CFP/PL cells on FZ Si with target efficiencies of 19% and fabricate 4cm^2 CFP/PL cells on various multicrystalline materials with target efficiencies in the range of 15-17%. Under Task 2, Development of High Throughput Cell Technologies, Georgia Tech will conduct basic research to preserve bulk lifetime in commercial silicon during RTP and BLP, conduct research to achieve optimum doping profiles and good surface passivation during short RTP and BLP steps, strive to reduce high temperature processing time from more than 6 hours to less than 30 minutes, fabricate 4cm^2 RTP/PL cells on FZ silicon with target efficiency of 19%, and fabricate 4cm^2 RTP/PL and BLP/PL cells on commercial substrates with target efficiencies in the range of 15-16%. Through Task 3, Development of Low-Cost and High-Performance Screen Printed Metallization for Silicon Solar Cells, Georgia Tech will obtain a fill factor of 0.79 on SP FZ silicon cells and obtain a fill factor of 0.76 on SP multicrystalline silicon cells. Under Task 4, Fabrication of High-Efficiency Advanced Cell Structures by Simplified Low-Cost Rapid Technologies, Georgia Tech plans to achieve BSRV values of less than 50 cm/s by stack passivation of undiffused commercial silicon substrates for fabricating high-efficiency bifacial and IBC cells and fabricate high efficiency screen printed bifacial cells with target efficiency of 18% on FZ and 15% on commercial substrates. Task 5, Collaborative Research and Development, will focus on Develop close working relationship with crystalline silicon PV industry in the U.S. by: 1) Characterizing and improving material quality; 2) Developing and transferring process techniques which would reduce cost, increase throughput, and improve cell performance; 3) Designing and fabricating high-efficiency cells in industry materials; 4) Providing guidelines to industry for achieving low-cost high-efficiency cells; and 5) Publishing joint technical papers. Under Task 6, Educational Support Program, Georgia Tech will operate an Education Support Program (ESP) laboratory that will routinely produce 19% and 16% efficient photolithography and screen printed silicon solar cells, respectively, on FZ silicon, document and disseminate equipment list and run sheets to students, sponsors and prospective universities which may need assistance in cell fabrication, teach at least one course per year on Solar Cells, provide hands-on training to students through a special topics course on fabrication and testing of solar cells, and support other University PV programs in the U.S. through collaboration and technical assistance in the areas of measurements, modeling, cell fabrication and analysis.

Major Reports Published in FY 2000: none to-date.

Major Articles Published in FY 2000:

A. Rohatgi, A. Ebong, V. Yelundur and A. Ristow, "Rapid Thermal Processing of Next Generation Silicon Solar Cells," Progress in Photovoltaics Research and Applications, vol. 8, pp. 515-527, July, 2000.

A. Rohatgi, V. Yelundur, J. Jeong, A. Ristow, A. Ebong, "Advances in Low-Cost Multicrystalline Silicon Solar Cell Processing in the Last Decade," Program: 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, 14-16 August 2000, Copper Mountain, CO, BK–520-28844, pp. 12-20 (2000).

B. Damiani, A. Ristow, A. Ebong, A. Rohatgi, "Reduction of Light Induced Degradation in Czochralski Silicon Solar Cells," Program: 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, 14-16 August 2000, Cooper Mountain, CO, BK-520-28844, pp. 194-199 (2000).

A. Ebong, M. Hilali, A. Rohatgi, "Rapid Photo-Assisted Forming Gas Anneal (FGA) for High Quality Screen-Printed Contacts for Silicon Solar Cells," Proceedings of the 28th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

B. Damiani, R. Ludemann, D. Ruby, S. Zaidi, A. Rohatgi, "Development of RIE-Textured Silicon Solar Cells," Proceedings of the 28th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

R. Ludemann, B. Damiani, A. Rohatgi, "Novel Processing of Solar Cells with Porous Silicon Texturing," Proceedings of the 28th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

Hydrogen Passivation of Defects and Impurities in Si Relevant to Crystalline Si Solar Cell Materials

Contract #: ACQ-9-29639-02	**Contract Period:** 2/16/00–4/16/03

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Lehigh University Dept. Physics, 16 Memorial Dr. E Bethlehem, Pennsylvania 18015-3046	
	Organization Type: CU	**Congressional District:**
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** M. Stavola **Phone:** 610-758-3946 **Fax:** 610-758-5730 **E-mail:** mjsa@Lehigh.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax**: 303-384-6481 **E-mail**: robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 2000: $34,990	**Cost Share Funding:**

Project Objective: The objective of the work is to perform experiments that will help to increase our fundamental understanding of the transition-metal-hydrogen complexes, the hydrogen molecule, and hydrogenated native vacancies and interstitials in Si.

Approach/Background: Silicon substrates used for solar cell fabrication have high concentrations of impurities and defects that limit device performance. Even though hydrogen is commonly introduced into solar-grade Si to reduce the deleterious effects of defects, the microscopic mechanisms by which hydrogen is introduced during low temperature processing steps, hydrogen's subsequent interactions with defects, and the mechanisms that might compete with defect passivation are poorly understood. The goal of this project is to provide microscopic information about hydrogen-containing defects and hydrogen introduction methods that will help elucidate the mechanisms that either assist or impede defect passivation in Si. In our experiments, we use vibrational spectroscopy to study the properties of transition-metal-hydrogen complexes and the interactions of H_2 molecules with native vacancies and interstitials in Si. IR absorption spectra are sometimes measured with multiple-internal-reflection methods to provide enhanced sensitivity for the study of thin hydrogenated surface layers. Uniaxial stress is used in conjunction with IR absorption spectroscopy to provide additional information about defect structure.

Status/Accomplishments:
Transition-Metal-Hydrogen Complexes in Si: In pioneering studies of the hydrogen passivation of deep-level defects in semiconductors, it was discovered that exposure of Si samples to a hydrogen-containing plasma can eliminate many of the levels associated with transition-metal impurities. Until recently, little was known about the microscopic properties of the hydrogenated defects or the mechanism of passivation. New results have come from several approaches. In our work at Lehigh University, hydrogen was introduced throughout bulk Si samples by annealing at high temperature (1250ºC) in H_2 gas. In this way, a sufficient number of hydrogenated defects could be produced for study by structure-sensitive, spectroscopic methods like electron paramagnetic resonance (EPR) and vibrational spectroscopy. In these studies, structures were proposed for PtH, PtH_2, AuH, and AuH_2 complexes. A few other groups have used wet-chemical etching at room temperature to introduce hydrogen into thin surface layers of Si samples that also contained a transition-metal impurity. In these studies, a number of new, electrically active transition-metal-hydrogen complexes were discovered and characterized by deep level transient spectroscopy (DLTS). An elegant analysis of the shapes of the concentration depth profiles measured by DLTS has allowed the number of hydrogen atoms in the transition-metal-hydrogen complexes to be determined.

The goal of the experiments completed during this grant period was to determine whether the structure-sensitive spectroscopies and electrical methods do indeed study the same transition-metal-hydrogen complexes. Unfortunately, typical samples used for DLTS experiments contain an insufficient number of defects for techniques like EPR or IR absorption. Conversely, samples prepared for structure-sensitive studies by high temperature annealing in H_2 gas and quenching are treated too roughly for DLTS experiments. In our experiments, performed in collaboration with the group of J. Weber (Max-Planck-Inst., Stuttgart), IR absorption and DLTS were both used to study the same, or similarly prepared, samples. In one set of experiments, samples were prepared from a Si boule that had been doped with Pt during growth by the floating zone method. Hydrogen had been unintentionally introduced throughout the bulk of the crystal, presumably either from H_2 in the growth ambient or water from the growth-chamber walls. These bulk crystals have been ideal for studies by DLTS and IR absorption spectroscopy. The DLTS peaks and IR absorption lines assigned previously to PtH and PtH_2 were both seen in these floating zone Si:Pt samples, permitting the intensities of the IR absorption lines to be calibrated. In a second set of experiments, multiple-internal-reflection samples were prepared so that the thin surface layers of hydrogenated defects that are produced in Si by etching could be studied by vibrational spectroscopy. The vibrational lines of small concentrations of PtH and PtH_2 defects (~10^{15} cm^{-3}) were detected in the thin surface layers (~ 5 µm) of Si:Pt that had been hydrogenated by etching. Our results support the conclusion that the structure-sensitive spectroscopies and DLTS study the same defect complexes.

Hydrogen Molecules in Si: In previous experiments, we studied the behavior of a vibrational line assigned to molecular H_2 at 3618.4 cm^{-1} under uniaxial stress. Our results were consistent with a defect structure with C_1 symmetry. During the present grant period, we have completed a uniaxial stress study of the corresponding vibrational line assigned to D_2 in Si at 2642.6 cm^{-1}. We have found the surprising result that the shift rates for the D_2 line under stress are the same as those of H_2, whereas we should expect shift rates proportional to the vibrational frequencies (i.e. shift rates for D_2 reduced by a factor of $1/\sqrt{2}$ from those of H_2.

These results show that the vibrational line assigned to molecular H_2 in Si is more complicated than previous experimental and theoretical work has proposed. An explanation of the experimental properties of H_2 in Si remains as a challenge.

Planned FY 2001 Activities:

- Vibrational spectroscopy of hydrogenated transition-metal impurities in Si with multiple-internal-reflection geometry samples. Our plan is to search for new defect complexes that might be fully passivated by hydrogen and to investigate the effects that result from different hydrogenation methods.
- Continue studies of H_2 and D_2 in Si with vibrational spectroscopy and uniaxial stress methods. The goal is to understand the configuration and puzzling microscopic properties of molecular H_2 in Si.
- Initiate studies of hydrogenated native defects in Si by vibrational spectroscopy. Hydrogen-containing Si will be irradiated with 2.5 MeV electrons to produce hydrogenated vacancies and interstitial defects for study by IR absorption spectroscopy.

Major Reports Published in FY 2000:

J.Anna Zhou, (2000), "Microscopic Properties of Defects in Semiconductors from Their Vibrational Spectra," Ph.D. Dissertation (advisor, M. Stavola), Department of Physics, Lehigh University, April, 2000.

Marcie Weinstein, (2000), "Identification of Hydrogen-Containing Defects in the III-V Nitrides and in Si from Advanced Applications of Vibrational Spectroscopy," Ph.D. Dissertation (advisor, M. Stavola), Department of Physics, Lehigh University, July, 2000.

Major Articles Published in FY 2000:

M. Stavola, M.G. Weinstein, K. Stavola, J. Weber, J.-U. Sachse, and H. Lemke, "Transition-Metal-Hydrogen Complexes in Si: Do Structure-Sensitive Spectroscopies and DLTS Study the Same Defects?," 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, 14-16 August 2000, Copper Mountain, CO, NREL/BK-520-28844, pp. 159-161 (2000).

J.A. Zhou, E Chen, and M. Stavola, "Hydrogen Molecules in Si, Zhou *et al.* Reply," Phys. Rev. Lett. **84**, 4778 (2000).

J. Anna Zhou, E Chen, and M. Stavola, "Microscopic Properties of H_2 in Si from the Dependence of the 3618.4 cm^{-1} Line on Temperature and Stress," *Physica B* **273-274**, 200 (1999).

Crystalline Silicon

Characterization and Ti Gettering of PV Substrates

Contract #: XAF-8-17607-03	**Contract Period:** 1/29/98–1/28/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: CU	**Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** G. Rozgonyi **Phone:** 919-515-2934 **E-mail:** rozgonyi@ncsu.edu	
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	DOE Funding Allocation: 1998: $80,000 1999: $98,400 2000: $128,267	**Cost Share Funding:** 2000: $18,000

Project Objectives: 1. Lifetime measurement of polycrystalline PV silicon materials using a contactless microwave photoconductance technique in both the time and frequency domains, and 2. Characterization of the gettering and anti-reflective properties of Ti thin films.

Approach/Background: 1. In previous reports it has been demonstrated that material parameters can be evaluated from their lifetime characteristics [1]. However, the described methods have been mainly used for CZ or FZ silicon wafers. In this report the lifetime technique has been implemented for the characterization of PV wafers. Contrary to monocrystalline silicon wafers, PV materials have higher conductivity and shorter lifetimes. Therefore, μ-PCD used for PV characterization requires a higher sensitivity and a faster response time. The new lifetime system at NCSU, called the JANUS 300, has an enhanced sensitivity and can measure the minimum lifetime of 200 ns. In addition, the frequency resolved (FR) PC method developed at NCSU can be applied to solar silicon due to a new sensitive lock-in technique. Formerly the low lock-in amplifier bandwidth was 150kHz, which has been expanded to 1 MHz to provide a new Frequency Resolved Photoconductance System (FR-PC-1M). **2.** The gettering strategy using thin Ti films described in our previous report [1], has been expanded with a new set of samples. These Ti films were deposited in an argon plasma and diluted nitrogen or oxygen in Ar. P-type CZ silicon wafers were intentionally contaminated with iron and then examined by DLTS, AFM, XRD, μ-PCD and optical reflectometer, before and after annealing.

Status/Accomplishments: 1. The capabilities of the new μ-PCD JANUS-300 and FR-PC-1M systems have been demonstrated for polycrystalline PV silicon. Lifetime maps were obtained at different temperatures and laser injection levels. The observed lifetime increases with injection indicate an operative recombination center in the silicon midgap [2]. A lifetime deterioration in the temperature range between 90^0C and 200^0C reveals the complicated nature of the recombination level, where two levels are active, resembling the iron recombination center in p-type monocrystalline silicon. A deep level has also been detected by the new-implemented FR-PC-1M system. The frequency dependent spectra were measured at 25^0C, 180^0C and 240^0C. A broad spectrum measured at room temperature is generated by the multilevel recombination centers. At moderate temperatures, above 200^0C, the unstable trapping/recombination level dissociates and the spectrum fits the Lorentzian profile for a single recombination center with $E_a = 0.43$eV, and $\sigma_p/\sigma_n = 9.7\times10^{-3}$. It should be emphasized here that the procedure, which has been used for above evaluation, assumes monocrystalline properties of the wafer. However, recombination processes on the grain boundaries (GB) modify the microwave reflection signal. The analysis of the ac microwave reflectance signal and the carrier recombination at the GB is carried out with the following assumptions: (i) Minority carrier diffusion controls carrier transport, (ii) Recombination processes at surfaces, GB, or within an individual grain do not depend on the injection level, (iii) Grain boundaries are perpendicular to the surface (columnar grains), (iv) The grain matrix has a regular square shape, (v) Recombination at a GB is high ($v_{GB} >> 1$), and (vi) Free carriers are generated inside the grain.

Fourier approach allows reducing the 3D case to the 1D case with the Lorentzian profile and the full width at half maximum (FWHM) of the form: $FWHM = \frac{\sqrt{3}}{\pi}\frac{1+2(\pi L/a)^2}{\tau}$, where L is the diffusion length, "a" is the grain size, and τ is the electron recombination lifetime. The FWHM takes the lowest value for a large grain size, (a >> L), indicating that the measured PV spectra at 240^0C are dominated by the carrier recombination in the bulk or on the surface, rather than at a grain boundary.

Contract #: XAF-8-17607-03

Status/Accomplishments (continued)

2. The new films (Set #2) were prepared by pulsed magnetron sputtering onto Si (100) substrates at room temperature. The Ti films were deposited in a 2mTorr Ar plasma, containing diluted gasses of 0.2 mTorr each of (1) Ar & CH_4 plasma and (2) Ar & CH_4 & N_2 plasma. The initial vacuum was $5x10^{-6}$ Torr and the Ti target was pre-cleaned in Ar plasma for 3min. The films were deposited for 15 min with a target current of 0.3A and the film thickness about 35 nm. The gettering-annealing process was performed at 700^0C for 150min in nitrogen and oxygen gas flows of 7200sccm and 720sccm. The film surface measurements were carried out using an AFM D-3000. The minimum roughness has been obtained for TiN_xO_y and the maximum for a TiC_x film. The roughness of the TiO_x film deposited at room temperature (RT) and at 150^0C are as low as ~0.19 nm. N_2 gas added to the plasma reduces surface roughness. 2D AFM images of the getter/annealing films show larger grain size after annealing, revealing "worm-like" patterns for TiN_xO_y and TiO_x samples. XRD measurements were made in the Bragg-Bretano arrangement. Of the three films measured (TiN_xO_y, TiO_x and TiC_x), only TiO_2 peaks were recognized for the first two films before annealing, while after annealing most of these peaks were diminished. The XRD lines observed for TiC_x disappeared after annealing, indicating low stability or low adhesiveness. A F20-UV optical reflectometer has been used to obtain wafer reflectance spectra from 224 nm to 845 nm. Because of a low film thickness, ~30 nm, the standard software could not be used for refractive index and extinction coefficient evaluation. A long-wavelength reflectivity of 0.3 has been seen for Si, TiN_xO_y, and TiO_x films. In the case of Ti, TiO-1500C, TiC and TiN_xC_y films, the reflectance increases with wavelength and reaches a value of about 0.6 due to the presence of metal atoms in the films. Metal domination is also seen for TiO_x deposited at 150^0C. After annealing, the TiN_xO_y and TiO_x film spectra remained the same, while the others changed.
In the modeling of the reflectance spectra, the Drude-Lorentz (D-L) oscillator model [3] was implemented. This model matches the whole wavelength range spectra of Ti and TiN_xO_y very well. Both curves yield a damping parameter, γ, and high frequency dielectric function, $\varepsilon_{\infty,}$ which both differs, indicating metallic domination in the first case and silicon domination in the second. The D-L model could not match the non-annealed TiO_x and non-annealed Ti spectra. In this case the dielectric function (DF) was obtained by a combination of Fresnel's single layer equations and the Forouhi Bloomer (FB) equations [4]. An agreement is indicated in the short wavelength part of the spectrum. The long wavelength part of the TiO_x spectrum has been simulated using Fresnel's equations and the D-L model. Deep levels have not been detected in the REF sample, where the effective lifetime was 6.1 µsec. Deep levels were also not present in the Ti and TiO_x, TiN_x films. A peak at E_a = 0.41eV (interstitial Fe_i), has been found for the TiN_xO_y, TiN_xC_y andTiC_x films. The highest lifetime enhancement of ~30% exist for the TiN_xO_y film.

Conclusions: TiN_xO_y is thermally stable with the highest gettering properties. TiN_xC_y, and TiC, and Ti films become less metallic after annealing. A low reflectance, below 0.3, is attributed to surface roughens, and confirmed by the AFM study. The high frequency dielectric function of a TiN_xO_y film of 14.5 is almost equal to the silicon ε_∞, indicating film transparency in the long wavelength range. The fitted E_{FB} energy of 2.15eV for TiO_x film agrees with literature data for crystalline Ti oxide [4].

References:

1) Annual Report 1999: NREL XAF-8-17607-03.
2) D. Shroder,"Recombination Lifetim in Silicon", in *Silicon Recombination Lifetime Characvterization Methods*, ASTM STP 1340, F. Bacher and W.H. Hughes Eds. (1998), p. 5.
3) M. Vergohl, N. Malkomes, T. Staedler, T. Matthee, U. Richter, Thin Solid Films **351**, 42(1999).
4) J. Rodriguez, M. Gomez, J. Ederth, G.A. Niklasson, C.G. Granqvist, Thin Solid Films **365**, 119(2000).

Planned FY 2001 Activities: (i) Undersigning of the point defects interactions, and clustering in pocrystalline PV silicon. Passivation of the damage area using Cu, In and Ga atoms. The atoms interactions with point defects, clustering, precipitation and catalytic role of the carbon atoms in ribbon silicons, (ii) Development of the contactless Frequency Resolved SPV methods, particularly (1) AC analysis of Epi-τ signal, and (2) determination of the robust output of the measurement system.

Major Reports Published in FY 2000:
Annual Report 1999: NREL XAF-8-17607-03

Major Articles Published in FY 2000:
Romanowski, A. Buczkowski, and G. Rozgonyi, "Contactless Characterization of Silicon Wafers Using Frequency Resolved Photo Conductance", accepted in J. Appl. Phys

Romanowski, L. Kordas, and G. Rozgonyi, "Lifetime Characterization of Polycrystalline PV Materials", NCPV Program Review Meeting 2000, Denver, Colorado, p. 135.

Romanowski, J. Kasichainula, J. Muth, and G. Rozgonyi, "Multifunctional Antireflective/Gettering Coating Ti Film", NCPV Program Review Meeting 2000, Denver, Colorado, p. 151.

Romanowski, J. Kasichainula, and G. Rozgonyi, "Characterization of the Gettering And Anti-Reflective Properties of Ti Thin Films", 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Copper Mountain, Colorado, 2000, p. 224.

Research in Hydrogen Passivation of Defects and Impurities in Silicon

Contract #: ACQ-9-29639-04	**Contract Period:** 5/2/00–7/2/03

<table>
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<tr><td>Organization Type: CU</td><td>Congressional District: 5</td></tr>
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<tr><td>DOE Funding Allocation:
2000: $15,115</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The work will consist of hydrogenating Si samples by different methods such as low-energy implantation, electron cyclotron resonance (ECR) plasma and thermal diffusion. The samples will be provided through NREL. The experimental work to be carried out at Penn State involves the study of hydrogen interaction with defects, trapping, migration and formation of complexes. The principal vehicle for the latter study will be ion implantation, and the intent is to understand mechanisms of defect passivation and activation by hydrogen.

Approach/Background: NREL has implemented a study of hydrogen passivation of impurities and defects in silicon solar cells. The work includes theoretical and experimental components that will be performed at different universities. The theoretical studies will consist of calculation of the structure and parameters related to hydrogen diffusion and interactions of hydrogen with transition metal impurities in silicon. Experimental studies will involve measurements of hydrogen and hydrogen-impurity complexes, and diffusion properties of various species of hydrogen in Si. The experimental work at Penn State includes introduction of hydrogen in a variety of PV Si by ECR plasma, low energy ion implantation and thermal diffusion. The specific tasks will be the evaluation of hydrogen interaction with defects engineered by ion implantation; defect passivation, activation and migration in hydrogenated Si under thermal anneal; electrical activity of hydrogen-impurity complexes. Electrical characterization will entail I-V and C-V measurements, spreading resistance, and deep level transient spectroscopy (DLTS).

Status/Accomplishments: The program was initiated at the end of May 2000. The first experimental study focused on the creation of buried cavity layers in by He implantation and thermal anneal, followed by hydrogenation. The ultimate motivation behind this work is evaluation of gettering ability of these nanocavities *and* using hydrogen-soaked cavities as a source of atomic hydrogen for passivation of defects elsewhere in the structure. The cavities were formed in crystalline Si with (80 keV) He ion implantation. We have been able to form He-induced cavities in Si with He doses as low as 5 x 10^{15} cm^{-2} and subsequent anneal at 800 -1000 ^oC. Fig. 1 shows a TEM cross-section of the cavities formed with 2 x 10^{16} cm^{-2} He implantation and 800 ^oC – 30 min. anneal; regular hexagonal shapes with specific orientation are evident. Sets of samples were subsequently hydrogenated in an ECR hydrogen plasma system [700 W, 250 ^oC - 30 min.]. The electrical properties of the cavities - with and without hydrogen - are being evaluated with deep level transient spectroscopy (DLTS).

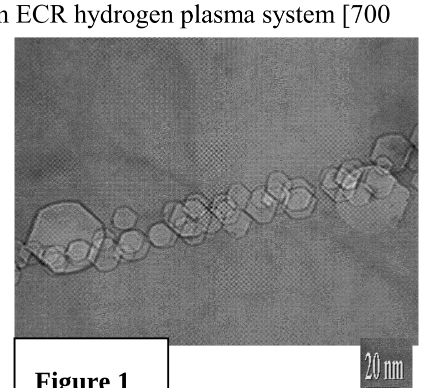

Figure 1

We have also successfully fabricated multiple layers of such He-induced cavity or void regions in Si. Such multi-layered cavity regions are of interest in tailoring the gettering and hydrogen passivation layers in thin film Si for photovoltaics. The generation of these layered cavity regions is found to depend critically on the implant/anneal sequences employed. For instance, a sequence of three implants with decreasing energy (160 keV, 130 keV and 110 keV) followed by a single 800 C - 1 hour anneal results in the formation of a single void layer. But the same sequence interspersed with 800 C - 1 hour anneal after each implant gives rise to three distinct void layers, with the void density decreasing progressively from the top layer. The void layers and their evolution have been evaluated using SEM and TEM. Under isothermal anneal, the cavity shape changes from a distinct hexagonal geometry to a rounded spheroidal shape as the anneal time is increased. PL spectra at 77 K reveal a broad peak at 0.8 eV for all the He-implanted and annealed samples, attributable to vacancy clusters.

I-V and C-V measurements show the expected influence of the disordered cavity regions and deep level transient spectroscopy (DLTS) gives a minority carrier (electron in p-type Si) peak at 0.6 eV. We have also evaluated the dependence on He dose, changes in electrical and optical properties under plasma hydrogenation, and the influence of Si self-implantation intended to alter the He-divacancy precursor reaction that ultimately impacts the He bubble (during implant) and void formations (following anneal). An abstract on this work has been submitted to the Materials Research Society Spring 2001 Meeting.

A number of Si FZ wafers and EFG ribbons have been received from NREL during the last quarter, for hydrogenation by various schemes – low-energy hydrogen/deuterium implantation and ECR hydrogen plasma treatment. These are intended primarily as reference samples to establish the hydrogen profile under normal process conditions. The ECR hydrogenation has been completed, and the low-energy deuterium ion implantation will be performed (in our Varian 350D ion implanter) during the next quarter.

Planned FY 2001 Activities: The He-implant induced multicavity regions will be hydrogenated with ECRplasma and the efficacy of the different layers in absorbing atomic hydrogen will be studied. The emphasis will be on electrical characterization of the defect complexes. Preliminary work on twin use of the hydrogenated cavity layers for impurity gettering and hydrogen passivation will be initiated.

Additional samples sent by NREL for various hydrogen treatments will be processed as required.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

S. Rangan, M. Horn and S. Ashok, "Void Evolution in Silicon by Multiple Helium Implants," Appl. Phys. Lett. (submitted).

Crystalline Silicon Device Research

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–6/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic System Components Department **Organization Type:** FF	**Congressional District:** 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Douglas Ruby **Phone:** 505-844-0317 **Fax:** 505-844-6541 **Email:** dsruby@sandia.gov	
Technical Monitor: Joe R. Tillerson **Phone:** 505-844-1806 **Fax:** 505-844-6541 **E-mail:** jrtille@sandia.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1999: $1,211,000 2000: $1,012,000	**Cost Share Information:** **Cost Share Funding:**

Project Objective: This task investigated new processes and device structures with the goal of improving commercial PV module performance (cost, efficiency, and reliability). This task was directed to terminate its activities by the end of June 2000, and so only pursued those research activities with high potential near-term impact that were identified collectively with major c-Si manufacturers from a survey of PV-industry research needs. This task also supported a world-class photovoltaic device characterization laboratory. An internally funded R&D program at SNL assisted the development of the plasma texturization process for multicrystalline Si cells.

Approach/Background:
Crystalline-Silicon Research Cooperative (CSRC). The CSRC coordinates national laboratory c-Si research with the needs of the domestic PV industry. The CSRC promotes early dissemination of research results to US Si PV manufacturers, assists with the setup of joint experiments, and incorporates the research needs of industry into the national PV program. Concepts identified as high-priority by the CSRC include: plasma-texturization of mc-Si cells, development of self-doping metallizations, and low-cost polysilicon feedstock purification techniques. This task includes the management activities associated with laboratory/industry team research, including preparation of semiannual reports and hosting an annual meeting. The final meeting of the CSRC was held in August 2000.

Plasma-texturing of multicrystalline (mc-Si), ribbon, and tri-crystalline (tc-Si) Si wafers. The quality of the best mc-Si wafers has increased to the point where cell performance is approaching that of single c-Si cells, with the major difference being due to the inability to texture mc-Si affordably using standard wet-chemical etches. This task examined reactive ion etching (RIE) for texturing entire wafers at once. The physics of texture formation by reactive ion etching, the optics of nanometer-scale surface texture, and the performance of RIE-textured cells, were examined by a multidisciplinary team of experts, with funding partially provided by an internal Sandia R&D program.

Back-contact cell development: The Emitter-Wrap Through, or EWT cell has been the focus of back contact cell development in past fiscal years. In FY99 the device demonstrated the potential for high efficiency with the fabrication of an 18.2%-efficient large-area back-contact EWT cell using photolithography. The focus in FY00 was the implementation of the device structure with an industrially applicable, screen-printed metallizations, which included demonstration of a 15%-efficient cell. This work will continue at a low-level in FY00 using low-cost Si materials such as multicrystalline silicon. The benefit of the EWT cell is expected to show up most clearly in these lower quality materials because the EWT's double-sided carrier collection will exceed the single-sided collection used in standard Si cell designs.

Self-doping metallizations: New metal compositions will be studied which have the potential to form self-aligned selective-emitters and back-surface fields using low-cost deposition and simple firing conditions. In the past fiscal year, a self-doping metal compound producing a p-type silicon layer was successfully demonstrated. In FY00, this work was extended to develop an n-type compound, as well as characterize the doping level and metal incorporation of the grown silicon layers. A new concept for depositing metallizations, known as cold-spray, was investigated.

Contract #: DE-AC04-94AL85000

Status/Accomplishments: Most of the current worldwide PV module production is cast multicrystalline (mc-Si), ribbon, or web Si. The main reason for lower performance of these modules compared to single crystal Si modules is lack of affordable cell texturing. One of the tasks of the Crystalline Silicon Project was to develop a plasma technique to texture mc-Si solar cells. This could have a profound effect on boosting cell and module efficiency at reasonable cost. Using the Reactive Ion Etching (RIE) process, the Sandia team was able to achieve the control milestone for fabricating plasma-textured cells which demonstrate increased current generation compared to planar cells, a 10% improvement. In fact, RIE-textured cells were made whose **current and efficiency both exceed** those of our best wet-textured **high-efficiency cells**. This new plasma process could boost performance to capture the full advantage of these lower cost mc-Si materials. A patent has been applied for by Sandia and a non-disclosure agreement to transfer this technology to industry has been signed. Continuing research to transfer this technology is ongoing, supported by an internal Sandia R&D program, and joint experiments with Georgia Tech and the PV industry.

Held final meeting of Crystalline Silicon Research Cooperative, a consortium of research professionals from most of the US silicon PV industry, both national labs, and the Univ. Center of Excellence in Si PV. Encouraged continued joint projects, now requesting funds-in from industry. Wrote and distributed final semi-annual report.
Other accomplishments: Publication of Review of Back-Contact Silicon Solar Cells for Low-Cost Application at 16th Eur. PV Solar Energy Conf., Glasgow, UK, May 2000. Record efficiency for large-area back-contact cell using low-cost metallizations (15.3%). This accomplishment met the DOE 5-year Plan milestone to assess viability of back-contact silicon solar cells and proved viability of a high-efficiency device design for low-cost Si material. Another accomplishment was to provide cell measurement and analysis to PV industry to speed development of passivating fire-through process. Expansion of this cell processing line will now incorporate this performance-enhancing process.

Planned FY 2001 Activities: Continue research on plasma-texturing of multi-crystalline Si cells, supported by an internal Sandia LDRD program. Continue measurement, performance analysis, and processing research for c-Si PV industry on funds-in basis. Continue to act as Technical contract monitor for Ga. Tech. Univ. Center of Excellence c-Si research program. Continue working with NREL and DOE to guide PVMaT program on Implementation Committee. Technical Monitor for 6 ongoing contracts. Review new proposals for next PVMaT procurement and PV Beyond the Horizon initiative. Support shutdown of PDFL laboratory and beneficial transfer of useful equipment to other participants in DOE c-Si PV program.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:
D. S. Ruby, T. F. Ciszek and B. L. Sopori, “Research Needs of c-Si Technology Required to Meet Roadmap Milestones,” NCPV Project Review Meeting, Denver, April 2000.

D. S. Ruby, S. H. Zaidi, S. Narayanan, “Plasma-Texturization for Multicrystalline Silicon Solar Cells,” 28th IEEE Photovoltaic Specialists Conference, Anchorage, September 2000.

B.M. Damiani, R. Lüdemann, D.S. Ruby, S.H. Zaidi, A. Rohatgi, “Development of RIE-Textured Silicon Solar Cells,” 28th IEEE Photovoltaic Specialists Conference, Anchorage, September 2000.

Saleem H. Zaidi, James M. Gee, and Douglas S. Ruby, “Diffraction Grating Structures in Solar Cells,” 28th IEEE Photovoltaic Specialists Conference, Anchorage, September 2000.

C. Edwin Witt, Richard L. Mitchell, and Martha Symko-Davies; Richard King, Douglas S. Ruby, “Ten Years of Manufacturing R&D In PVMaT - Technical Accomplishments, Return On Investment, And Where Do We Go Next,” 28th IEEE Photovoltaic Specialists Conference, Anchorage, September 2000.

D.D. Smith et al., “Review of Back-Contact Silicon Solar Cells for Low-Cost Application”, 16th Eur. PV Solar Energy Conf., Glasgow, UK, May 2000.

Crystalline Silicon

Research in Hydrogen Passivation of Defects and Impurities in Silicon

Contract #: ACQ-9-29639-01	**Contract Period:** 2/10/00 – 4/10/03

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<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>DOE Funding Allocation:
1999: $39,944
2000: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of the research is to perform state-of-the-art static and dynamic calculations to study, at a fundamental level, selected defect and impurity complexes in Si, their interactions with each other and with hydrogen. The goal to establish how defects and impurities interact, which complexes are the most likely to form, what their geometrical and electron' structures and binding energies are, whether or not they can be passivated by hydrogen, whether or not they are gettering centers, and other relevant features.

Approach/Background: Approach/Background: Several photovoltaic manufacturers now commercially use passivation of impurities and defects by hydrogen to improve the performance of their solar cells. There is, however, a severe lack of basic understanding of such issues the interaction of hydrogen with transition metals (which appear to be the most detrimental to solar cell performance), passivation decorated dislocations, vacancy complexes, "clean" dislocations, and role of trapping in solar cell substrates. These issues are important for a solar cell process-engineer to design a process sequence for the fabrication of high efficiency cells.

The theoretical tools which we use to provide insights into the fundamental behavior of hydrogen in silicon include (1) density-functional (DF) based ab-initio tight-binding molecular-dynamics (MD) in periodic supercells (64 to 216 Si atoms), and (2) ab-it Hartree-Fock (HF) calculations in saturated clusters (38 to 100 Si atoms). Today, most of the calculations are done with the MDT packages, but HF can provide additional chemical information such as single-orbital properties or population analyses. The stable configurations and binding and formation energies can be obtained at both levels of theory, which ensures that the results are independent of the way the host crystal is represented or the Schrodinger equation solved. But MD simulations are ideally suit the systematic study of complicated potential-energy surfaces and provide valuable insights into the dynamics, such as real-tulle defect reactions or diffusion.

Status/Accomplishments: Four projects have been completed or are near completion for this budget year.
1. Identification of the hexavacancy: In the course of studying the formation of vacancy aggregates, we predicted that a the mod stable aggregate is the ring-hexavacancy (V6) a complex which reconstructs so well that it should be electrically inactive except 3 shallow and unoccupied energy level near the conduction band. This defect should be thermally very stable but nearly impossible. detect by conventional techniques. However, the calculation of binding energies of impurities such as H, O, Cu, or C to V6 imp that it is a powerful gettering center and therefore an important defect. We have now shown that two photoluminescence (PL), are related to pairs of H trapped inside V6 and that V6 itself is the defect responsible for the B_{80}^{4} PL center. This identification is an important step forward.

2. Precipitation of self-interstitials: In the course of studying the structures and properties of I aggregates (I_n), we discovered that both I_2 and (one of the) I_3 complexes are extremely mobile. These two complexes are centered at one bond-centered site and each diffusion steps occurs following a single exchange process. Exchange is facilitated by the fact that 2 or 3 I's join forces to displace one host atom. Each time a host atom is displaced, one of the self-interstitials takes its place and the entire complex moves.

Contract #: ACQ-9-29639-01

Status/Accomplishments (continued):
3. Hydrogen trapping at a self-interstitial: A lot of theoretical and experimental work has been done on vacancy-H complexes, but much less is know about the interactions between H and the self-interstitial (1). We performed systematic calculations of H trapping at one 1. The key results are as follows. The (neutral) I is stable in the split-<110> configuration, but the center of the split is shifted by 0.76A in the < 100> direction. The defect has several levels in the gap, a prediction consistent with, minority-carrier enhanced diffusion. At least four H's can bind to I or to the strain field associated with it. H does not fully passivate I. Upon H trapping, some energy levels shift but the gap is never empty of localized states. We found a dozen configurations, the most stable is one of the two $\{I,H_2\}$ structures which has been identified by FTIR. The interstitial SiH4 and SiH3 molecules are much less stable than the dissociated species, and should not form in crystalline Si. The binding energies of H to I are low, at most half of those of H-vacancy complexes. This implies that any H trapped at I, I aggregates, or strained region of the crystal is released by moderate thermal treatments. The most stable of the complexes, $\{1,H_2\}$, anneals out at 225 C (experimental).

4. Dynamics of interstitial H_2: Interstitial H_2 molecules have been detected by Raman and FTIR. Although the lines are very small, up to 70% of the total H in the crystal can be in molecular form. The molecules easily dissociate when V's or I's are injected into the bulk. Many experimental data have yet to be explained. For example, no ortho/para splitting is observed, the symmetry is C_l, and the intensity of the single HD line is almost one order of magnitude lower than expected. Our MD simulations show that the center of mass moves very rapidly within the tetrahedral cage. The molecule bounces around, implying a strong coupling to phonons. The absence of ortho/para splitting implies that a magnetic moment lies near H_2, and the rapid motion of its center of mass provides the gradient needed to flip the nuclear spin and promote the ortho-to-para conversion. We speculate that the culprit is interstitial H.

Planned FY 2001 Activities: Three projects are under way and a fourth one more will begin soon.
First is software development. We need to be able to calculate quantitative local vibrational modes at arbitrary temperatures without fitting a potential to some polynomial. This involves the Fourier transform of the v-v autocorrelation function. We also need a technique to calculate activation energies for defects or impurities which won't diffuse by themselves during high-T MD runs lasting a few thousand time steps. The idea is to add a constant force at zero K to push the defect over the barrier while maintaining all the others degrees of freedom. **Second**, we will pursue ongoing work on the precipitation of self-interstitial using the I3 complex as a building block. **Third,** begin studies at the MD level of a `simple' transition metal impurity, namely copper. It is a good test case since we have done quite a bit of work on copper-defect interactions using static HF techniques. Since copper has a very low activation energy for diffusion, it seems to be an ideal test case for MD simulations. The long-term plan is to discover the dynamics of copper-defect and copper-impurity interactions, including Cu-O or Cu-O-vacancy combinations and their interactions with H. **Fourth,** work is under way with a group in Europe to do systematic calculations of H-related vibrational modes for the identification and prediction of infrared or Raman lines.

Major Reports Published in FY 2000:
S.K. Estreicher, "Structure and Dynamics of Defects in Silicon", *Phys. Stat. Sol. (b)* 217, 513-532 (2000).

S.K. Estreicher, (2000), "Hydrogen, Passivation, and Related Issues", NRELBK 520-28844, Golden, CO, pp 84-91.

Major Articles Published in FY 2000:
S.K. Estreicher, "Rich Chemistry of Copper in Silicon", *Phys. Rev. B 60,* 5375-5382 (1999).

S.K. Estreicher and J.L. Hastings, "Copper-Related Complexes in Silicon", *Mater. Sci. Engr. B* 58, 155-158 (1999).

J.L. Hastings, M. Gharaibeh, S.K. Estreicher, and P.A. Fedders, *"Hydrogen Interactions with Intrinsic Defects in Silicon",* Physica B **273-274**, 216-219 (1999).

S.K. Estreicher, and P.A. Fedders, *"Molecular-Dynamics Studies of Self-Interstitial Aggregates in Silicon",* Physica 34 (1999).

S.K. Estreicher, "C*opper-Related Defects in Silicon",* Physica B **273-274,** 424-428 (1999).

B. Hourahine, R. Jones, A.N. Safonov, S. Oberg, P.R. Briddon, and S.K. Estreicher, *"Identification of the Hexavacancy in Silicon with the* B^4_{80} *Optical Center", Phys.* Rev. B **61**, 12594-12597 (2000).

J.R. Byberg, B. Bech, Nielsen, M. Fanciulli, and S.K. Estreicher, *"Dimer of Substitutional Carbon in Silicon Studied by EPR and ab-initio* Methods", Rev. B **61**, 12939-12945 (2000).

Crystalline Silicon

Impurity Precipitation, Dissolution, and Gettering in PV Silicon

Contract #: XAF-8-17607-04	**Contract Period:** 1/30/98–1/29/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $105,000 2000: $170,537
1999: $138,130</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To improve the carrier collection efficiency of large area solar cells, limited by regions of high recombination activity which contain defect clusters. This is to be accomplished by a) gaining an understanding of the nature of diffusion of transition metals to sinks, formation of precipitates and clusters of these metals, particularly in the regions of defect clusters, and their dissolution; b) analysis of recombination activity of precipitates with different morphology to characterize quantitatively the impact of transition metals in different chemical states on recombination of minority carriers; c) using this knowledge to design efficient gettering and passivation processes to improve the regions in silicon containing defect clusters, or to develop recommendations how to modify growth process to avoid formation of gettering-resistant defect clusters or to decrease their recombination activity

Approach/Background: PV-grade multicrystalline silicon contains higher concentrations of transition metals than FZ or CZ-grown crystalline silicon because growth techniques based on rapid solidification of melt, which are used in photovoltaics to reduce costs, cannot fully benefit from the effect of segregation of transition metals in the melt remaining in a crucible. Additionally, PV-grade mc-Si may contain very high concentrations of oxygen and carbon, which may form clusters in the bulk during cooling. This clusters along with the grain boundaries and dislocations formed during solidification of the melt may serve as nucleation or trapping sites for unintentional contaminants - transition metals.

While interstitial transition metals or metal-acceptor pairs are generally very efficient lifetime killers, they usually have only weak detrimental effect on solar cell performance since they can be easily gettered. For example, aluminum gettering can be easily incorporated into the PV technological process. However, it was found that gettering is not entirely effective for the improvement of the minority carrier lifetime in PV materials, especially in regions of high dislocation densities. Additionally, it was found that the recombination activity of structural defects is greatly enhanced by the precipitation and/or decoration of impurities at the defects. This suggests that the low lifetimes of the regions with defect clusters are a result of impurity precipitation/decoration in these regions. Since it is unlikely that simple diffusion kinetics alone can account for inefficiency of gettering of impurities from those regions, we have suggested that there exist barriers to dissolution of precipitates in PV silicon materials, which may be associated either with local lattice strains, or more likely with the formation of a crystalline phase other than metal-silicides. Hence, this project is focused on studies on physics of precipitation and dissolution of transition metals in silicon, and on understanding of the possible nature of gettering-resistant defect clusters. The approach to solve this problem is, on the one hand, to study the diffusion of transition metals to lattice defects, their precipitation, recombination activity of these precipitates, and their dissolution using well-characterized crystalline silicon materials, and, on the other hand, to study the location and the nature of gettering-resistant metal clusters in PV-grade mc-Si by using a combination of advanced X-ray microprobe techniques, available at the Advanced Light Source at Lawrence Berkeley National Laboratory, lifetime characterization techniques, electrical measurement techniques, and scanning and transmission electron microscopy.

Contract #: XAF-8-17607-04

Status/Accomplishments: The following results were obtained in FY2000:

- We suggested and proved experimentally that Fermi level position determines the kinetics of nucleation and growth of copper-precipitates in silicon. This implies that copper is more likely to precipitate in n-type doped region of a solar cell than in p-type doped region.
- Studies of the kinetics of precipitation of copper at oxygen precipitates in CZ and EFG – grown silicon at room temperature indicated that copper precipitates only in samples with high density of oxygen precipitates, and only if its initial concentration exceeds approximately 2×10^{14} cm^{-3}. This indicates that nucleation of copper precipitates may depend on both the electrical charge state of the extended defect and on interstitial copper concentration.
- Synchrotron-radiation-based analysis of the chemical state of iron and copper in mc-Si revealed iron oxide and iron silicate clusters in the areas of low diffusion length in the wafer. Since the formation of iron oxides and iron silicates was reported to occur at temperatures above 900^0C, it is likely that these clusters were formed during growth of mc-Si wafers. These clusters are very difficult to dissolve by heat treatment, and it is not surprising that they cannot be removed by gettering. Cu precipitates were also found to be more difficult to dissolve by heat treatments than it was expected for copper-silicide clusters. However, X-ray analysis revealed predominantly copper silicide. Hence, precipitate stabilization is more likely to be associated with the local strain fields.
- XRF analysis of impurities at the location of a shunt, identified on a processed solar cell by thermography, revealed significant concentration of titanium at the location of a shunt. This strongly indicates that the problem of shunts is associated with metal contaminants inadvertently introduced during processing of a cell.
- Detailed EBIC studies of self-supporting thin polycrystalline mc-Si grown by new modification of EFG technique revealed that the material is extremely inhomogeneous, with the average minority carrier diffusion length between 10 and 20 microns. We suggested that faster cooling rate is responsible for higher density of recombination centers.

Planned FY 2001 Activities: In FY 2001 we plan to perform the following studies:

- Quantitative analysis of recombination activity of precipitates of copper, iron and nickel in silicon, as well as that of their complexes. This includes recombination activity of oxygen precipitates decorated with small concentrations of the metals, recombination activity of oxygen precipitates at higher metal contamination levels, when metals start forming precipitates; precipitates of metals in the bulk, formed either homogeneously or heterogeneously at very small lattice defects which cannot be recognized after the formation of a precipitates; and finally metal precipitates at dislocations.
- Studies of metal contaminants at shunts in processed solar cells by X-ray fluorescence technique to accumulate database of probability of appearance of each particular metal at the location of a shunt and to correlate it with possible sources of contamination on a production line.

Major Reports Published in FY 2000:

E.R.Weber, C.Flink, H.Hieslmair, and A.A.Istratov, *"Impurity precipitation, dissolution, gettering and passivation," in PV silicon NCPV FY 1999 Annual Report*, NREL/BK-210-27479, p. 81.

Major Articles Published in FY 2000:

E.R.Weber, S.A.McHugo, A.A.Istratov, C.Flink, and H.Hieslmair, "Identification of metal-oxygen complexes as lifetime limiting defects in solar cell materials," Program and Proceedings: NCPV Program Review Meeting 2000, April 16-19, Denver, CO, BK-520-28064, p.131-132 (2000).

S.A. McHugo, A.C.Thompson, G.Lamble, C.Flink, and E.R.Weber, "Metal impurity precipitates in silicon: chemical state and stability," Physica B **273-274**, 371-374 (1999).

A.A.Istratov, H.Hieslmair, and E.R.Weber, "Iron contamination in silicon technology," *Applied Physics A* **70**, 489-534 (2000).

A.A.Istratov, C.Flink, H.Hieslmair, S.A.McHugo, and E.R.Weber, "Diffusion, solubility and gettering of copper in silicon," *Materials Science and Engineering B* **72**, no.2-3, p. 99-104 (2000).

C.Flink, S.A.McHugo, W.Seifert, M.Langenkamp, A.A.Istratov, R.Sachdeva, and E.R.Weber, "Application of synchrotron radiation-based X-ray fluorescence microprobe to detect impurities at the location of shunt," in proceedings of the 10-th workshop on crystalline silicon solar cell materials and processes (Copper Mountain, CO, Aug. 14-16, 2000), p.212-5 (2000), BK-520-28844.

H.Hieslmair, A.A.Istratov, R.Sachdeva, and E.R.Weber, "New synchrotron-radiation based technique to study localized defects in silicon: "EBIC" with X-ray excitation," in proceedings of the 10-th workshop on crystalline silicon solar cell materials and processes (Copper Mountain, CO, USA, Aug. 14-16, 2000), p.162-5 (2000), BK-520-28844.

E.R.Weber and A.A.Istratov, "Transition metals in silicon: the continuing story," in proceedings of the 10-th workshop on crystalline silicon solar cell materials and processes (Copper Mountain, CO, USA, Aug. 14-16, 2000), p.8-11 (2000), BK-520-28844.

C.Flink, S.Balasubramanian, A.A.Istratov, R.Sachdeva, and E.R.Weber, "Study of precipitation/outdiffusion of copper in CZ and EFG silicon wafers," in proceedings of the 10-th workshop on crystalline silicon solar cell materials and processes (Copper Mountain, CO, USA, Aug. 14-16, 2000), p.216-9 (2000), BK-520-28844.

Crystalline Silicon

Characterization of Defects in PV Crystalline Silicon

Contract #: ACQ-9-29639-03	**Contract Period:** 3/9/00–5/9/03

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** S. Ostapenko **Phone:** 813-974-2031 **E-mail:** ostapenk@eng.usf.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax**: 303-384-6481 **E-mail**: robert_mcconnell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 2000: $15,000	**Cost Share Information**: **Cost Share Funding:**

Project Objective: The objective of the work is to characterize microcrystalline silicon samples from various vendors by a variety of advanced techniques such as surface photovoltage, room-temperature photoluminescence (PL) and scanning light scattering. Specific goals are to identify the nature of contamination at the “bad” regions and to investigate the modification of the recombination activity along with solar cell processing steps.

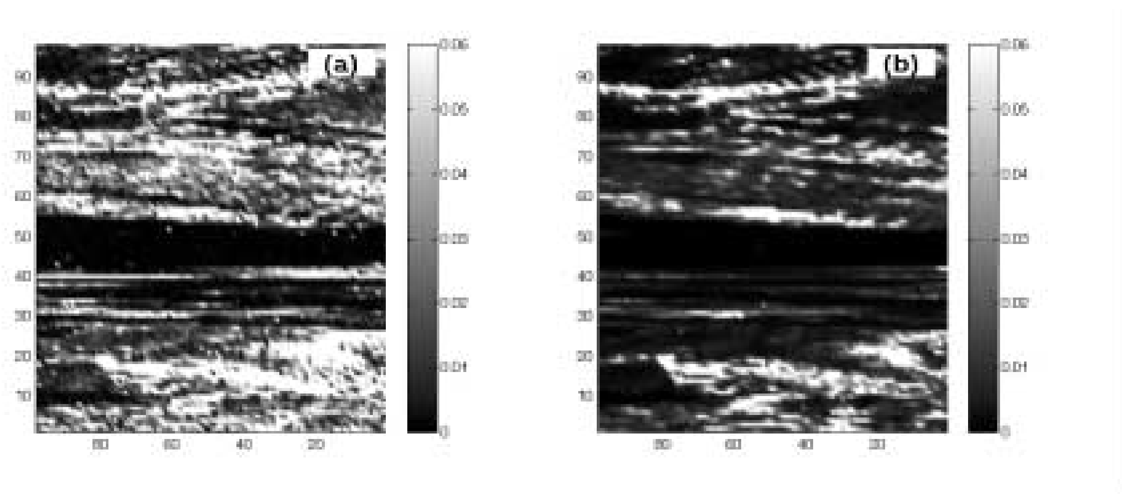
Approach/Background: Multicrystalline silicon (mc-Si), which is produced by a number of competing techniques, can meet both a low-cost production and a high efficiency requirement for solar cells. The highest efficiency solar cells require both a high bulk lifetime in the starting material and effective lifetime upgrading during processing into solar cells. An improvement of minority carrier lifetime, or diffusion length, which is used to track recombination properties of silicon wafers, can be readily accomplished through solar cell processing steps such as P-diffusion, hydrogenation, and Al backside alloying. Since mc-Si wafers are inhomogeneous, lifetime upgrading is not uniform, and areas with initially high and low recombination activity respond differently to a given processing step. For example, as-grown Edge-defined Film-fed Growth (EFG) wafer diffusion lengths of 10 to 100 □m are upgraded to the range of 75 to 300 □m in a solar cell. The requirement to track large inhomogeneities has motivated development of mapping techniques with high spatial resolution and high speeds to aid in electronic quality control in manufacturing. A new approach to lifetime monitoring is offered by photoluminescence (PL) mapping at room temperature. An additional advantage from room-temperature PL mapping arises from its spectroscopic capability, which allows a selective monitoring of different luminescence centers. We report here on PL mapping of recombination centers in low recombination regions of mc-Si wafers at different stages of solar cell processing. These regions limit solar cell performance, and their monitoring, characterization, and reduction is a primary goal in the search for approaches to achieve high cell conversion efficiencies.

Status/Accomplishments: Room-temperature scanning PL was applied to full-size 4”x4” as-grown and processed EFG wafers to investigate the evolution of low lifetime areas after different solar cell processing steps. PL mapping of the band-to-band PL intensity provides a means to identify low lifetime areas. In these areas we consistently observe an additional “defect” PL band with the maximum at about 0.8 eV attributed to electrically active dislocations. A simple approach of selective monitoring the concentration of the defect centers is introduced. It consists of the mapping of intensities in two PL bands: band-to-band (I_{bb}) and defect band (I_{def}). The following two-step process will illustrate the approach, which is similar to the doping control in Si using the exciton luminescence. First, we obtain consecutively two PL maps, one for the band–to-band peak and the second for the “defect” peak, by scanning exactly the same points in the wafer. Next, the concentration of the defect centers and its distribution is deduced from the point-by-point ratio of both intensities. By taking the ratio $R=I_{def} / I_{bb}$ one can generate a distribution of the concentration of the dislocation centers and to track their modification in processed wafers. We shown that consecutive solar cell processing steps gradually increase band-to-band and defect PL intensities due to lifetime upgrading. This result is a consequence of the effective gettering and passivation mechanisms, which accompany solar cell processing. Concurrently, it was observed that the rate of reduction of the defect concentration is much lower than the lifetime and PL intensity upgrading. This is illustrated in Table 1. The rate of increasing of the band-to-band PL intensity spans the range from 27 to 70 times and in a case of the defect band it is between 15 and 30 measured on as-grown and finally processed EFG wafers. At the same time, the R-parameter proportional to the concentration of active dislocations is changing only by a factor of 1.5 to 3.3, which documents that the passivation of the dislocation centers using a standard solar cell processing is strongly terminated.

Table 1. Change of band-to-band PL (I_{bb}), defect PL (I_{def}), and their ratio (R) averaged across five 10cmx10cm EFG wafers after the solar cell processing. The wafer ASE3 corresponds to R-maps in Figure.

	ASE1	ASE2	ASE3	ASE 4	ASE5
I_{bb} (processed)/ I_{bb} (as-grown)	55	42	70	27	43
I_{def} (processed)/ I_{def} (as-grown)	22	30	25	15	26
R (as-grown)/ R (processed)	2.1	1.5	2.0	3.3	2.5

In Figure 1 we show room-temperature mapping of the ratio of two PL intensities, $R=I_{def}/I_{bb}$, measured on an as–grown EFG wafer (a), and the same wafer after solar cell processing (b) corresponding to the wafer #ASE3 in Table 1. The average R-value is reduced in the processed wafer by a factor of two only. The front contact grid was not deposited to eliminate blocking of the excitation and luminescence light. A similarity of the pattern of electrically active dislocations is straightforward. Interesting observation was that a minimum value of the R-parameter was observed on wafers subjected only to the P-diffusion, while following hydrogenation and Al-firing are generally increased the dislocation activity. It may be suggested that contamination of the dislocations is reduced after P-diffusion by a dissolving impurity precipitates into the bulk. However, these dissolved atoms are unstable and re-capture at dislocations again after following processing steps.



Planned FY 2001 Activities: Scanning PL spectroscopy will be extended to as-grown and processed mc-Si wafers prepared by a different competing technologies, including cast and various ribbon techniques. The data will be correlated with distribution of the dislocation and minority carrier lifetime measured on the same wafers. The effect of electronic quality upgrading will be compared and analyzed quantitatively.

Major Articles Published in FY 2000:

I. Tarasov, S. Ostapenko, and J. P. Kalejs, "Defect Monitoring Using Scanning Photoluminescence in mc-Si Solar Cells" *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

I. Tarasov and S. Ostapenko "Defect Monitoring in Crystalline Si Using Scanning PL Spectroscopy" Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. xx-yy (2000).

S. Ostapenko, I. Tarasov, J. P. Kalejs, C. Haessler, and E.-U. Reisner, "Defect Monitoring Using Scanning PL in mc-Si Wafers," *Semicond. Sci. Tecnol*., **15,** 840 (2000).

PV Electronic Materials and Devices

III-V High Efficiency and Concentrators

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Sarah Kurtz **Phone:** 303-384-6496 **Fax:** 303-384-6531 E-**mail**: sarah_kurtz@nrel.gov	
Technical Monitor: John Benner **Phone:** 970-663-6496 **Fax:** 970-663-6430 **E-mail**: john_benner@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1997: $918,200 1999: $962,900 1998: $942,300 2000: $1,444,000	**Cost Share Funding:**

Project Objective: To establish III-Vs as a competitive terrestrial PV technology by developing III-V photovoltaic technologies, advancing related science and engineering, coordinating the allied efforts with our partners, and facilitating commercialization.

Approach/Background: The successful deployment of PV concentrator systems would begin to address the DOE goal of generating a significant portion of our electricity from renewable sources. The GaInP/GaAs/Ge cell has been successful in capturing market share for space applications. The current production capacity of these cells, if used for 1000X terrestrial concentrator systems, would be 1 GW/year. Furthermore, such cells are estimated to contribute only about 25 cents/peak watt to the cost of a concentrator system. Thus, the GaInP/GaAs/Ge cells are well on their way to help make PV energy significant.

This project currently has two main directions: (1) work toward implementation of the successful GaInP/GaAs/Ge cell in terrestrial concentrator systems, and (2) development of the next-generation concentrator cells.

Status/Accomplishments: The GaInP/GaAs/Ge cell continues to be very successful as a space solar cell. However, there are a number of the aspects of this device that are not completely understood, especially when it is expected to perform under high concentration. During growth of the active layers of a solar cell, a very thin version of the solar cell is accidentally grown on the back of the wafer. This is usually removed with a short etch. However, the normal etch which is adequate for one-sun operation of the solar cell is not adequate for concentrator cells. A careful investigation this past year showed that a bucking junction is formed on the back side of the Ge wafer. The quality of this junction is poor, so its photovoltage increases linearly, instead of logarithmically, with intensity. Thus, the loss from the back junction at 500X is 500 times greater than at one sun. The problem was easily fixed by increasing the time used for etching the back of the Ge wafer before metallization.

As the third junction in the stack, the Ge junction provides the smallest voltage. However, it is also the part of the device that has been least optimized. An analysis of the loss mechanisms in the Ge junction showed that the passivation of the emitter frequently determines the dark current. This interface is formed when III-V growth is nucleated on the Ge wafer. The details of the interface are defined by the prenucleation anneal, the anneal conditions, and the subsequent growth conditions (during subsequent growth, interdiffusion may occur). The effect of the passivation was clearly observed by removing the III-V, passivating layer. It was found that a GaInP nucleation layer usually passivated the Ge emitter better than a GaAs nucleation layer. While Vocs of 240 mV can be routinely achieved under one-sun conditions, it may be difficult to increase this voltage.

As the industry has begun to fabricate preliminary designs for concentrator systems using multijunction III-V cells, they have become concerned about the best spectrum to use to design the cells. The reference spectrum that is usually used for characterizing concentrator cells is blue-deficient compared with the direct spectra that are usually measured outdoors. The reference spectrum that is used for one-sun characterization of solar cells is closer to the observed direct spectra in many or most cases. Neither of these spectra is optimal for designing the cells for outdoor use. Indeed, the "optimal" spectrum is a function of location. Efforts are being made to identify direct spectra for use in the Energy Rating Standard that is being developed with the IEEE. This approach will allow cell design using a set of spectra. The standard days include spectra for both high- and low-altitude sites, covering the most important range of possibilities. Thus, the Energy Rating Standard will provide companies with the spectra they need to design the cells. Efficiency measurements can be performed using either of the two reference spectra.

Addition of a junction with a band gap of about 1 eV should give the multijunction cell a significant boost in efficiency. Toward this end numerous new materials have been investigated. Most of the effort in FY00 was spent on the BGaInAs and GaInAsN alloys.

BGaInAs with significant boron content is very difficult to grow. In a narrow range of parameter space, boron will incorporate in the 2-4% range. The addition of 2-4% boron to GaAs increases the band gap just slightly, but reduces the lattice constant. If indium added to return the lattice is

Contract#: DE-AC36-98-G010337

Status/Accomplishments (continued): constant to that of GaAs, the resulting BGaInAs alloy has a band gap of about 1.35 eV. This 1.35 eV material could increase the efficiency of a GaInP/GaAs/Ge cell by lowering the 1.4 eV band gap of the GaAs, if the material is of high quality.

Fabrication of BGaInAs cells resulted in less-than-ideal open-circuit voltages of 0.57–0.66 V and fill factors of 69%–73%. Poor red response of the quantum efficiencies and low short-circuit currents of 10–14 mA/cm^2 under AM1.5D conditions indicated that the minority-carrier diffusion lengths are short (< 0.1 µm). Thus, the material quality will need to be dramatically improved before this material can be useful for replacing the GaAs cell. Successful addition of larger quantities of boron is necessary before the material can be useful as a 1 eV material.

GaInAsN continues to be the best candidate for a 1-eV material, lattice matched to GaAs. However, its quality is still too low to make it a low-risk candidate. Fortunately, many groups around the world are studying GaInAsN, and progress can best be made by collaborating with many of these groups. Worldwide, GaInAsN lasers and solar cells have both improved slowly in quality, showing that both the promise and the difficulties of this material are great. Further work is needed before it can be determined as to whether it will make a useful third junction for a GaInP/GaAs/GaInAsN/Ge solar cell.

Planned FY 2001 Milestones:
- Evaluate and compare Boron incorporation into BGaInAs from three different MOCVD boron precursors
- Evaluate growth parameter space in $ZnGeAs_2$
- Contribute chapter on III-V cells for the Handbook of Photovoltaic Engineering to be published by John Wiley & Sons
- Test concentrator cells under continuous, high-flux illumination

Major Articles Published in FY 2000:

J. Geisz, et al, "BGaInAs solar cells lattice-matched to GaAs," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

D. Friedman, et al, "Ge concentrator cells for III-V multijunction devices," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

J. Geisz, et al, "BGaInAs Alloys Lattice-matched to GaAs for High-Efficiency Solar Cells," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 123-124 (2000).

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PV Electronic Materials and Devices

Amorphous Silicon

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
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<tr><td>Directing Organization:
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1617 Cole Blvd.
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None</td></tr>
<tr><td>DOE Funding Allocation:
1997: $1,072,600 1999: $1,189,400
1998: $1,145,300 2000: $1,417,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The NREL Amorphous Silicon Team pursues breakthrough advances in materials and devices in order to improve the stabilized efficiency of amorphous-silicon-based PV cells and meet DOE PV cost goals by increasing deposition rates. We collaborate closely with the PV industry and academic researchers through participation and direction of the National Amorphous Silicon Teams.

Approach/Background: During FY2000, we focussed on several research areas with the potential to dramatically increase the efficiency or reduce the cost of hydrogenated amorphous silicon (a-Si:H) PV. These were improvement in the quality of ultra-high rate devices with hot-wire chemical vapor deposition (HWCVD) i-layers deposited at 80-130 Å/s, development of processes for completing hot-wire devices in-house, and increasing our understanding of amorphous silicon metastabilty through theory and experiment. To improve the rate of our research progress, we constructed an improved combinatorial research system.

Status/Accomplishments: We improved “high rate” HWCVD (15-20 Å/s) a-Si:H solar cells and moved toward “ultra-high” deposition rates (50 – 150Å/s) that will enable all the active solar cell layers to be deposited in less than 1 minute. The industry presently deposits solar cells by plasma-enhanced (PE) CVD at 1-3Å/s. Higher deposition rates would reduce the industry's up-front and total capital equipment costs if stable efficiencies can be raised to 8%. Even low efficiency (e.g., 5% stable) PV grown at 166Å/s (micron/min) rates might be inexpensive enough to open up new niche markets.

By using multiple hot-wire filaments, decreasing filament-to-substrate spacing, increasing SiH_4 flow rate, and increasing chamber pressure, we made ultra-high deposition rate HWCVD a-Si:H with stable defect densities roughly equal to that of standard 1-3Å/s a-Si:H and far better than any previous efforts at these deposition rates. We deposited HWCVD a-Si:H at above 0.5 µm/min (83 Å/s) with a stabilized defect density of 4×10^{16} cm^{-3}, a level comparable to the best low-rate a-Si:H used in production. The University of Oregon group confirmed, by the sensitive drive-level capacitance spectroscopy technique, a defect density of below 3×10^{16} cm^{-3} on films that were light-soaked to saturation by 2 suns illumination for 120 hours. Oregon also measured defect densities below 4×10^{16} cm^{-3} by photocapacitance. These results were also confirmed by our own measurements. This material will be incorporated in ultra-high deposition rate amorphous silicon druing FY2001.

We fabricated 8.4%-efficient a-Si:H n-i-p solar cells with all doped and undoped Si layers made in-house by HWCVD. The a-Si:H i-layer of this device is deposited at 18Å/sec and the doped layers at 5-11Å/ s. Previously, we collaborated with United Solar Corp. (Uni-Solar) to fabricate a 9.8% hybrid HW/PE CVD device, but that cell had PECVD p and i-p interface layers deposited at low rates by Uni-Solar using their proprietary techniques. Also, on untextured stainless steel, we reached an initial efficiency of 7.2%, eclipsing the previous record of 5.7 % for an all-HWCVD cell. The increased efficiencies result primarily from a new i-p interface layer of 60Å of "edge" a-Si:H material grown at conditions near the transition to microcrystallinity. This led to an increase of the fill factor from 0.60 to 0.69. The top contact is indium-tin oxide that we deposit. Due to improved light-trapping, our earlier n-i-p solar cell recipes yielded over 2% improvement in efficiency when transferred to textured Ag/ZnO-coated. Cell stability against light-soaking is now under test.

The efficiency of amorphous silicon PV is limited primarily by the "Staebler-Wronski" light-induced metastable degradation of a-Si:H. The degradation mechanism is a 25-year old scientific puzzle, but recent work suggests that photocarrier-induced excitation of H from Si-H bonds is a key step in the process. For example, NREL's H-collision model of metastability requires Si-H bond breaking as a first step in metastable defect formation. Also, non- radiative recombination (NRR) of electron-hole pairs is rather efficient in a-Si:H, but the details of the energy transfer mechanism from carriers to the metastable configuration has never been explained.

Our new model of Si-H bond-breaking involves the NRR of two photo-generated electrons and two photo-generated holes. The model is supported by ab intitio pseudopotential calculations of defect electronic and total energy performed with our collaborator S. Zhang of NREL. Trapped-biexciton formation leads to a low-barrier reconfiguration of the H atom, accompanied by crossing of doubly-occupied electron and hole levels in the bandgap. This crossing represents the non-radiative recombination of the carriers, without multi-phonon emission. Once emitted from Si-H to the bond-center configuration (Si-H-Si) the H is mobile and can migrate far from the site of its excitation; the dangling-bond defect that it left behind may become metastable.

Planned FY 2001 Milestones:
- In-house-grown solar cell with a-Si:H i-layer deposited at 0.5 micron/min that maintains efficiency above 4% after 1000 hour light-soak (on untextured stainless steel substrate)
- Use edge materials and other changes to the p/i interface to improve V_{oc} of all-HWCVD devices to above 0.9 volts
- Complete and publish experiments seeking evidence of non-local effects due to light-induced H migration in amorphous silicon metastability
- Deposit HWCVD microcrystalline Si at 30 Å/s (permits i-layer deposition as fast as a-Si:H cells)

Refereed Journal Articles Published in FY 2000:

S. Zhang and H.M. Branz, “Non-radiative electron-hole recombination by a low-barrier pathway in hydrogenated silicon semiconductors. ” *Phys. Rev. Lett.*, **84**, 967 (2000).

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A.H. Mahan, J. Yang, S. Guha and D.L. Williamson, "Structural changes in a-Si:H films deposited 'on the edge of crystallinity' and their effect on film properties," *Phys. Rev. B,* **61**, 1677 (2000).

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PV Electronic Materials and Devices

Cadmium Telluride Research

Contract #: DE-AC36-98-G010337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Timothy Gessert **Phone:** 303-384-6451 **Fax:** 303-384-6430 **E-mail**: tim_gessert@nrel.gov	
Technical Monitor: John Benner **Phone**: 303-384-6496 **Fax**: 303-384-6430 **E-mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $1,072,600 1999: $1,090,400 1998: $1,156,900 2000: $1,201,000	**Cost Share Funding:**

Project Objective: The CdTe Team/Task was formed in FY91 to establish an in-house research program that supports the CdTe PV community. FY2000 activities reflected our goal of pursuing research toward both fundamental understanding and supporting industrial partners.

Approach/Background & Status/Accomplishments: Research tasks in FY2000 were divided into the following study areas: (1) Investigations of CdTe back contacts, (2) Investigations of CdTe/CdS heterojunction physics and chemistry, (3) Development of CVD precursors for CdTe-relavent TCO materials, and (4) Development of advanced processes relevant to device manufacturing.

Contact and Stability studies utilized both the ZnTe- and powder-based (dag) contacts. The ZnTe studies involves stability analysis in collaboration with First Solar LLC, who have maintained an ongoing interest in assessing this reproducible and potentially manufacturable contact. Preliminary stability analysis for storage under laboratory conditions revealed small changes in performance, possibly due to changes in the CdTe/ZnTe band alignment and/or changes in tunneling at the ZnTe/Ti junction. Measurements of contact resistance indicated that changes are likely due to the ZnTe:Cu/Ti tunneling interface. High-resolution SIMS analysis of these same structures showed that, during the ~400°C contact fabrication process, Cu diffuses through the CdTe and into the CdS, and that only devices with this diffusion demonstrate reasonable performance. These observations were reported at the NCPV Review Meeting in April 2000. Studies with the dag-based contact studies have exploited the ease of constituent variation in this contact as a means to test a range of contact dopant species. These studies indicated, although dopants of Sb and Bi can both produce devices at a 12-13% efficiency, the efficiency and stability of these devices is not as good as devices using Cu as the dopant. The presence of HgTe in the back contact may further reduce device stability. Contact fabricated from Cu((1.4)Te demonstrated the best stability under accelerated stress testing (1.5-2 suns, 100°C) with <10% degradation after 60 days. Results from the above contact studies were presented at the 28th IEEE Photovoltaic Specialists Conference.

In Junction Physics and Chemistry, we have continued to investigate the formation and function of the alloy region between the CdS and CdTe layers. As reported at the April NCPV Review Meeting, we made a significant breakthrough in our understanding of alloying at the CdS/CdTe by comparing CdS/CdTe interfaces formed using CdS grown by close-spaced sublimation (CSS) and chemical bath deposition (CBD). In this study we showed that the degree of alloying at the CBD CdS/CdTe planar interface (i.e., parallel to the film surface) was much greater (~12 at.% S) compared to CSS CdS/CdTe interfaces (~2-3 at.% S). Subsequent, depth-profiling data using Auger Electron Spectroscopy (AES) showed that penetration of S was much greater across CSS CdS/CdTe interface. In another study, we have continued efforts to produce discrete CdS/CdTe alloy films (CdSTe) within the composition region when S exceeds ~10% (i.e., where phase separation normally occurs). Initial measurements, using specially prepared CdS/CdTe and SnO_2/CdTe devices, show an electric field of 30 kV/cm in Te-rich CdSTe alloy. We expect that the information from this analysis will help us establish exact nature of p-n junction in CdS/CdTe devices and contribute significantly to the understanding of CdS/CdTe devices.

CdTe-related TCO research was conducted close collaborations with the NREL TCO and Chemical Sciences Teams. These collaborations focused primarily on development and testing of novel CVD precursors to produce Cadmium Stannate (CTO) and Zinc Stannate (ZTO) by chemical vapor deposition (CVD). Sputter deposition of these layers were previously used to produce NREL-confirmed 15.8% efficiency, thereby matching the world-record efficiency for a CdS/CdTe device. Production of these materials by CVD would allow production of the large quantity of the material(s) required to enable incorporation into the CdTe Team's baseline devices. We developed a Cd-containing organometallic precursor that has a higher reaction temperature with oxygen than afforded by commercially available dimethylcadmium (DMCd). This allowed for simultaneous reaction of the Sn precursor (tetramethyltin - TMT) with the Cd species and oxygen to produce Cd- and Sn-containing oxide films. Although these initial studies were encouraging (a CTO phase was formed in a limited region of the reaction zone), complications due to an air leak in the system compromised the new source before it could be fully tested. Nevertheless, studies continued with CdO and CdO:F films, and these led to the production of CdO films with record electron mobilities of <260 cm^2/V-sec.

In the study area related to Advanced Processes for Manufacturing, we focused on documenting the materials and procedures leading to the world-record device efficiency of 15.8% achieved in FY99, and understanding the effect of moisture on the vapor $CdCl_2$ processing procedure. In a collaboration with the NREL Chemical Sciences, we tested moisture uptake of $CdCl_2$ source powders in the production of $CdCl_2$ source plates. Although still ongoing, the preliminary results indicated, although moisture uptake may be a serious problem if uncontrolled, it may also be part of a key to accelerating this processing step in a manufacturing environment. Preliminary results of this work were presented at the NCPV review meeting in April 2000.

The CdTe Team maintained collaborations with several industrial partners including First Solar LLC., and BP Solar. Collaborations with First Solar included efforts to effect transfer of information related to the NREL buffer layer process (i.e., ZTO) to enable layer testing at the First Solar facility. Additionally, training was provided by the NREL CdTe and Clean Room Teams to First Solar staff to enable measurements of specific contact resistance using the transfer-length technique (TLM) at First Solar. Collaborations conducted with BP Solar included sending NREL staff to the BP Solar Fairfield facility for presentation of a seminar related to NREL buffer layer studies, as well as coordinating analysis of numerous BP Solar samples at NREL. This analysis was aimed at identifying current loss mechanisms, testing the use of the NREL vapor $CdCl_2$ process on BP Solar samples, and assisting with electrical and optical characterization of buffer layers produced at BP Solar. The team also continued significant interactions with the National CdTe Team through presentations at the meetings, and assistance with the steering committee.

Planned FY 2001 Activities:
- Coordinate studies and produce publications discussing role of Cu, Zn and Cl species in CdS/CdTe polycrystalline devices.
- Coordinate studies and produce publications discussing role of CdSTe and CdZnTe alloy formation in CdS/CdTe polycrystalline devices.
- Perform feasibility studies using CVD Deposition of either CdO, p-ZnO, or Cd_2SnO_4 to test replacement of CdS, ZnTe:Cu and SnO_2:F respectively..

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

T.A. Gessert, C. Narayansyamy, S. Asher, and D. Rose, "Copper in Contacts to CdTe*," NCPV Review Meeting, April 16-19, Denver, CO.*

D. Albin, D. Levi, S. Asher, A. Balcioglu, and R. Dhere, "Precontact Surface Chemistry Affects on CdS/CdTe Solar Cell Performance and Stability," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

R.G. Dhere, M.M. Al-Jassim, K.M. Jones, H.R. Moutinho, T.A. Gessert, L.L. Kazmerski, "CdS/CdTe Interface Analysis by Transmission Electron Microscopy," *46th International Symposium of the American Vacuum Society, Seattle, WA, Oct. 24-29, 1999.*

X. Li, D. Young, H. Moutinho, Y, Yan, C. Narayanswamy, T.A. Gessert, and T.J. Coutts, "Properties of CdO Thin Films Produced by Chemical Vapor Depositon," *Spring Meeting of the Materials Research Society, San Francisco, CA, April 24-28, 2000.*

X. Li, "Comparison of CdO Films Made by Dimethylcadmium and Dimethylcadmium with Tetrahydrothiophere Ligand," *42nd Electronic Materials Conference, Denver, CO, June 21-23, 2000.*

X. Wu and P. Sheldon, "A Novel Manufacturing Process for Fabricating CdS/CdTe Polycrystalline Thin-Film Solar Cells," *16th European PVSEC, Glasgow, May 1-5, 2000.*

X. Wu, R. Ribelin, R. Dhere, S. Albin, T. Gessert, "High-Efficiency Cd2SnO4/Zn2SoO4/ZnxCd1-xS/CdS/CdTe Polycrystalline Solar Cells," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Patents:

Disclosure filed #00-04 "A Novel Method for Preparation of Modified Cadmium Stannate Films with Plasma Edge of 0.85 µm" Xuanzhi Wu.

Allowed #98-39, "Novel Process for Fabrication Polycrystalline Semiconductor Thin-Film Solar Cells", by Xuanzhi Wu and Peter Sheldon.

Allowed #97-21 "Photovoltaic Devices Comprising Zinc Stannate Buffer Layers and Method for Making" by X. Wu, P. Sheldon, and T. Coutts.

PV Electronic Materials and Devices

Crystalline Silicon Materials Research

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	Congressional District: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Ted Ciszek **Phone:** 303-384-6569 **Fax:** 303-384-6531 **E-mail**: ted_ciszek@nrel.gov	
Technical Monitor: John Benner **Phone:** 970-663-6496 **Fax:** 970-663-6430 **E-mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $593,900 1999: $820,000 1998: $790,200 2000: $808,900	**Cost Share Funding:**

Project Objective: The goal of the Crystalline-Silicon (c-Si) Materials Research R&D Project is to accelerate the development of c-Si PV and to enhance the United States position in c-Si technology. This goal is approached through the following objectives:

- Develop innovative methods for the growth of next-generation c-Si, which have the potential to improve the throughput, lower the energy consumption, and reduce the cost of future c-Si manufacturing.
- Improve the fundamental understanding of impurities and defects in crystalline silicon and their effects on PV performance.
- Provide technical assistance to industry in selected material, crystal growth, characterization, and modeling problems.

Approach/Background:

Thin-layer silicon growth and devices on low-cost substrates: We continued to develop chemical vapor transport (CVT) growth of Si thin layers on low-cost substrates using our novel iodine transport system that has potential for high throughput with industry-friendly, open-system operation. Our specific new objectives included: (1) Comparison of CVT growth of silicon layers on a variety of substrates, (2) An investigation of device structures with this material, to demonstrate material quality for solar cells, and (3) The fabrication of a second-generation reactor for CVT growth which will allow deposition of a conducting layer on insulating substrates prior to active layer deposition and direct deposition of the entire device structure (N+/P/P+) by the iodine vapor transport technique.

Transition metal impurity effects on PV performance: After completing repairs and upgrades to the equipment required for this project, we began crystal growth by ultra-clean float zoning to create a set of controlled samples with selected amounts of transition metals that exhibit weak effects on solar cell performance (e.g. Cu), moderate effects (e.g. Fe), and strong effects (e.g. Ti). This sample set, free of extraneous impurities such as O and C, will be valuable in understanding fundamental differences in Shockley-Read-Hall recombination and lifetime degradation caused by the various transition metals. The metals mentioned are prominent impurities in metallurgical-grade silicon and low-cost silicon feed stock, and thus are important to the growing Si PV industry. Lifetime characterization, modeling, and diagnostic solar cell analysis will be used to quantify degradation effects.

Research with the Si PV industry to address silicon materials research needs: We continued to work with selected PV companies to solve Si materials problems. These activities range from small several-day projects to larger CRADA activities spanning more than a year. In one of the largest projects, a new chemical vapor deposition (CVD) process for solar silicon feed stock is under investigation. An industrial company is building a silane reactor for this research. We will assist in the design and fabrication of the reactor, install it at NREL and provide the infrastructure for it. We will help the company demonstrate the new deposition technique, and then subsequently use the reactor (which will remain at NREL for an extended period) for our internal thin-layer Si research.

Status/Accomplishments:

Thin-layer silicon growth and devices on low-cost substrates: After extensive search and experiments, we have found that mullite ceramic ($3Al_2O_3$: $2SiO_2$) and Corning LGA-139® transparent glass-ceramic are two of the most suitable substrates for the iodine vapor transport growth of silicon polycrystalline layers. Both have an excellent thermal expansion match to silicon. In addition tantalum shows the necessary corrosive resistance in high temperature iodine vapor, and thus could be used to coat LGA-139® or mullite, serving as a back reflector and back contact in a light trapping device structure. With a separate substrate heater decoupled from the source heater, we were able to significantly expand the silicon deposition zone from a few millimeters in the original single heater configuration to more than 10 centimeters, thus allowing much more freedom in substrate placement and orientation. Deposition rate as a function of source temperature was also determined using the independent source/substrate temperature controls, and exhibited a super-linear behavior with increasing temperature difference between source and substrate.

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Status/Accomplishments (continued):
We demonstrated device structures with diffused junctions, with an interdigitated contact scheme, and with an amorphous Si HIT (Heterojunction with Intrinsic Thin-layer) structure on as grown p-type ICVT poly-Si layers deposited on p^+ c-Si substrates. Without any texturing or post-deposition treatment, we've attained a V_{oc} of 480 mV under AM1.5 illumination, which is among the highest reported for the given grain sizes ($<20\ \mu$m). The best fill factor is 72%.

Transition metal impurity effects on PV performance: Repairs and modifications to the float zone crystal growth apparatus used in this project were completed, including new transport drive motors, power supplies and controls, a new cryo-pumped high vacuum system, and a PLC control system for vacuum/gas valve sequencing and drive motor operation. Doping calibration ingots have now been float zoned, each with three concentrations of Cu, Ti, and Fe, for investigation of their effects, with and without Ga defect pairing, on Shockley-Read-Hall recombination in otherwise high-purity silicon. We are in the process of determining the most effective technique for measuring the achieved impurity concentrations, which we expect to be in the following ranges: Ti: $1x10^{11}$ to $2x10^{14}$, Fe: $2x10^{13}$ to $2x10^{15}$, and Cu: $1x10^{15}$ to $6x10^{16}$ atoms cm^{-3}. After dopant calibration is established, actual ingots for the experimental tests will be grown.

Research with the Si PV industry to address silicon materials research needs: A CRADA with GT Equipment Technologies, Inc. (GTi) was formally initiated on June 12. GTi will build a silicon CVD reactor for installation at NREL to be used initially for experiments on a new method of silicon feedstock deposition and later for experiments on thin-layer silicon growth. We have designed the silane/hydrogen gas handling system and safety interlocks, specified and ordered an effluent treatment system, designed and ordered various other infrastructure components, and assisted GTi with many aspects of the CVD reactor design.
We also participated in specific crystal growth problem solving activities with four Si PV companies and in collaborative research on defect and impurity effects with several university research teams. A final peer-reviewed draft was made of the invited book chapter "Silicon Crystal Growth for Photovoltaics," by T. F. Ciszek to appear in a John Wiley & Sons book titled "The Technology of Crystal Growth."

Planned FY 2001 Activities: We will continue to develop iodine chemical vapor transport (ICVT) growth of silicon thin layers on low-cost substrates, obtain thin layers with improved material properties, and demonstrate an effective device structure utilizing novel light trapping techniques on foreign substrates. We will conclude research on effects of the transition metal impurities Cu, Fe, and Ti (with Ga background doping) on Shockley-Read-Hall recombination. CRADA activities on a silane-based c-Si CVD reactor for lower-cost Si feedstock growth will continue. Computational Fluid Dynamics (CFD) simulations of novel configurations for continuous, high-throughput Czochralski ingot growth with melt replenishment will be performed and evaluated. This is of high importance to both the PV and IC industries. In addition, we will provide opportunities for discussion and problem solving of other Si materials issues with companies and universities.

Major Articles Published in FY 2000:
Theodore F. Ciszek and Tihu Wang, "Method for Purifying Silicon Feedstock via Silicon Recrystallization for Impure Silicon in Selected Metals," Provisional Patent Application .

Theodore F. Ciszek, "Device for high throughput growth of thin silicon rods used as substrates in polycrystalline silicon production," Provisional Patent Application.

T.F. Ciszek, "PV Silicon Materials Research," website: http://www.nrel.gov/silicon/.

T.F. Ciszek and T.H. Wang, "Silicon Float-Zone Crystal Growth as a Tool for the Study of Defects and Impurities," in HIGH PURITY SILICON VI, Eds. C.L. Claeys, P. Rai-Choudhury, M. Watanabe, P. Stallhofer, and H.J. Dawson, Electrochemical Society, Pennington, NJ, 2000, p.105 (Invited).

T.F. Ciszek, T.H. Wang, M. Page, M. Landry, J. Casey, R. Bauer, and E. Good, "Crystalline Silicon Materials Research," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 179-180 (2000).

D.S. Ruby, T.F. Ciszek, and B.L. Sopori, "Research Needs of c-Si Technology Required to Meet Roadmap Milestones," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 27-28 (2000).

T.H. Wang and T.F. Ciszek, "Growth of Large-Grain Silicon Layers by Atmospheric Iodine Vapor Transport," J. of the Electrochemical Soc, **147** (5) 1945-1949 (2000)

T.H. Wang, T.F. Ciszek, M. Page, Y. Yan, R. Bauer, Q. Wang, J. Casey, R. Reedy, R. Matson, R. Ahrenkiel, and M. M. Al-Jassim, "Material Properties of Poly-Silicon Layers deposited by Atmospheric Pressure Iodine Vapor Transport," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000, To be published.

T.H. Wang, T.F. Ciszek, and Y. Zhang, "Calibration Factors for Lifetime Measurements on Si Ingots with a Localized PCD Method," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000, To be published.

Y. Yan, M. M. Al-Jassim, T. H. Wang, and T. F. Ciszek, "Structure and Effects of Extended Defects in Polycrystalline Si Thin Films", Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 193-194 (2000).

PV Electronic Materials and Devices

New Ideas and User Functions

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** David Ginley, Timothy Coutts, and Scott Ward **Phone:** 303-384-6573, 6561, 6533, and 6529 **Fax:** 303-384-6430 **E-mail:** David_Ginley@nrel.gov	
Technical Monitor: John Benner **Phone:** 970-663-6496 **Fax:** 970-663-6430 **E-mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1997: $ 149,100 1999: $ 570,400 1998: $ 327,500 2000: $848,000	**Cost Share Funding:**

Project Objectives:
This Technology Area rolls together three activities within NREL's Electronic Materials and Devices Project that provide shared laboratory and intellectual resources among the primary materials task areas. These activities include exploratory research in new ideas for photovoltaic materials, processes, process integration, and device fabrication. The task activities are:

- Atmospheric processing utilizing nanoparticle based inks
- Non-conventional and p-type transparent conducting oxides (TCO)
- Provide state-of-the-art device design and fabrication capabilities for PV semi-conductors

Approach/Background: The overall approach is to look for opportunistic areas where some basic research activities could lead to an eventual substantial practical impact on PV technology and deployment. For example, TCOs are used in a variety of thin-film solar cells and are being introduced into crystalline cell designs as well. Advanced TCOs can both improve the performance of existing cell designs and enable implementation of new designs. Nanoparticle materials offer a range on novel properties that might be exploited to enable new processing methodologies. Finally, the clean room is a facility used throughout the project and in support of other projects, to produce sophisticated structures needed to characterize materials and improve solar cell performance.

Status/Accomplishments: The major accomplishments this period were the development of metallic inks for solar cell and semiconductor contacts. Working with our CRADA partner Argonide we developed inks of Al, Cu, Ag. The work on the generation and production of high quality nanoparticles won an R&D100 award this year. High quality films with ohmic contact were obtained on silicon using these inks. This work led to a CRADA with Evergreen Solar. In the case of Ag and Cu the addition of an organometallic binder significantly enhanced performance including adhesion, contact resistance and sheet resistance. Ag films showed essentially the same conductivity as vacuum evaporated Ag. These inks were employed with similar results in terms of adhesion, conductivity and contact resistance by ink jet printing.

In TCOs, we have established n-type oxides with mobilities of 260 cm^2/volt-sec grown by metalorganic chemical vapor deposition (CVD). This achievement was made possible by design and synthesis of new molecular precursors for Cd. These will become increaingly important because as the area of thin-film PV panels increases, TCO performance must achieve higher conductivities with no added optical absorption. We have also achieved p-type conduction in TCOs. This is important both fundamentally and practically. If low resistivity, high transmittance p-type TCOs can be developed successfully, then they would offer additional device design options, provide low resistance contacts to p-type semiconductors of relevance to the PV program, and the possibility of developing transparent tunnel junction interconnects in tandem thin-film cells.

Our device design emphasized improvements in concentrator cells with the investigation of Monolithically Integrated Modules using GaInP/GaAs tandem structures that have been designed for operation at both 500 suns and 1000 suns. Preliminary fabrication work has begun with encouraging results. The task also supported the identification and solution to a problem with the back contact on the GaInP/GaAs/Ge three junction devices in cooperation with the High Efficiency Team. This extended the usable concentration range for the devices and pushed the peak efficiency higher.

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Planned FY 2001 Activities: Overall we will continue the development of metallic inks composed of MO precursors and nanoparticles for PV contacts. Key goals are the printing of a contact grid on Si with good resolution and ohmic properties for the Ag front contact and the development of improved Al based inks for the back contact. We also expect to explore the next generation of precursors for CIS based thin films. If possible we would like to explore atmospheric processing approaches to TCO and anti-reflection coatings.

Our TCO activity will continue improvements in n-type materials with the preparation of spinel structure TCOs by CVD that yield improved conductivity and optical transmission. The work in developing novel CVD precursors will be suspended, while the existing systems are fully tested. Improvements in p-type conductors will push toward higher carrier concentrations through exploration of concepts for incorporation of dopants in ZnO and other materials.

Clear room device development work will shift radically in focus to emphasize support for the CIS technology. In 2001, the NREL CIS team will implement a number of materials and junction improvements to push toward the 20% efficiency goal. Device optimization and materials characterization will be supported by the clear room research in improved AR coatings and contacts. For example, high performance metalization and mesa definition techniques have been applied to reveal separate layers and expand CI(G)S diagnostic device efforts.

Major Articles Published in FY 2000:

Schulz, Doug; Ribelin, R.; Wu, X.; Jones, K. M.; Matson, R. J.; Curtis, C. J.; Gessert, T.; Ginley, D. S,..*Solar cell contacts using nano-sized dispersions* National Renewable Energy Laboratory, Golden, CO, USA. Mater. Res. Soc. Symp. Proc. (2000), 581(Nanophase and Nanocomposite Materials III), 157-162.

Schulz, Douglas L.; Curtis, Calvin J.; Ginley, David S. *Solution synthesis of mixed-metal chalcogenide nanoparticles and spray deposition of precursor films.* (Midwest Research Institute, USA). U.S. (2000), 13 pp., Cont.-in-part of U.S. 5,711,803. CODEN: USXXAM US 6126740 A 20001003 Patent written in English. Application: US 98-14326 19980127. Priority: US 95-536348 19950929. CAN 133:272243 AN 2000:699038 CAPLUS (Copyright 2000 ACS).

Schulz, Douglas L.; Curtis, Calvin J.; Ginley, David *S. Passivating etchants for metallic particles for forming particle-derived ohmic contacts in silicon solar cells.* (Midwest Research Institute, USA). PCT Int. Appl. (2000), 9 pp.

Coutts, T. J., Young, D. L., Li, X., Mulligan, W. P. , and Wu, X*, Search for improved transparent conducting oxides: A fundamental investigation of CdO,* Cd_2SnO_4*, and* Zn_2SnO_4*.* J. Vac. Sci. Tech A 18(6) Nov. 2000.

PV Electronic Materials and Devices

Polycrystalline Thin Film Solar Cells Based on $Cu(In,Ga)Se_2$

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Kannan Ramanathan **Phone:** 303-384-6454 **Fax:** 303-384-6430 **E-mail**: kannan_ramanathan@nrel.gov	
Technical Monitor: John Benner **Phone**: 303-384-6496 **Fax**: 303-384-6430 **E-mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $1,365,700 1999: $1,356,900 1998: $1,418,500 2000: $1,436,000	**Cost Share Funding:**

Project Objective:
- Advance the development of CIS-based PV through fundamental science and understanding.
- Enhance the CIS R&D laboratory capabilities and technical skills to achieve a facility that supports the development of thin films from the fundamental stage to pre-communications.

Approach/Background:

Activity 1: Fabricating a 20% CIGS Thin Film PV Device

We have taken on a Key milestone of demonstrating a 20% device. It is a formidable task to improve the efficiency by more than 1% from our current record of 18.8%. Effort is directed toward demonstrating reproducible fabrication of high efficiency absorber material, optimization of Mo/glass substrates, and in achieving uniformity in the properties of absorber materials. CdS and ZnO window layers properties are being re-optimized. This effort will identify the opportunities for further improvements as well as limiting factors.

Activity 2: Doping and Alternative Junction Formation

We have demonstrated the role of Cd and Zn dopants in the formation of junctions. This led to several devices without Cd and a patent for NREL. We will extend the extrinsic doping ideas to standard CIGS and high Ga CIGS alloys with a view to make homojunctions. Such devices will collect more current in the blue region. Theoretical calculations will also be made.

Activity 3: Improvement of Surface Microstructure

Recent work has shown the existence of a defective surface region in some of the CIGS films grown by the three stage process. This has caused concern because a line of extended defects could be limiting the performance of the devices. It is also an opportunity to examine the microstructure carefully and improve the growth methods to eliminate the defective region. This is expected to lead to improvements in device performance. A thorough study of the three stage process is also under way with a view to improve the microstructure of the bulk properties.

Activity 4: Simplified Processing of CIGS absorbers

We will continue to investigate simpler methods for converting Electrodeposited, Autoplated, and Sputtered Precursors. With the former two precursors, the emphasis during FY 01 will be to use the newly acquired selenization chamber to make the transition from high vacuum processing to near-atmospheric pressure processing. The study will also attempt to find ways to minimize or eliminate the need for (In+Ga) addition.

Activity 5: Baseline activities

This task is aimed at maintaining current state-of-the-art baseline materials, deposition, and on-going improvements in ZnO, Mo. A new sputter coater from MRC will be installed in first quarter of 2001.

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Activity 6: Partnership with Industry/Technology Transfer
The CIS Team continues to be very productive in assisting the CIS Industries. We have helped Siemens Solar with their studies on transient behavior, and in mapping uniformity of their reactors. Consistent help has been provided to Energy Photovoltaics, Inc., ISET, GSE/ITN. We will continue these relationships on a one-on-one basis and through the Thin Film Partnership's National Teams.

Status/Accomplishments:

- Demonstrated reproducible absorber fabrication with efficiencies exceeding 18% on a routine basis.
- In-house Mo/glass substrates were optimized to yield high efficiency devices.
- CBD CdS process has been optimized.
- A thorough study of preferred orientation has been made, resulting in several publications.

Planned FY 2001 Activities:
Tasks described in previous section are all under way.
CdS and ZnO thickness dependence is being studied for further understanding of device performance.
Extrinsic doping of CIGS materials with Cd, Zn and co-doping experiments will begin in second quarter.
Detailed microstructure studies will also begin in second quarter.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:
"Preferred Orientation in CIS and Its Effect on Thin-film Absorbers and Devices, Proceedings of the 16th European PVSEC, Glasgow, May 2000" (in press).

"The performance of CuIn1-xGaxSe2-based photovoltaic cells prepared from low-cost precursor films" Solar Energy Materials and Solar Cells, Volume: 63, Issue: 4, August 31, 2000, pp. 367-374. Bhattacharya, R.N.; Batchelor, W.; Ramanathan, K.; Contreras, M.A.; Moriarty, T.

"15.4% CuIn1-xGaxSe2-based photovoltaic cells from solution-based precursor films" Thin Solid Films, Volume: 361-362, Issue: 1, February 21, 2000, pp. 396-399. Bhattacharya, R.N.; Hiltner, J.F.; Batchelor, W.; Contreras, M.A.; Noufi, R.N.; Sites, J.R.

"Study of the effect of gallium grading in Cu(In,Ga)Se2" Thin Solid Films, Volume: 361-362, Issue: 1, February 21, 2000, pp. 478-481. Dullweber, T.; Hanna, G.; Shams-Kolahi, W.; Schwartzlander, A.; Contreras, M.A.; Noufi, R.; Schock, H.W.

"Charging and discharging of defect states in CIGS/ZnO junctions" Thin Solid Films, Volume: 361-362, Issue: 1, February 21, 2000, pp. 140-144. Delahoy, A.E.; Ruppert, A.; Contreras, M.

"A Critical Analysis of Photovoltaic Action in CIGS Solar Cells", presented in ICTMC-12, to appear in peer reviewed Jap. J. Appl. Phys. (K. Ramanathan et. Al).

"Transient Effects of CIGSS Based Solar Cells" IEEE PVSC 2000, K. Ramanathan, et. al.

Thin Film PV Partnership

Monolithically Interconnected Silicon-Film Module Technology

Contract#: ZAK-8-17619-1	**Contract Period:** 11/25/97–12/15/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Jeffrey Mazer
Phone: 202-586-2455
Fax: 202-586-8148
E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">AstroPower, Inc.
Solar Park
Newark, DE 19716-2000</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
James A. Rand, Paul E. Sims
Phone: 302-366-0400 Fax: 302-368-6474 E-mail: pesims@astropower.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Ken Zweibel
Phone: 303-384-6441
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E-mail: ken_zweibel@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
AstroPower, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $625,000
1999: $790,000
2000: $814,174</td><td>Cost Share Funding:
1998: $384,000
1999: $526,000
2000: $541,000</td></tr>
</table>

Project Objective: AstroPower is employing Silicon-Film™ technology toward the development of an advanced thin-silicon-based, photovoltaic module product. This module combines the design and process features of advanced thin-silicon solar cells, is light trapped, and integrated in a low-cost monolithic interconnected array. This advanced product includes the following features:

- silicon layer grown on a low-cost ceramic substrate.
- a nominally 50 micron thick silicon layer with minority carrier diffusion lengths exceeding 100 microns.
- light trapping due to back- surface reflection and random texturing.
- back surface passivation.

These performance design features, combined with low-cost manufacturing using relatively low-cost capital equipment, continuous processing and a low-cost substrate, will lead to high performance, low-cost photovoltaic panels.

Approach/Background: Thin film polycrystalline silicon grown on a low cost substrate is one of the most sought after paths to low-cost photovoltaic power. Cost reductions can be realized in module fabrication through the use of large-area, series-interconnected submodules. This design incorporates a method of partitioning the thin-film photovoltaic layer into sub-elements and reconnecting them as a series array. The sub-element device design consists of a thin (35-50 μm) polycrystalline silicon layer grown on a low-cost substrate. The thin silicon device structure allows the use of imperfect materials and increased doping levels, and lowers cost by minimizing the use of relatively expensive feedstock material. Diffusion lengths equivalent to twice the device thickness are required to assure high carrier collection through the bulk of the base layer.

The solar cell device structure incorporates light trapping and back surface passivation to improve energy conversion efficiency. Light trapping is achieved by using diffuse reflection from a randomly textured back surface resulting in enhanced optical absorption of weakly absorbed light and improved current generation. Electrical passivation of the back surface is achieved by minimizing surface recombination velocity at the barrier/silicon interface. Back surface passivation results in improved voltage, fill factor, and current.

Status/Accomplishments:
Accomplishments for FY00 include the following:

Ceramic: A ceramic substrate has been developed that meets the chemical, mechanical, electrical, thermal, and economic criteria required for the growth and device processing of thin films of silicon. The size of this ceramic is presently 15 x 15 cm and the materials cost is on the order of $10 per square meter. There is no evidence of contaminants in silicon films due to the ceramic after high-temperature processing. The ceramic-silicon structure is compatible with standard laboratory wet processes. During FY00, minor modifications to the composition and firing schedule to affect changes in the ceramic surface morphology and CTE were evaluated, tape casting of green ceramics was successfully outsourced, and polycrystalline germanium layers were successfully formed on the ceramic substrate.

Contract#: ZAK-8-17619-1

Status/Accomplishments (continued):
Silicon Deposition: A large CVD system was evaluated during FY00. This system is capable of deposition on 15 x 15 cm substrates. Process variables including temperature, silicon precursor flow rate, residence time, and dopant precursor flow rate were optimized for silicon layers. These results were used to design a new CVD system which is expected to be qualified in the first quarter of FY01. This system will have a higher throughput and will also be designed for 15 x 15 cm substrates. AstroPower is also collaborating with the Institute of Energy Conversion at the University of Delaware to evaluate the potential of using hot-wire CVD to deposit silicon on ceramic substrates.

Silicon Solar Cell Fabrication: Standard laboratory procedures have been employed to evaluate silicon-on-ceramic layer quality. These processes have been found to be adequate and do not require modification due to the presence of the ceramic. During FY00, monolithic interconnection of silicon on ceramic solar cells was successfully accomplished.

Planned FY 2001 Activities:
- Investigate the effects of small additions of CTE modifiers in the basic ceramic formulation
- Investigate the effects of changing the surface finish of ceramics with respect to final silicon layer quality
- Design, construct, and qualify a large-area chemical vapor deposition system capable of depositing silicon on ceramics and silicon-on-ceramic laminates with short cycle times
- Develop and implement additive metallization process for the monolithically integrated module structure
- Investigate the effects of silicon-layer upgrade processes such as gettering, annealing, and hydrogenation and optimize each process using LBIC data
- Deliver final technical report.

Major Reports Published in FY 2000:
P.E. Sims, (2000), "Monolithically Interconnected Silicon-Film™ Module Technology – 1999 Year-End Report," 15 pp. NREL/SR-520-00000, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000:
A.M. Barnett, J.A. Rand, P.E. Sims, J.C. Bisaillon, E.J. DelleDonne, B.W. Feyock, D.H. Ford, A.E. Ingram, M.G. Mauk, J.P. Yaskoff, and R.B. Hall, "High Performance, Thin Silicon-on-Ceramic Solar Cell," *Proc. 16th EC PVSEC*, Glasgow 2000.

P.E. Sims, A.E. Ingram, E.J. DelleDonne, J.P. Yaskoff, D.H. Ford, R.B. Hall, J.A. Rand, and A.M. Barnett, "Progress on Thin Silicon-on-Ceramic Solar Cells", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

P.E. Sims, E.J. DelleDonne, A.E. Ingram, D.H. Ford, J.P. Yaskoff, J.A. Rand, R.B. Hall, and A.M. Barnett, "Monolithically Interconnected Silicon-Film Module Technology," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 97-98 (2000).

Thin Film PV Partnership

Apollo Thin Film Process Development

Contract #: ZAK-7-17619-27	**Contract Period:** 5/1/98–4/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	BP Solar 2300 North Watney Way Fairfield, CA 94533	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D.W. Cunningham **Phone:** 707-438-3818 **Fax:** 707-428-7878	
Technical Monitor: H S. Ullal **Phone**: 303-384-6486 **Fax**: 303-384-6430 **E-mail**: harin_ullal@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: BP Solar Inc.
	DOE Funding Allocation: 1998: $187,500 2000: $475,000 1999: $470,833	**Cost Share Funding:** 1998: $322,052 2000: $572,022 1999: $717,470

Project Objective:
The objectives of this subcontract are to optimize CdTe electroplating and CdS chemical bath deposition operations, conduct process development, determine device performance and reliability, optimize laser process techniques, and enhance waste treatment and abatement systems to achieve zero-discharge.

Approach/Background:
BP Solar is currently introducing the Apollo CdTe technology at its Fairfield, CA production plant. The plant in California is designed and built to produce its thin-film module in high volume. This commitment is the result of BP Solar's extensive R&D program over the past ten years which has been successful in developing and characterizing a stable 8% CdTe 929 cm^2 module at the limited pilot line level. At Fairfield, BP Solar. will scale up the Apollo CdTe process to produce a 5,518 cm^2 and ultimately a 9,449cm^2, monolithic CdS/CdTe module.

Status/Accomplishments: Further CdTe and CdS optimization has lead to improvements in aperture area efficiency. For the 5,518 cm^2 area module, a 10.8% aperture area efficiency was confirmed at NREL during 2000. This module gave a Pmax of 53.9W (STC). Large area electro-deposition improvements increased the 9,400cm^2 module performance to a 10.6% efficiency (aperture area), further reinforcing the scalability of the technology. The efficiency and power (91.5W) were confirmed at NREL OTF.
In addition to process improvements, a sophisticated internal light soaking station was installed for stressing full size modules under various load conditions; Isc, Pmax and Voc. The unit has the capability to expose modules to temperatures up to 100^{o}C and insolation levels in excess of 1 sun. Work will commence on this equipment in Phase 3. Under standard conditions (60C and 0.8 suns), both 5,518 cm^2 and 9,400cm^2 modules have shown good stability for extended periods.
During 2000, a second outdoor test system was installed at the Fairfield plant . This grid tied system utilizes 60, 5,518 cm^2 modules with an average module power of 38W each (DC, STC). A data acquisition system was installed to track performance. In addition to this, work also started on installing building integrated modules in the front facade of the Fairfield plant. It is anticipated that this work will be complete in Phase 3 of the contract.
Further optimization and advances in the Cd waste treatment system has occurred during this period.

Planned FY 2001 Activities:
Produce glass - glass encapsulated CdTe module (9,400cm^2) with aperture area efficiency of at least 8.0%.

Major Reports Published in FY 2000:
NREL Photovoltaic Program FY May 1999 to May 2000 Phase 2 Annual Report, , ZAK-7-17619-27. (June 2000).

Contract #: ZAK-7-17619-27

Major Articles Published in FY 2000:

D W Cunningham, K Davies, L Grammond, J Healy, E Mopas, N O'Connor, M Rubcich, M Sadeghi, D Skinner, T Trumbly, "Advances in Large Area Apollo® Development," NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO.

D W Cunningham, K Davies, L Grammond, J Healy, E Mopas, N O'Connor, M Rubcich, M Sadeghi, D Skinner, T Trumbly. " Large Area Apollo® Thin Film Module Development" 16th European Photovoltaic Solar Energy Conference. 1-5 May 2000.

D W Cunningham, K Davies, L Grammond, J Healy, E Mopas, N O'Connor, M Rubcich, M Sadeghi, D Skinner, T Trumbly, "Large Area Apollo® Module Performance and Reliability" *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Thin Film PV Partnership

Research on Amorphous Silicon Cells and Modules

Contract #: ZAK-8-17619-02	**Contract Period:** 3/9/98–5/8/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Jeffrey Mazer
Phone: 202-586-2455
Fax: 202-586-8148
E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">BP Solar
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Toano, VA 23168</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
R. Arya
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BP Solar</td></tr>
<tr><td>DOE Funding Allocation:
1998: $655,019 2000: $743,000
1999: $715,000</td><td>Cost Share Funding:
1998: $760,700 2000: $760,000
1999: $774,000</td></tr>
</table>

Project Objective: The overall objective of this project is to develop high performance, large-area, amorphous silicon tandem modules on glass substrates. In Phase I, BP Solar had the objective of demonstrating a stabilized conversion efficiency of 10% in 1 ft^2 tandem modules and increasing this stabilized efficiency to 11% in Phase II and 12% in Phase III. Another major objective is to demonstrate a stabilized aperture area efficiency of 9.5% in 8 ft^2 tandem modules in Phase III.

Approach/Background: BP Solar plans to investigate several new amorphous silicon deposition modes with the goal of increasing deposition rate, feedstock utilization and PV module performance. The new approaches include hot-wire, Ar-dilution, He-dilution and modified PECVD reactors. BP Solar will also be developing new diagnostic characterization tools to assist in the development of high quality amorphous silicon alloys and PV modules. The diagnostic tools under development include laser-defined diodes, in-line PV characterization of partially processed plates, real time spectroscopic ellipsometry (Penn State), optical interference spectroscopy (Univ. of VA), polarization differential reflectance (Univ. of VA) and optical emission spectroscopy.

Status/Accomplishments: Recent efforts have focused on increasing the deposition rates for both tandem and single-junction cells and modules while maintaining conversion efficiencies adequate for commercial applications.

- The deposition rate for the intrinsic a-Si layer has been increased from 1 to 3 Å/s and the rate for the a-SiGe layer has been increased from 1 to 1.5 Å/s without any adverse effect on the performance of a-Si/a-SiGe tandem devices (initial efficiencies are about 10.1% for 1 ft^2 modules made on Asahi type U tin oxide coated glass)
- Initial conversion efficiencies of 8.2% have been obtained for 1 ft^2 single-junction modules made at deposition rates of 10 Å/s on Asahi type U tin oxide coated glass.
- We have also demonstrated initial conversion efficiencies of 8.6% for 1 ft^2 single-junction modules made at deposition rates of 1 Å/s on commercial low-e tin oxide coated glass and efficiencies of 6.8% for modules made at 10 Å/s.
- While the initial conversion efficiency of single-junction devices was reduced by about 15 - 20% when the deposition rate was increased from 1 to 10 Å/s, the light-induced degradation remained at about 23%.

We have found that the conversion efficiency of a-Si tandem solar cells can be improved by about 7% by altering the oxygen content of the ZnO back contact. We also developed a low-temperature process for depositing an a-Si p-layer without methane. Devices made with this low-temperature p-layer exhibit similar performance to devices made with conventional a-SiC p-layers.

In addition, we have discovered that the performance of both tandem and single-junction cells can be improved by annealing the cells at successively lower temperatures for successively longer times. Thus, annealing tandem cells for 30 minutes at 170°C, 5 hours at 150°C and then 24 hours at 125°C leads to an improvement in the initial efficiency in the range of 3 – 6% as compared to control cells that were only annealed for 30 minutes at 170°C. This effect can be explained in terms of a re-equilibration of thermally generated defects associated with a redistribution of hydrogen atoms.

Contract #: ZAK-8-17619-02

In an effort to develop a further understanding of the Staebler-Wronski effect in a-Si alloys, we fabricated single-junction cells that exhibited an extraordinarily large light-induced degradation (the efficiency fell by 77% after 600 hours illumination at 1 sun). The degraded cells exhibited an accelerated improvement in performance when annealed under reverse bias conditions in the dark. The average efficiency of cells that were reverse biased at – 6 V for 303 hours at 100°C was ~ 25% higher than that of cells that were maintained at open circuit. When these cells were light soaked for a second time, the cells that had been reverse biased annealed continued to exhibit improved performance over the cells that had been annealed under open-circuit conditions. The beneficial effect of reverse bias annealing on light-soaked cells can been explained by a model based on hole trapping at partially hydrogenated microvoids containing molecular hydrogen.

We have also examined the effect of substrate temperature on the initial and light-degraded performance of standard tandem devices similar to those produced in the BP Solar PV manufacturing facility in Virginia. While the initial efficiency fell by about 10% when the substrate temperature was increased by 30°C, the stabilized efficiency was relatively constant over this range. However, the stabilized efficiency dropped by about 10% when the substrate temperature was decreased by 20°C.

Real time spectroscopic ellipsometry has been used at Penn State to optimize the growth of microcrystalline p-layers on specular zinc oxide coated glass substrates. A femtosecond laser energy diffusion technique has been used at the University of Virginia to characterize both a-Si and a-Ge films grown on tin oxide coated glass. In addition, we have used an array of fiber optic probes to measure the optical emission spectra during the PECVD process as a means of monitoring the uniformity of the film growth conditions.

In other work, we found that a-Si solar cells exhibit relatively little temperature dependence once they are operating in an equilibrated state, and thus the output power at elevated temperatures will be significantly larger than that produced by other types of solar cells with the same output power rating measured under standard conditions (25°C).

Planned FY 2001 Activities: We plan to continue optimizing the stabilized performance of both single-junction and tandem a-Si solar cells made at high deposition rates. We will also investigate methods of depositing a-Si rapidly and uniformly on large-area, electrically floating substrates. Efforts will also be focused on achieving further improvements in the optoelectronic properties of both the front and rear transparent conductive oxide contact layers. We also plan to continue the development of in-situ diagnostic tools for the characterization and control of the a-Si PECVD process. In addition, we will continue to investigate the light-induced degradation of a-Si alloys and will conduct a number of experiments to check the validity of the hydrogenated microvoid model.

Major Reports Published in FY 2000:

G. Ganguly, R. Arya, M. Bennett, D. Carlson, M. Gleaton, M. He, G. Lin, J. Newton, G. Wood (2000), "Research on Amorphous Silicon Cells and Modules", 34 pp. Annual Technical Report 4/1/1999 – 3/31/2000, NREL Subcontract No. ZAK-8-17619-02.

Major Articles Published in FY 2000:

G. H. Lin and D. E. Carlson, "Photovoltaics in the Year 2025", International Journal of Hydrogen Energy **25**, 807-811 (2000).

D. E. Carlson, M. Gleaton and G. Ganguly, "Effects of Oil and Dopant Contaminants on the Performance of Amorphous Silicon Solar Cells", 16th European Photovoltaic Solar Energy Conference, Glasgow, UK, 1 – 5 May 2000, to be published (2000).

D. E. Carlson, G. Lin and G. Ganguly, "Temperature Dependence of Amorphous Silicon Solar Cell PV Parameters", *28th IEEE Photovoltaic Specialists Conference*, Anchorage, AK, 17-22 September 2000.

R. R. Arya, "Advances in a-Si Development and Manufacturing", *28th IEEE Photovoltaic Specialists Conference*, Anchorage, AK, 17-22 September 2000.

R. R. Arya, M. Bennett, G. Lin, F. Willing, J. Newton, G. Ganguly and S. Liu, "Amorphous Silicon Based Tandem Junction Thin-Film Technology: A Manufacturing Perspective", *28th IEEE Photovoltaic Specialists Conference*, Anchorage, AK, 17-22 September 2000.

D. Carlson, G. Ganguly, G. Lin, M. Gleaton, M. He, J. Newton, G. Wood, R. Arya, M. Bennett, F. Willing, "Research on Amorphous Silicon Solar Cell and Modules at BP Solar," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, (2000).

Thin Film PV Partnership

Future CIS Manufacturing Technology Development

Contract #: XAK-8-17619-32	Contract Period: 7/8/98–10/17/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Chemical Engineering Department, University of Florida (UF) P.O. Box 116005 Gainesville, FL 32611-6005	
	Organization Type: CU	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** T.J. Anderson **Phone:** 352-392-0882 **Fax:** 352-392-9513 **E-mail:** tim@nersp.nerdc.ufl.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $105,000 1999: $228,000 2000: $240,200	**Cost Share Funding:**

Project Objective: The objective of this project is to develop improved processing schemes for the fabrication of $CuInSe_2$-based solar cells. Equally important is the advancement of our understanding of the important thermochemical and structural properties of the absorber material, as well as the mechanisms of thin film growth and recrystallization. The objective will be accomplished through innovative material and device preparation methods, modeling of the chemical reaction pathways, comparison of deposition control schemes, and using characterization techniques to correlate film properties and device performance.

Approach/Background: A team of researchers from 3 disciplines is working to demonstrate a process for rapid fabrication of CIS absorber layers which is suitable for the manufacture of high efficiency thin film modules. This process first deposits a thin 'seed' layer of large grain size CIS at low rate by a migration enhanced process, followed by high rate deposition of a mixed phase precursor material using a plasma assisted process. An analysis of the phase equilibria in the Cu-In-Se system has suggested the use of stacked binary compounds of CuSe, Cu_3Se_2 or $CuSe_2$, and InSe, In_6Se_7 or In_4Se_3 will produce a low temperature liquid phase to assist in the formation of large grain size CIS films. This work will verify the approach in CIS, extend it to CIGS, explore the use of Rapid Thermal Processing (RTP) and implement advanced process control strategies. The project will also investigate the use of the alternative buffer layer materials In_x (OH,S) and ZnS.

Status/Accomplishments: Progress has been made on several areas, including (1) the growth CIS precursors films, (2) the modeling of elemental fluxes and of thermal gradients in the PMEE (plasma migration-enhanced epitaxial) reactor, (3) the development of thremodynamic phase relations, (4) the deposition of TCO and Mo films, (5) the RTP of CIS absorber layers, (6) the use of XAFS on the structure of CIS, and (7) the simulation of CIS devices. More specifically, CIS precursor films of varying compositions have been deposited using a bilayer-precursor structure, focusing on single-crystal substrates for the purpose of understanding the growth mechanism. An Electron Cyclotron Resonance plasma cracker was installed to produce a more reactive Se flux. Models for the mass fluxes produced by metal effusion sources and a model for the temperature distribution on the substrates have been developed to provide information needed to supplement the available on-line measurements. It has been found that better-quality CBD $In(OH)_xS_y$ buffer layers are obtained by adding acetic acid to the reaction bath. Preliminary solid-state EMF experiments have been performed to measure the Gibbs energy of formation of $CuGaSe_2$. A new sputtering system for the deposition of TCO and Mo was successfully installed and commissioned using metallic Zn, metallic Mo, and ceramic ZnO:Al sources. A new susceptor that prevents the cracking of the substrates and the loss of elements during RTP was designed and successfully tested. An optimal RTP recipe has been developed for a bilayer structure of the form CuSe/InSe/Mo/glass, and XRD and ICP studies confirm that a CIS phase is produced. Extensive EXAFS studies have demonstrated that the Cu-Se interatomic distance is independent of composition in nominally stable $CuInSe_2$ and $CuIn_5Se_8$ materials. In addition, it has been shown that the Cu-Se bond-length remains constant whereas the In-Se bond-length decreases as a function of the Cu occupation number. Progress has been made in identifying effective methods for modeling CIS/CIGS devices allowing the prediction of I-V and spectral response curves, and it has been determined that the SCAPS-1D simulation package is at least ten times faster than the AMPS-1D package. A software and data-acquisition system has been fully developed and tested to allow the automatic measurement of photo I-V curves, and a similar system for the automatic acquisition of QE measurements is near completion.

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Planned FY 2001 Activities: Milestones include the fabrication of CIS PV devices from stacked binary compound precursor films using RTP, and establishing a viable CBD process for depositing MgSe and $In(OH)_xS_y$. Gibbs energy measurements in the Ga-Se system will continue, and the ternary Cu-Ga-Se phase diagram will be assessed. The parameters for the RTP process and the ZnO deposition process will be optimized. Refinements of the thermal and flux models for the PMEE reactor will be refined and validated using experimental data. The parameters of the CBD process for the deposition of alternative buffer-layers will be optimized. A device model that incorporates the alternative buffer layers will be optimized to predict current-voltage and spectral-response curves.

Major Reports Published in FY 2000:

T. J.Anderson, O. D. Crisalle, S. S. Li, and P. H. Holloway (2000), "First Annual Summary Progress Report", NREL, Golden, CO: National Renewable Energy Laboratory (unpublished).

T. J.Anderson, O. D. Crisalle, S. S. Li, and P. H. Holloway (2000), "Second Annual Summary Progress Report", NREL, Golden, CO: National Renewable Energy Laboratory (unpublished).

Major Articles Published in FY 2000:

S. Kincal and O. D. Crisalle, "Thermal Effusion Source Modeling for Control in Molecular Beam Epitaxy Applications", *Proc. American Control Conference*, Chicago, IL, pp. 4401-4405 (2000).

B.J. Stanbery, C.-H. Chang, S. Kim, S. Kincal, G. Lippold, S.P. Ahrenkiel, L. Li, T.J. Anderson, M.M. Al-Jassim, "Epitaxial Growth of CuAu-Ordered CuInSe2 Structural Polytypes by Migration Enhanced Epitaxy", in Self Organized Processes in Semiconductor Alloys, MRS Symposium Proceedings, Vol. **583**, 195-200, (2000).

C.-H. Chang, S.H. Wei, J.W. Johnson, R.N. Bhattacharya, B.J. Stanbery, T.J. Anderson, R. Duran, "Long and Short Range Ordering of CuInSe2," accepted for publication in *Jpn. J. App. Phys*, to appear in 2000.

C.H. Huang, Sheng S. Li, L. Rieth, A. Halani, M.L. Fisher, Jiyong Song, T.J. Anderson, and P.H. Holloway, "A Comparative Study of Chemical-bath-deposited CdS, (CdZn)S, ZnS, and In(OH)xSy Buffer Layers for CIS-based Solar Cells," *27th IEEE Photovoltaic Specialists Conference*, Anchorage, Alaska (2000).

C.H. Huang, Sheng S. Li, L. Rieth, A. Halani, Jiyong Song, T.J. Anderson, and P.H. Holloway, "A Comparative Study of Chemical-bath-deposited CdS, (Cd,Zn)S, ZnS, and In(OH)xSy Buffer Layers for CIS-based Solar Cells," NCPV Program Review Meeting, Denver, CO, USA, pp. 229-230, (2000).

C.-H. Chang, A.A Morrone, B.J. Stanbery, C. McCreary, M. Huang, C.-H. Huang, S.S. Li, and T.J. Anderson, "Growth and Characterization of CdS Buffer Layers by CBD and MOCVD", *AIP Conference Proceeding* 462, p.114-119, (1999).

C.H. Huang, Sheng S. Li, W.N. Shafarman, C.-H. Chang, J.W. Johnson, L. Rieth, S. Kim, B.J. Stanbery, and T.J. Anderson, "Study of Cd-free Buffer Layers Using $In_x(OH,S)_y$ on CIGS Solar Cells," Technical Digest of *11th International Photovoltaic Science and Engineering Conference*, Hokkaido, Japan, pp. 855-856, (1999).

B.J. Stanbery, C.H Huang, C.-H. Chang, S.S. Li and T.J. Anderson, "Characterization and Processing of CuInSe2 Solar Cells", *Proceedings of 2nd World Conference on Photovoltaic Solar Energy Conversion*, Vol.**1**, p.529-532, (1998).

C.-H. Chang, A.A. Morrone, B.J. Stanbery, C. McCreary, M. Huang, C.-H. Huang, Sheng S. Li, and T.J. Anderson, "Growth and Characterization of CdS Buffer Layers by CBD and MOCVD," AIP Conference Proceedings no. 462, *NCPV Photovoltaics Program Review: Proceedings of the 15th Conference*, Denver, CO, USA, pp. 114-119, (1998).

B.J. Stanbery, C.H. Huang, C.H. Chang, Sheng S. Li, and T.J. Anderson, "Characterization and processing of CuInSe2 solar cells," *Conf. Record of the 2nd World Conference on Photovoltaic Solar Energy Conversion*, Vienna, Austria, pp. 529-532, (1998).

Nanostructure of a-Si:H and Related Alloys by Small-Angle Scattering of Neutrons and X-rays

Contract #: XAK-8-17619-31	**Contract Period:** 5/22/98–9/2/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Colorado School of Mines (CSM) 1500 Illinois St. Golden, CO 80401 **Organization Type**: CU	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D. Williamson and D.W.M. Marr **Phone:** 303-273-3837 **Fax:** 303-273-3919 **E-mail:** dwilliam@mines.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $37,000 2000: $79,089 1999: $83,664	**Cost Share Funding:**

Project Objective: To improve the understanding of which nanostructural features are related to electronic materials properties that determine the performance of a-Si:H based solar cells. The project will determine whether small-angle neutron scattering can be used to determine hydrogen-related nanostructures and any changes that might occur in them during light soaking. The ASAXS technique shall be established as to determine non-uniform Ge incorporation into a-SiGe:H material. Determine the role of medium range order (MRO) in light stability and other device behavior.

Approach/Background: Use both small-angle neutron (SANS) and x-ray scattering (SAXS) and conventional wide-angle x-ray diffraction techniques to investigate the nanostructures of amorphous and microcrystalline silicon-related solar cell materials and correlate them with optoelectronic and device properties. Extensive prior work with SAXS has established its value in correlating certain nanostructural features with degraded solar cell performance.

Status/Accomplishments: The heterogeneity of a-Si:H and a-Si:D films has been probed on the nano-scale by SANS. Films were deposited by two techniques, plasma-enhanced chemical-vapor deposition (PECVD) and hot-wire chemical-vapor deposition (HWCVD) using conditions that yield high-quality films and devices. Four samples were examined in a light-soaked state (AM1, 300 h) and then re-examined after annealing (190^{o}C, 1 h) *in-situ* to look for any change in SANS associated with the Staebler-Wronski effect. No changes were observed in the SANS intensity to a precision that could have readily detected the 25% change reported in 1985 (Chenevas-Paule *et al*). Significant differences are observed in hydrogenated and deuterated films, as well as in the PECVD versus the HWCVD materials. These initial experiments establish that statistically significant SANS data can be obtained from device-quality films so further experiments are planned.

The advantage of using very high frequencies for preparation of a-Si:H materials at high rates (above 5 Å/s) for intrinsic layers (i-layer) of solar cells has been well documented. In an effort to identify film properties which may be related to this superior device performance, a study has been made of the structural, optical and electrical properties of films prepared by ECD at various deposition rates between 1 and 15 Å/s using rf frequencies of 13.56 and 70 MHz. The films were characterized using a number of techniques including SAXS, infrared absorption spectroscopy, and scanning electron microscopy. For the films made using the 70 MHz frequency, the amount of nanovoids with sizes of < 100Å increases systematically as the deposition rate increases beyond 5 Å/s. Accompanying the increase in void fraction in the films are increases in the hydrogen content and the amount of 2070 cm^{-1} mode in the infrared absorption spectra. In addition to an increase in the amount of nanovoids in the films as the deposition rate exceeds 5 Å/s, the films made using the 13.56 MHz and high deposition rates have larger amounts of SAXS related to scattering features with sizes > 200 Å. This scattering is associated with large bulk density fluctuations and/or enhanced surface roughness. None of the films in the study displayed signs of having columnar-like microstructures. The nanovoids are not related to changes in the solar cells with increasing i-layer deposition rate for both fabrication processes, perhaps due to the relatively small volume fractions of less than 0.2% and/or good void-surface passivation. However, the larger-scale structures detected in the films made using the 13.56 MHz technique could cause the observed poorer performance in cells prepared at high growth rates.

Contract #: XAK-8-17619-31

SAXS studies of the films grown at NREL in the HWCVD tube reactor reveal a significant increase in the nanovoid volume fraction when converting from one to two filaments to reach the ultra-high deposition rates of up to 1 μm/min. Compared to the one- filament films made near 2 nm/s, all two-filament films have an increase in integrated SAXS of at about two orders-of-magnitude, corresponding to about 1-2 vol.% voids. This increased SAXS is independent of deposition rate (with two filaments) from about 3 to 13 nm/s. Similarly, x-ray diffraction studies of the medium-range-order show no variation in order over this same rate change. The MRO is not as good as detected in the best quality PECVD and HWCVD films reported earlier.

PECVD films prepared by USSC under different H dilution conditions have been examined by IR, XRD, and H evolution. The high-H-dilution material is deemed "on-the-edge" material because of its observed tendency to be near the boundary between amorphous and microcrystalline states. Upon annealing, a low temperature H-evolution peak appears, and film crystallization is observed at temperatures as low as 500^{o}C, which is far below that observed for a-Si:H films grown without H dilution. Although not detected directly by XRD in the as-grown state, very small crystallites are postulated that catalyze the low-temperature crystallization of the films upon annealing. The large spatial inhomogeneity in the H bonding associated with the very small crystallites is suggested to be one of the reasons for the reduced Staebler-Wronski effect observed in solar cells utilizing the "on-the-edge" material.

From extended anomalous-SAXS (ASAXS) measurements at numerous x-ray energies, structural and physical properties such as non-uniform Ge-concentrations and – in combination with flotation density results – the densities of Ge-enriched regions in amorphous a-$Si_{1-x}Ge_x$:H alloys were deduced based on a two-phase model. Depending on the preparation technique (with and without H dilution of the source gases), a dense phase with volume fractions of about 90% and with Ge-enrichments only slightly higher with respect to the entire alloy were observed. These denser regions with average sizes between 10 and 23 nm can be interpreted as a phase containing slightly enhanced numbers of homopolar Ge-bonds, surrounded by a small volume fraction phase of low density, H-rich regions containing much less Ge (sometimes none) with averages sizes from 0.6 to 1.6 nm.

Four samples of μc-Si:H prepared by the gas-jet technique developed at ECD were examined by SAXS. The silane flow was increased from 15 to 45 sccm for the series of samples and the integrated SAXS was found to decrease systematically from a high value corresponding to about 11% voids to a value for about 1.5% voids. This is consistent with an expected trend of decreasing amount of microcrystalline material with increasing gas flow. This was confirmed by XRD. The scattering features are only about 2 nm in diameter and show a relatively weak tilting effect.

Planned FY 2001 Activities: Another 3-day run at the NIST SANS facility is planned for late 2000. Several new samples have been prepared by NREL, USSC, BP Solar, and Ecole Polytechnique specifically for these new measurements. Most of the effort during FY 2001 will be concentrated on the analysis and interpretation of all the SANS data collected. SAXS and XRD measurements, analyses, and interpretation will continue on films of current interest, particularly related to higher deposition rates and microcrystallinity and the associated changes in nanostructure.

Major Reports Published in FY 2000:

D.L. Williamson, (2000), "Nanostructure of a-Si:H and Related Alloys by Small-Angle Scattering of Neutrons and X-rays," 35 pp. NREL/SR-520-29121, Golden, CO: National Renewable Energy Laboratory.

D.L. Williamson, D.W.M. Marr, B.P. Nelson, E. Iwaniczko, J. Yang, B. Yan, and S. Guha, "Small-Angle Neutron Scattering Studies of a-Si:H and a-Si:D," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, pp. 221-222 (2000).

Major Articles Published in FY 2000:

D.L. Williamson, "Medium-Range Order in s-Si:H Below and Above the Onset of Microcrystallinity," *Mat. Res. Soc. Symp. Proc.* **557**, 251 (1999).

J. Shinar, R. Shinar, D.L. Williamson, S. Mitra, H. Kavak, and V.L. Dalal, "Microstructure and Hydrogen Dynamics in Hydrogenated Amorphous Silicon Carbides," *Phys. Rev.* **B60**, 15875 (1999).

A.H. Mahan, J. Yang, S. Guha, and D.L. Williamson, "Structural Changes in a-Si:H Film Crystallinity with High H Dilution," *Phys. Rev.* **B61**, 1677 (2000).

P. Chuadhuri, U.K. Das, J.K. Rath, and D.L. Williamson, "Correlation of Nanostructural Heterogeneity and Light Induced Degradation in Amorphous Silicon Solar Cells," *Jpn. J. Appl. Phys.* **39**, 2530 (2000).

U.K. Das, A.R. Middya, J.K. Rath, C. Longeaud, D.L. Williamson, and P. Chaudhuri, "Nanostructures and Defects in Silicon-Hydrogen Alloys Prepared by Argon Dilution," *J. Non-Cryst. Solids* **276**, 46 (2000).

Thin Film PV Partnership

Process Development and Basic Studies of Electrochemically Deposited CdTe-Based Solar Cells

Contract #: #: XAK-8-17619-28	**Contract Period:** 5/22/98–7/21/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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<tr><td>Organization Type: CU</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
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E-mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $251,426
1999: $327,472
2000: $275,268</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Advance the processing for high-performance stable CdTe photovoltaic devices, by: (1) advancing the understanding how the basic electronic properties of CdTe thin film solar cells are related to composition, structure and processing procedure of the constituting layers; (2) studying microscopic processes in different parts of the cell responsible for degradation of electronic properties as a function of stress conditions; (3) optimizing the composition of the constituting layers, deposition procedures and postdeposition treatments to enhance cell performance; and (4) contributing to the development of accelerated lifetime prediction tests for the CdTe solar cells.

Approach/Background: Study electronic properties of polycrystalline thin films, in particular of grain boundaries, and devices prepared and stressed under varying conditions using variety of experimental methods and models. Optimize processing procedure of CdS/CdTe structure, composition and processing procedure of the front and back contacts.

Status/Accomplishments: Comparative studies performed by CSM at different stressing conditions of the cells prepared with the CdTe vapor transport deposition and with electrodeposition and also with different back contacts provided evidence that (a) the Cu-related degradation depends on the back contact structure. In particular, ZnTe interlayer not only provides low back contact resistance but also controls the Cu content and distribution throughout the cell; (b) differences caused by deposition techniques in the film morphology, intragrain material imperfection and grain boundary properties lead to different degradation rates; (c) stressing leads to a significant redistribution of electrically active defects and hence of the "doping profile"; a strong influence of the applied bias when stressing indicates a significant role of electromigration and perhaps transformation of the defects in strong electric fields.

Joint studies of deep traps in the electrodeposited CdTe cells were performed at CSM and NREL by using impedance spectroscopy in frequency, temperature and bias voltage domains, along with deep level transient spectroscopy (DLTS), time resolved photoluminescence, and SIMS. These studies provided evidence of: (a) a few Cu-related deep levels in CdTe whose concentration is comparable or for some of them even higher than the majority carrier concentration; (b) strong influence of the levels located close to the midgap on the minority carrier lifetime; (c) differences in the trap concentration and distribution in CdTe prepared with electrodeposition (CSM) and close space sublimation (NREL).

CSM successfully applied Near Field Scanning Optical microscopy (NSM), a high spatial resolution technique, for two dimensional mapping of current collection over the cell cross section. Evidence was provided for S preferential diffusion along the grain boundaries in polycrystalline CdTe. In some cross sectional photocurrent images, enhancements in photocurrent collection efficiency were observed which are present from photon energies well above the CdTe bandgap to below the gap. This information is important for clarifying mechanisms of grain boundary effect on cell performance.

Impedance spectroscopy studies at CSM of CdTe polycrystalline films revealed a strong dependence of the grain boundary electronic properties on the CdTe postdeposition treatment and doping with Cu. Variations were demonstrated in density of deep grain boundary states, the space charge density near grain boundaries, and transparency of grain boundaries for the majority carriers (holes)

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Status/Accomplishments (continued): A new experimental method for studies of basic electronic properties in transparent conducting oxides (TCO) was developed by CSM and NREL. The method is based on simultaneous measurements of four transport coefficients in stationary external fields: electrical conductivity, Hall, Seebeck, and Nernst-Ettingshausen coefficients. The Four Coefficient (FC) method provides establishment of band structure and electron scattering parameters which are crucial for the TCO figure of merit. Combined with measurements of optical frequency transport phenomena characteristics (plasma and collision frequency), the FC method provides information on the shape of the band minimum, values of the effective mass components, their dependence on the electron energy (non-parabolic spectrum), dominating scattering mechanism, as well as an estimate of the grain boundary contribution to the film sheet resistance. The method was applied for studies of ZnO, Cd_2SnO_4, and SnO_2:F thin films.

Planned FY 2001 Activities: Continue studies of basic electronic properties of the cells and their thin films constituents differently processed and stressed. Particularly, devices and CdTe films prepared with vapor transport-, atmospheric pressure chemical vapor-, and electro-deposition techniques will be studied. Back contacts will include Cu/Au, ZnTe:Cu/Au, ion-implanted N/ZnTe/Au and ion-implanted N/Au. Impedance spectroscopy in temperature and bias voltage domains will be used for detection and characterization of deep traps. Based on these studies it is planned to improve the standard procedure of derivation of doping profile from C-V measurements. Impedance spectroscopy, photoluminescence studies of cells and films as well as resistivity and Hall measurements on the latter, will be aimed at determination of grain boundary properties, carrier concentration and mobility, nature and energy levels of defects that control the majority carrier concentration and the minority carrier recombination rate. Studies of thin films will be performed on the samples that underwent the same processing steps as in the real cells.

Major Reports Published in FY 2000:

V.I. Kaydanov and T.R. Ohno, "Process Development and Basic Studies of Electrochemically Deposited CdTe-Based Solar Cells. *Annual Technical Report, Phase I, 15 May 1998-14 May 1999*", 64 pp., NREL/SR-520-28762 (August 2000), Golden, CO: National Renewable Energy Laboratory.

V.I. Kaydanov and T.R. Ohno, "Process Development and Basic Studies of Electrochemically Deposited CdTe-Based Solar Cells. *Annual Technical Report, Phase II, 16 May 1999-13 May 2000*", 63 pp., draft received.

Major Articles Published in FY 2000:

M.K. Herndon, A. Gupta, V. Kaydanov, and R.T. Collins, "Evidence for grain-boundary-assisted diffusion of sulphur in polycrystalline CdS/CdTe heterojunctions", *Applied Physics Letters* 75, 3503 (1999).

D.L. Young, T.J. Coutts, V. I. Kaydanov, "Density-of-states effective mass and scattering parameter measurements by transport phenomena in thin films", *Rev. of Sci. Instr.* 71, 462 (2000).

A.S. Gilmore, V. Kaydanov, U. Laor, A. Gupta, T.R. Ohno, B. McCandless, "AC Characterization of Grain Boundary Electronic Properties in CdTe Thin Films", Program and Proceedings: *NCPV Program Review Meeting 2000*, 16-19 April 2000, Denver, CO, BK-520-28064, pp 259-260 (2000).

A.Gupta, S. Townsend, V. Kaydanov and T.R. Ohno, "Comparison of Degradation in Vapor Transport- and Electro-Deposited CdTe Solar Cells with ZnTe:Cu/Au and Cu/Au Back Contacts", Ibid, pp. 271-272.

Thin Film PV Partnership

Device Physics of Thin-Film Polycrystalline Solar Cells

Contract #: XAK-8-17619-07	**Contract Period:** 1/20/98–3/19/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Colorado State University Department of Physics Fort Collins, CO 80523	
	Organization Type: CU	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** James R. Sites **Phone:** 970-491-5850 **Fax:** 970-491-7947 **E-mail:** sites@lamar.colostate.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $140,318 2000: $150,845 1999: $135,629	**Cost Share Funding:**

Project Objective: To (1) characterize and quantitatively separate individual losses in CI(G)S and CdTe cells and small modules, (2) explore mechanisms that allow small changes in impurity materials to have a significant performance impact, (3) develop a micron-size light probe, (4) characterize stability and transient response of cells at elevated temperature, and (5) integrate CdTe grain-boundary modeling with experimental data.

Approach/Background: Partnership with industry, NREL, and other universities to form an effective division of labor and communication network to collectively increase the commercial viability of thin-film polycrystalline modules.

Status/Accomplishments: (1) Small-spot stepping system refined to include simultaneous reflection measurement, real-time correction for modest substrate tilt, and wavelength variation by cooling lasers. (2) Small-spot probe applied to several CIGS and CdTe cells with successful analysis of bias and intensity dependence. (3) Systematic studies of CI(G)S transients with different combinations of absorbers and buffers. (4) Continued documentation of elevated-temperature induced changes in CdTe cells. (5) Reasonable fits to CdTe and CIGS cell data with AMPS modeling. (6) Quantitative loss analysis of several CIGS and CdTe cells.

Planned FY 2001 Activities: (1) Use small-spot probe to explore bandgap variations in CdTe cells, to document microscopic changes in CdTe cells after thermal stress, and to identify the local causes for reduced performance in CIGS and CdTe cells. (2) Pin down the materials combinations and mechanisms responsible for transients in some CI(G)S cells. (3) Help build a consensus on the baseline parameters and common variants relevant to realistic solar-cell model calculations. (4) Continue measurement and loss-mechanism analysis in collaboration with thin-film partners. (5) Co-author a book chapter on CdTe solar cells.

Major Reports Published in FY2000:

J.R. Sites, Phase II Annual Report, Subcontract XAK-8-17619-07.

J. Sites, J. Hiltner, P. Johnson, A. Pudov, and P. Macedo, “CdTe Cells: How Does One Demonstrate 30-year Stability,” Record of National CdTe R&D Team Meeting, Jan. 2000.

J.R. Sites, “The National CIS and CdTe R&D Teams,” Proc. NCPV Program Review Meeting, Denver, April 2000, p.39.

P. Johnson and J. Sites, “CIS Carrier Profiles Derived from Capacitance,” Proc. NCPV Program Review Meeting, Denver, April 2000, p. 233.

Major Articles Published in FY 2000:

J.F. Hiltner and J.R. Sites, “High-Resolution Laser Stepping Measurements on Polycrystalline Solar Cells,” 16th European PV Solar Energy Conference, Glasgow, May 2000.

P. Johnson, J. Sites, K. Ramanathan, L. Olsen, and D. Tarrant, “Effects of Buffer Layers on SSI CIGSS-Absorber Transient I-V and C-V Behavior.” Proc. 28th IEEE PV Specialists Conf., Anchorage, Sept. 2000.

Contract #: XAK-8-17619-07

J.F. Hiltner and J.R. Sites, “Local Photocurrent and Resistivity Measurements with Mircon Resolution,” Proc. 28th IEEE PV Specialists Conf., Anchorage, Sept. 2000.

S.E. Asher, F.S. Hasoon, T.A. Gessert. M.R. Young, P. Sheldon. J. Hiltner, and J. Sites, “Determination of Cu in CdTe/CdS Devices Before and After Accelerated Stress Testing,” Proc. 28th IEEE PV Specialists Conf., Anchorage, Sept. 2000.

Thin Film PV Partnership

Development of a Thin-Film Based "Micro-Concentrator" Photovoltaic Technology

Contract #: ZAK-8-17619-25	**Contract Period:** 5/1/98–4/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	DayStar Technologies, Inc. 303 S. Broadway, PMB-415 Denver, CO 80209	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** John R. Tuttle, Ph.D. **Phone:** 303-279-9505 **Fax:** 303-742-1899 **E-mail:** jtuttle@daystartech.com	
Technical Monitor: K. Zweibel **Phone**: 303.384.6441 **Fax**: 303.384.6430 **E-mail:** ken_zweibel@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: DayStar Technologies, Inc.
	DOE Funding Allocation: 1998: $38,383 2000: $87,000 1999: $115,000	**Cost Share Funding:** 1998: $4,754 2000: $9,500 1999: $12,496

Project Objective: DayStar Technologies, Inc. is developing a "flat-plate" concentrator PV module packaging technology as a reduced cost alternative to conventional module designs. This product is ideally suited for multi-megawatt projects where the opportunity exists to design dedicated 10-50KW systems at a 50% cost savings and to require only 15-25% of the costly cell material used in non-concentrator modules.

The optical lens and cell interconnect scheme was originally designed for use with thin-film solar cell components fabricated on flexible metallic sheet such as stainless steel. The package is now capable of accepting wafer-Si cell components as well, increasing the products market viability. The overall 3-year goals of the project are: 1) identify and address module and system product development issues; 2) produce module and system detailed design package; 3) produce pilot and full-scale system manufacturing tooling design package; 4) launch and operate pilot, followed by full-scale production facility.

The objective of this contract is to address research and development issues at the module level. DayStar will work through development issues in: 1) solar cell design, performance, and reliability under 2-8 suns of illumination; 2) cell modification and interconnection into multi-cell strings; 3) lamination of interconnected cell package to lens and lens to coverglass; and 4) optical lens performance. The solar cell materials presently under consideration are single junction ZnO / $Cu(In,Ga)Se_2$ on a sheet stainless-steel substrate, and wafer-Si (poly or single x-tal) cells from various vendors.

Approach/Background: Replacing costly solar cell material with inexpensive ($20/m^2) optical lens material is, by design, an effective means for reducing the manufacturing cost of PV modules. DayStar has created a module design that more closely emulates the mechanical nature of conventional flat-plate PV products and realizes significant cost savings through optical concentration of 2-8 suns. In order to achieve these benefits, technical and cost issues pertaining to cell modification (grid design / dicing), interconnect, component lamination, and optics performance require investigation.

The salient technical issues include thermal matching of plastic lens with coverglass, cell isolation and interconnection methodology for automated assembly, optical efficiency of lens / coverglass couple, taking into account optical reflectivity of cell material, and thermal heating of cell materials under concentration. Many of these issues have corollaries in conventional module fabrication and hence are an advantage of this approach to concentration packaging. Those issues that are unique to this technology will be investigated thoroughly by DayStar.

Status/Accomplishments: We have refocused our efforts towards the fabrication of thin-film CIGS-based solar cells on flexible metal substrates for inclusion into our 4.5-sun flat-plate concentrator module. Individual cell components and completed submodules are subsequently characterized optically, mechanically, and electrically to establish criteria for design and production improvements. We have tested several different metal substrates for suitability with the thin-film CIGS cell technology. We have successfully produced solar cells on two different metals with performance in excess of 16% for 1.1-cm^2 devices. Metal thickness' range from less than 25µm to 150 µm.

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- We have expanded our process development activities related to CIGS cell fabrication to include substrate temperature calibrations to account for variable metal types and thickness, Na incorporation, and CdS deposition. We are also developing proprietary "buffer layers" to improve film adhesion to the metal substrates. Cell isolation on metal substrates presents particular challenges that are unique to this cell structure. Most of the challenges are related to the manual processes employed and are expected to improve when semi-automated processes are introduced.
- We have designed large-area format (60-cm wide web), in-line deposition and multi-substrate, batch-process tooling for thin-film CIGS solar cells and expect to implement these capabilities during Phase III at our facilities.
- We have focused our module development efforts in Phase II on the characterization of the reflective optics and the fabrication of larger module prototypes. In characterizing the optics, we desire to differentiate between completed modules with wafer-Si and those with thin-film CIGS as the cell material. Our major challenge in fabricating larger module prototypes is the size of the lens material that is available to us at this stage of development.
- We have characterized the module optics in several configurations. Silver (Ag) and Aluminum (Al) have been tested as the reflective material and Ag has been determined to be superior. Glass and Acrylic optical superstrates have been tested and glass has proven to be optically superior. The surface reflectivity of wafer-Si and thin-film CIGS solar cells has been evaluated and the thin-film materials exhibit much lower surface reflectivity.
- A 600-cm^2 module was fabricated using wafer-Si cell materials. The performance is limited by an imperfect optical seam that is present between two 300-cm^2 acrylic optical pieces. A 300-cm^2 module using CIGS cell components was being fabricated at the end of the Phase II effort.
- We are developing manufacturing technology for fabrication of the optical lens system and for interconnection of the cell components. Several vendors have been identified who have similar tooling in place for different product applications. We are participating in a development program with one vendor to optimize the acrylic-glass couple that is a critical component of the optical lens system.

Planned FY 2001 Activities: Substantial emphasis in FY'01 will be placed on improving the Company's ability to fabricate greater quantities of thin-film CIGS for this technology development effort. The desired milestones for FY'01 under this subcontract include: 1) reliable 12% 10-20 cell strings; and 2) >10% (active-area) 50-cm^2 CIGS-based mini-modules. Additionally, effort will be expended towards outdoor measurements, outdoor testing, and module qualification testing.

Major Reports Published in FY 2000:

J.R. Tuttle, A. Szalaj, and K. Beninga, "Development of a Thin-Film Based "Micro-Concentrator" Photovoltaic Technology," Annual Report to the National Renewable Energy Laboratory under Subcontract ZAK-8-17619-25, May 16, 1999 – June 16, 2000.

Major Articles Published in FY 2000:

J.R. Tuttle, A.Szalaj, and K. Beninga, "Progress Toward Commercialization of a 4.5-Sun, Flat-Plate Concentrating PV Module and System," Proceedings of the 28th IEEE PVSC, Anchorage, AK, September, 2000 (in press).

"Development and Commercialization of a 4.5-Sun, Flat-Plate Concentrating PV System," **J.R. Tuttle** *et al*, *Proceedings of the NCPV Program Review Meeting 2000*, Denver, CO, USA, 16-19 April, 2000, p. 109.

Use of Very High Frequency Plasmas to Prepare a-Si:H Based Triple-Junction Solar Cells at High Deposition Rates

Contract#: ZAK-8-17619-18	**Contract Period:** 3/11/98–5/10/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Energy Conversion Devices, Inc.
1675 West Maple Rd.
Troy, MI 48084</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 12</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
S.J. Jones
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<tr><td rowspan="2">Technical Monitor:
K. Zweibel
Phone: 303-384-6441
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E-mail: ken_zweibel@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
ECD</td></tr>
<tr><td>DOE Funding Allocation:
1998: $235,000 2000: $285,000
1999: $311,000</td><td>Cost Share Funding:
1998: $235,000 2000: $285,000
1999: $311,000</td></tr>
</table>

Project Objective: To develop a very high frequency (70 MHz), plasma-enhanced, chemical vapor deposition process for the fabrication of intrinsic layers for high efficiency amorphous silicon-based triple-junction solar cells at high deposition rates. These intrinsic layers are either amorphous silicon or amorphous silicon germanium alloy materials. The eventual goal is to prepare these materials at rates of 10 Å/s or higher while maintaining the cell efficiencies at the high values presently obtained for devices made using the standard 13.56 MHz frequency and low deposition rates (near 1 Å/s). Upon completion of a successful program, application of this high rate process to ECD's roll-to-roll solar cell production design will lead to higher machine throughput and reduced solar module cost.

Approach/Background: The deposition conditions used to prepare single-junction amorphous silicon (a-Si:H) and silicon germanium alloy (a-SiGe:H) cells by the very high frequency (VHF) technique will be optimized to obtain the highest cell efficiencies. These component cells will then be combined to create high efficiency a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells. The deposition conditions for these multi-junction cells will also be optimized to further increase the device performance. For the future incorporation of the technique into an ECD built roll-to-roll solar cell production line, cathode hardware designs will be tested which will allow for the uniform deposition of i-layers over a large area using the VHF technique and high deposition rates.

Status/Accomplishments: The following has thus far been accomplished: 1) preparation of a single-junction a-Si:H cell with a stable 8.0% AM1.5 efficiency using the VHF technique and a 10 Å/s rate, 2) preparation of a single-junction a-SiGe:H cell with a stable 2.7% red light efficiency (AM1.5 light filtered with 630nm cutoff filter) using the VHF technique and a 10 Å/s rate, 3) preparation of a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells with initial (pre-light soaked) AM1.5 active area efficiencies above 11% (11.2% highest) and total area efficiencies of 10.6% using the VHF technique and a 10 Å/s rate for all of the i-layers. After 1000 hrs. of light soaking, the cell efficiencies only degrade by 10-12% to light soaked AM1.5 total area efficiencies of 9.0%, and 4) initial tests of large area cathode hardware for application of the VHF technique in a production environment.

Planned FY 2001 Activities:
The following are goals for this fiscal year: 1) preparation of a single-junction a-SiGe:H cell with a stable 2.8% red-light (630 nm filtered) efficiency using the VHF technique and a 10 Å/s rate, 2) preparation of a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells with light soaked AM1.5 total area efficiencies of 10% using the VHF technique and a 10 Å/s rate for all of the i-layers and 3) complete development of large area cathode hardware that will allow for the uniform deposition of amorphous silicon-based films at rates near 10 Å/s using the VHF technique.

Major Reports Published in FY 2000:
S.J.Jones, T. Liu, D. Tsu and M. Izu, "Use of Very High Frequency Plasma to Prepare a-Si:H Based Triple-Junction Solar Cells at High Deposition Rates.", *NREL Photovoltaic Program FY 1999 Annual Report* (Submitted May 2000).

Contract#: ZAK-8-17619-18

Major Articles Published in FY 2000:
S.J. Jones, T. Liu, X. Deng and M. Izu, "a-Si:H-based triple-junction cells prepared at i-layer deposition rates of 10 Å/s using a 70 MHz PECVD technique," *28th IEEE PV Specialists Conference*, Anchorage, AK, 17-22 September 2000 (in press).

S.J. Jones, T. Liu and M. Izu, "Development of VHF PECVD technique to prepare amorphous silicon-based multi-junction cells at high i-layer deposition rates," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064,(2000) (in press).

S.J. Jones, D.L. Williamson, T. Liu, X. Deng and M. Izu, "Comparison of structural properties and solar cell performance of a-Si:H films prepared at various deposition rates using 13.56 and 70 MHz PECVD methods," *Mat. Res. Soc. Proc 2000 Spring Meeting,* 24-28 April 2000, San Francisco, CA (in press).

Thin-Film CIGS Photovoltaic Technology

Contract #: ZAK-8-17619-21	**Contract Period:** 4/16/98-5/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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Fax: 202-586-8148   Fax: 202-586-8148
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E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Energy Photovoltaics, Inc. (EPV)
276 Bakers Basin Road
Lawrenceville, NJ 08648</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 4</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
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<tr><td rowspan="2">Technical Monitor:
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Energy Photovoltaics, Inc. (EPV)</td></tr>
<tr><td>DOE Funding Allocation:
1998: $698,515   2000: $852,475
1999: $811,328</td><td>Cost Share Funding:
1998: $174,629   2000: $213,119
1999: $202,832</td></tr>
</table>

Project Objective: The overall objective of this R&D program is to develop processing procedures and recipes to be implemented on novel, large-scale, all-vacuum coating equipment to produce high efficiency, thin film CIGS PV modules. Sub-objectives include: an optimized Mo back electrode, a CIGS process capable of better than 15% device efficiency, transfer of process to 4300 cm^2 and 7900 cm^2 systems, demonstrated control of Cu/(In+Ga) and Ga/(In+Ga) ratios, utilization of a Cd-free buffer layer, high rate ZnO deposition, low loss patterning operations, a qualified encapsulation process, and stability testing. Accomplishment of these goals will provide a foundation for manufacturing of CIGS modules using safe, all-vacuum processing.

Approach/Background: R&D and process development are conducted in the Hercules 4-source system (four 5cm x 10cm stationary substrates per run) and in the Zeus 4-source system (one 4300 cm^2 moving substrate per run), with CIGS module efficiency reaching 7.6% at 3100 cm^2. To deliver materials downwards to the moving glass, EPV utilizes custom-built source heads housing four independent linear evaporative sources, the source axes being perpendicular to the direction of glass travel. This approach allows a wide range of vacuum-based CIGS recipes to be implemented.

For junction formation, EPV relies on chemical bath deposition of CdS on a day-to-day basis, while pursuing alternative methods in parallel. These methods may include linear source evaporation of CdS or a Cd-free buffer material, and direct deposition of ZnO onto the CIGS. Exploration of Cd-free junctions is being pursued by the EPV sub-team of the National CIS R&D Team.

For high rate ZnO deposition, EPV is currently exploring planar magnetron sputtering using ceramic ZnO targets.

Module encapsulation is based on glass-glass vacuum lamination using EVA, the processing being similar to that employed for the EPV-40 a-Si/a-Si module.

Status/Accomplishments: The large area sputtering of Mo films that are suitable for supporting very high efficiency cell processing has been demonstrated. Using EPV Mo sputtered using a bi-layer process, NREL has deposited a 17.1% CIGS cell (no AR coating). The parameters of this cell are V_{oc} 644 mV, J_{sc} 35.7 mA cm^{-2}, and FF 74.7%. The Mo was produced on EPV's 0.43 m^2 pilot line equipment.

Using linear source evaporation, CIGS is prepared on 4300 cm^2 Mo-coated glass substrates. The Zeus system is capable of quite uniform deposition, the best result being for a run yielding an average thickness of 3.96 µm measured across the plate (i.e. along the source axis) with a standard deviation of 0.1 µm. Of special significance is EPV's ability to build linear sources capable of Cu evaporation. This is a notable technological feat given the high Cu source temperature. By employing different flux/temperature/time recipes, CIGS films were produced with both flat and graded Ga depth profiles. Diagnostic devices produced on portions of the substrate have been prepared with efficiencies of 12% (V_{oc} = 581 mV, J_{sc} = 30.1 mA/cm^2, FF = 68.7%).

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Status/Accomplishments, (continued): To facilitate the achievement of proper CIGS composition and morphology, in-house characterization of CIGS films has been strongly upgraded through the recent establishment of a modern analytical laboratory containing ICP-AES and SEM/EDS facilities. Both the optimization of CIGS and the maintenance of a desired process are expected to benefit strongly from these capabilities. As an example, after a Zeus source head interchange, the CIGS composition was quickly tuned to Cu 23.0%, In 19.4%, Ga 6.0%, Se 51.6% as measured in-house.

Modules were fabricated with 81 monolithically-integrated segments, and exhibited open-circuit voltages in excess of 36V.

Various ternary compounds were synthesized and explored as possible source materials to produce a Cd-free buffer layer. $ZnIn_2Se_4$ was found to be photoconductive, and consistently provided reasonable cell efficiencies. Using a T_s of 200°C for the ZIS deposition, an 11.6% cell was achieved with V_{oc} 562 mV, J_{sc} 30.8 mA cm^{-2}, and FF 67.2%. The cell exhibited no dark-light crossover of the I-V curves and no light soaking effect.

A useful improvement in both the conductivity and transmission of DC sputtered ZnO:Al was achieved by deposition onto heated substrates. By increasing the deposition temperature to 190°C, an improvement in conductivity from 420 to 870 Ω^{-1}cm^{-1} and weighted transmission from 88.3 to 92.2% was obtained. The increased ZnO conductivity allows a sheet resistance of 20 Ω/sq. to be achieved at a thickness of less than 0.6 µm.

Planned FY 2001 Activities: Further work is required concerning Mo deposition, namely, confirmation of the signature of "good" Mo, and delineation of its process window. A target small area device efficiency of 15% has been set for the Hercules system. More efficient procedures will be developed for rapid attainment of target CIGS thickness and composition for both the Hercules and Zeus systems. Zeus films will be more thoroughly characterized using area maps. Hardware improvement will continue, including reduction of thermal cross-talk to enable back-to-back runs without process drift. A definitive evaluation of the ZIS buffer layer will be undertaken. Module wattages in excess of 40W will be aggressively sought. Outdoor and reliability testing of this new generation of modules will be instituted.

Major Reports Published in FY 2000:

Delahoy, A.E., Bruns, J., Ruppert, A., Akhtar, M., Chen, L., and Kiss, Z.J. (2000) "Thin-Film CIGS Photovoltaic Technology," Annual Technical Report, NREL/SR-520-28786, 22 pp. Available from U.S. DOE, OSTI, Oak Ridge, TN 37831, or U.S. Dept. of Commerce, NTIS, Springfield, VA 22161.

Major Articles Published in FY 2000:

Delahoy, A.E., Ruppert, A., and Contreras, M., "Charging and Discharging of Defect States in CIGS/ZnO Junctions," *Thin Solid Films 361-362* (2000) pp. 140-144.

Delahoy, A.E., Bruns, J., Akhtar, M., Chen, L., Ruppert, A., and Kiss, Z. "Advances in CIGS PV Technology," *Proc. NCPV Program Review Meeting*, Denver, CO, April 16-19, 2000.

Delahoy, A.E., Akhtar, M., Bruns, J., Ruppert, A., Chen, L., and Kiss, Z. "Ternary Source Materials for CIGS Buffer Layers," *16th European Photovoltaic Solar Energy Conference*, Glasgow, UK, May 1-5, 2000.

Alan Delahoy, Juergen Bruns, Liangfan Chen, Masud Akhtar, Zoltan Kiss, and Miguel Contreras "Advances in Large Area CIGS Technology," *28th IEEE Photovoltaics Specialists Conference*, Anchorage, Alaska, Sept. 17-22, 2000.

Thin Film PV Partnership

Technology Support for High-Throughput Processing of Thin-Film CdTe PV Modules

Contract#: ZAK-8-17619-17	**Contract Period:** 4/1/98–3/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	First Solar, LLC. 28101 Cedar Park Blvd. Perrysburg, OH 43551	
	Organization Type: IN	**Congressional District:** 9
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D.H. Rose, R.C. Powell, and G.L. Dorer **Phone:** 419-872-7661 **Fax:** 419-872-7665 **E-mail:** drose@firstsolar.com	
Technical Monitor: H.S. Ullal **Phone:** 303-384-6486 **Fax:** 303-384-6430 **E-mail**: harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** First Solar, LLC.
	DOE Funding Allocation: 1998: $1,032,511 2000: $1,059,776 1999: $ 945,416	**Cost Share Funding:** 1998: $258,128 2000: $1,613,675 1999: $654,623

Project Objective:
The project objective is to develop processes for large-scale production of high-efficiency CdS/CdTe thin-film photovoltaics. This subcontract focuses on the development of high-rate semiconductor deposition, improvement of module efficiency, development of all-dry device and other high-speed processes, and testing of long-term stability.

Approach/Background:
The subcontract covered by this summary was awarded to Solar Cells, Inc. (SCI) in 1998. SCI had been conducting research on CdS/CdTe solar panels since 1991. In February 1999, SCI and True North Partners, LLC jointly formed First Solar, LLC. First Solar assumed all activities of SCI, including the research described in this report. The goal of First Solar is to produce photovoltaics at very large volumes at costs competitive with traditional energy sources. To achieve this goal, this subcontract leverages First Solar's extensive knowledge of high-speed thin-film deposition and hot-glass transport and focuses new research in four areas: 1) process and equipment development, 2) efficiency improvement, 3) characterization and analysis, and 4) environmental, health, and safety.

Status/Accomplishments:
During FY 2000, First Solar made significant progress in all four areas of this subcontract as described below:

- Process and equipment development:
  - In concert with other programs and additional internal funding, completed a new semiconductor deposition system with a throughput of four plates per minute (each 0.72 m^2) and a module finishing line with a throughput of one 0.72 m^2 module/min. For 10% efficient modules, these throughputs would provide a production capacity of 100 MW/yr for the deposition system and 25 MW/yr for the remainder of the line. In the final month of the fiscal year, yields of over 85% were consistently demonstrated with the production line. While process development work for both the deposition system and finishing line remains, over the course of the fiscal year more than 15,000 CdS/CdTe-coated plates (each 0.72 m^2) were produced.
  - Transferred pilot production to the new deposition system, including the gathering of data on film characteristics. Spatial mapping of CdS thickness of a plate from the new deposition system showed a standard deviation of only 1.3% in the down-web direction and 7% in cross-web direction.
  - Modeled deposition process from the perspectives of flow dynamics and species-diffusion and condensation.
  - Supported the development of a new laser-scribing system with linear scribing speeds of up to 3 m/s. The system provides throughput of one plate/min with one laser, thus reducing system downtime and costs compared to a multi-laser approach.
  - Verified heat-treatment profiles and identified vapor delivery issues for a module-sized vapor-$CdCl_2$ system.
  - Improved large-area characterization systems, including laser-based CdS and CdTe thickness mapping systems and in-situ CdS sensors.

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Status/Accomplishments (continued):

- Efficiency improvement:
  - Demonstrated increased module efficiency by using an atmospheric-pressure chemical-vapor deposition (APCVD) buffer layer and thin CdS. Aperture efficiencies of 9.5% for a module (unconfirmed), 10.6% for a minimodule, and 13.4% for a cell were all achieved on commercially available SnO_2-coated soda-lime float glass substrates with the semiconductor layer deposited with the new high-throughput system. Related highlights include the development of a new chemistry for the APCVD of buffer layers and a new APCVD system for 7200 cm^2 substrates.
  - Improved module diagnosis techniques and used them to provide guidance for improvement of the production process.
  - Conducted experiments in many areas which can influence efficiency, including the effect of $CdCl_2$ treatment process variables, module-scale non-uniformity, and back-contact process variables.
- Characterization and analysis:
  - Increased capabilities in cell characterization, including spectral response, energy-dispersive spectroscopy, spectrophotometry, and admittance spectroscopy (optical and electrical).
  - Made significant progress in characterization and modeling, including i) proposed micro-non-uniformity as the cause of large suppression of V_{oc} in some cells, ii) modeled the effect of non-uniformity and developed an analytical solution based on the mean-field approximation and an analytical model for shunt screening, iii) used PL to ascertain electronic states in CdTe films and cells, and iv) characterized contact resistance, grain boundaries, and other cell and module properties.
  - Developed and used two new high-acceleration-factor tests for cell life testing (planar EBIC and laser light soak).
  - Completed 2^{nd} round of accelerated-life tests, including tests of alternative processes at First Solar and cells by National CdTe Team members.
  - Produced modules with a new interfacial-layer back-contact which shows superior stability under high-stress tests.
  - Demonstrated field stability to a period of greater than 5 years with further analysis of the array at NREL -- the average efficiency of the 24 modules in the array was essentially unchanged (increased 3%) from 5.5 years of field exposure.
- Environmental, health, and safety:
  - Replaced methanol-based $CdCl_2$ step with an aqueous-based process and thereby retained “De Minimus” emissions rating for the new production facility.
  - Wrote a Lab Standard Compliance Plan and improved lab safety procedures in R&D

Planned FY 2001 Activities:

- Explore process parameters for new production coater and production line and thereby improve product uniformity and reproducibility.
- Advance understanding of device operation through characterization and analysis.
- Provide modules with alternative contacts and variations in other process parameters for field testing.
- Demonstrate additional gains in module efficiency through improved uniformity of processes in concert with thin CdS and a buffer layer.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

D. Grecu, A. D. Compaan, D. Young, U. Jayamaha, and D. H. Rose, “Photoluminescence Study of Cu-Doped CdTe and Related Stability Issues in CdS/CdTe Solar Cells,” *Journal of Applied Physics*, vol. 88, pp. 2490-2496, 2000.

R. Harju, V. G. Karpov, D. Grecu, and G. Dorer, “Electron-Beam Induced Degradation in CdTe Photovoltaics,” *Journal of Applied Physics*, vol. 88, pp. 1794-1801, 2000.

R. C. Powell, K. Kormanyos, G. Faykosh, D. Rose, U. Jayamaha, D. Grecu, D. Giolando, and G. Dorer, “Technical Issues in Large Area CdS/CdTe Thin Film Deposition,” *16th NCPV Program Review*, pp. 37-38, 2000

Papers presented at the 28th IEEE Photovoltaic Specialists Conference, Anchorage, AK, September 19-22, 2000:

- J. Bohland, K. Smigielski, “First Solar’s CdTe Module Manufacturing Experience; Environmental, Health, and Safety Results”
- D. Grecu, U. Jayamaha, G. Rich, V. Karpov, “Admittance spectroscopy of CdTe Based Solar Cells”
- R. Harju, V. Karpov, D. Grecu, G. Dorer, “Electron Beam-Induced Effects in CdTe Photovoltaics”
- V.G. Karpov, R. Harju, G. Dorer, “Nonuniform Power Generation in Polycrystalline Thin Film Photovoltaics”
- D. Rose, R. Powell, U. Jayamaha, M. Maltby, D. Giolando, A. McMaster, K. Kormanyos, G. Faykosh, J. Klopping, G. Dorer, “R & D of CdTe-Absorber Photovoltaic Cells, Modules, and Manufacturing Equipment: Plan and Progress to 100 MW/yr”

Thin Film PV Partnership

$CuIn_{1-x}Ga_xSe_2$ Thin Film Solar Cells

Contract #: XAK-8-17619-12	**Contract Period:** 1/5/98–5/4 /01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Florida Solar Energy Center, University of Central Florida 1679 Clearlake Road Cocoa, FL 32952-5703	
	Organization Type: CU	**Congressional District:** 15
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Neelkanth G. Dhere **Phone:** 321-638-1442 **Fax**: 321-638-1010 **E-mail:** dhere@fsec.ucf.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail**: bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $31,700 2000: $35,194 1999: $42,800	**Cost Share Funding:**

Project Objective: To develop selenization, sulfurization, and gallium incorporation techniques for the preparation of $CuIn1_{-x}Ga_x$ $Se_2{-}_yS_y$ thin films and solar cells. Apply the techniques developed during the study of the durability of crystalline silicon PV modules for the study of thin-film PV modules. Monitor the performance of thin-film PV modules in the hot and humid climate of Florida.

Approach/Background: Enhance gallium incorporation and the bandgap of device quality $CuIn_{1-x}Ga_xS_2$ (CIGS2) thin films by using CuGa excess and etching Cu-phases segregated at the surface. Design and build a large-area "in-line" sputter-deposition system. Monitor thin-film modules in the hot and humid Florida climate with an objective to identify degradation mechanisms.

Status/Accomplishments: Attempts were made to enhance gallium incorporation and hence the bandgap of $CuIn_{1-x}Ga_xS_2$ (CIGS2) thin films by using CuGa(22%) excess and etching Cu-phases segregated at the surface. Large grain, thin films having $CuIn_{0.5}Ga_{0.5}S_2$ and $CuIn_{0.6}Ga_{0.4}S_2$ crystallographic phases were prepared. However, the etched CIGS2 films were porous. A dual-chamber magnetron-sputtering unit was fabricated. The larger chamber is equipped with a 1500 liter/sec cryopump, and three 4"x12" DC magnetron sputtering sources for deposition from molybdenum, indium, and copper, CuGa(22%) or CuGa(67%) targets. The thickness uniformity along the 12" dimension is expected to be better than ± 2% over the center width of 5" and better than ± 3% over the center width of 6" for linear substrates motion along the 4" dimension. Moreover, the sputtering sources are expected to provide excellent (>40%) target utilization. Techniques have been optimized for RF sputter deposition of ZnO and ZnO:Al window bilayer. At present, glass/Mo/CIGS/CdS/ZnO/ZnO:Al solar cell samples are being prepared routinely at FSEC. Monitoring of thin-film PV modules is being continued at FSEC. A student successfully defended MS thesis based on research carried out at the FSEC PV Materials Lab.

Planned FY 2001 Milestones: Try to enhance gallium content using a combination of CuGa(22%) and CuGa(67%) targets with an objective to prepare device quality CIGS2 thin films with bandgap in the range 1.7-1.9 eV. Carry out round robin AES and SIMS analysis of baseline CIGS samples from Siemens, NREL, and IEC. Add two 4"x12" RF magnetron sputtering sources for ZnO and ZnO:Al bilayer window deposition and a four-hearth e-beam source for vacuum evaporation of Ni/Al contact grids. Continue testing of the First Solar CdTe PV array on the low-bay lab roof of FSEC. Carry out light I-V characterization of First Solar CdTe into the first quadrant to approximately 1.3xVoc or +0.5x Isc.

Major Reports Published in FY 2000: Phase 2 Annual Report (unpublished).

Major Articles Published in FY 2000:

N. G. Dhere, S. R. Kulkarni and S. R. Ghongadi, "System Improvement for Preparation of $CuIn_{1-x}Ga_xS_2$ Thin Film Solar Cells", Proc. NCPV Review Meeting, Denver, CO, April 16-19, 2000, p. 257.

N. G. Dhere, S. R. Kulkarni and P. K. Johnson, "Bandgap Optimization Of CIGS2 Space Solar Cells", Proc. 16^{th} European Photovoltaic Solar Energy Conference, Glasgow, UK, during May 1-5, 2000, (to be published).

N. G. Dhere, S. R. Kulkarni and S. R. Ghongadi, "PV Characterization of CIGS2 Thin Film Solar Cells", Proc. 28^{th} IEEE Photovoltaic Specialists' Conference, Anchorage, Alaska, Sept. 15-22, 2000, (to be published).

Thesis entitled, "Process Optimization and Characterization of $CuIn_{1-x}Ga_xS_2$ (CIGS2) Polycrystalline Thin Films", Shashank R. Kulkarni, Mech. Materials, & Aerospace Eng. Dept. UCF, Orlando, FL.

Process Development of Large-Area, Thin-Film CIGS Based PV Modules

Contract #: ZAK-8-17619-04	**Contract Period:** 2/5/98–2/4/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Global Solar Energy, LLC 5575 S. Houghton Rd. Tucson, AZ 85747	
	Organization Type: IN	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J. Britt **Phone:** 520-546-6313 **Fax:** 520-546-6318 **E-mail:** jbritt@globalsolar.com	
Technical Monitor: H.S. Ullal **Phone**: 303-384-6486 **Fax**: 303-384-6430 **E-mail:** harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Global Solar Energy, LLC
	DOE Funding Allocation: 1998: $503,263 2000: $438,140 1999: $584,765	**Cost Share Funding:** 1998: $115,815 2000: $343,971 1999: $238,781

Project Objective: As a technology partner with NREL, Global Solar Energy (GSE) has initiated an extensive and systematic plan to accelerate the commercialization of thin film photovoltaics (PV) based on Copper Indium Gallium Diselenide (CIGS). GSE is developing the technology to deposit and monolithically integrate CIGS photovoltaics on a flexible substrate. CIGS deposited on flexible substrates can be fabricated into either flexible or rigid modules. Attaching the flexible CIGS to an inexpensive rigid panel by lamination or adhesive will lead to low cost rigid PV panels for remote power, bulk/utility, telecommunication, and rooftop applications.

The specific objectives of this research and development include optimization of continuous roll-to-roll CIGS deposition processes; development and optimization of novel scribe and interconnect processes for module formation, and viable encapsulation and finishing methods to produce flexible and rigid mounted PV products.

Approach/Background: At GSE, all thin film coatings are deposited on a moving web in a roll-to-roll process. Stainless steel substrate is utilized as the initial vehicle for entry into the market place and polymer substrate is under development to enable longer-term terrestrial and space-based applications. In combination with roll-to-roll processing, GSE is developing evaporation deposition operations that enable low-cost and high-efficiency CIGS modules. The manufacturing process relies on in-line multi-source evaporation to deposit high-quality CIGS films in a continuous roll-to-roll operation at rates sufficient for hi-volume manufacturing.

Status/Accomplishments:
- Improved control of composition, thickness, and uniformity of the production CIGS deposition process
- Developed a monolithic integration scheme on polyimide with low shunting and interconnect series resistance
- Demonstrated baseline designs, materials, and methods for lamination and lead connection
- Developed low-cost methods for lamination on both flexible and semi-rigid substrates for early stages of manufacturing
- Delivered prototype Transportable AC Systems (TACS) utilizing flexible 2-5 kW photovoltaic arrays (TACS) to the US Army for field evaluation

Planned FY 2001 Activities:
Produce flexible encapsulated CIGS modules (0.75 m^2) with aperture-area efficiency of 8%.

Major Reports Published in FY 2000:
Britt, J., Wiedeman, S., Albright, S. (2000) "Process Development for CIGS based Thin Film Photovoltaic Modules," Phase II Technical Report. Available from NTIS, Springfield, VA 22161.

Major Articles Published in FY 2000:
S. Wiedeman, J. Fogleboch, J. Muha, R. Wendt, J. Britt, "Monolithic Integration of CIGS based PV on Flexible Substrates", presented at the NCPV Program Review Meeting, April 2000.

Thin Film PV Partnership

Optimization of Processing and Modeling Issues for Thin Film Solar Cells

Contract #: ZAK-8-17619-33	**Contract Period:** 8/24/98–10/23/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Institute of Energy Conversion (IEC) University of Delaware Newark, DE 19716	
	Organization Type: CU	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** R.W. Birkmire **Phone:** 302-831-6220 **Fax:** 302-831-6226 **E-mail:** rwb@udel.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Institute of Energy Conversion
	DOE Funding Allocation: 1998: $150,000 1999: $1,316,010 2000: $1,275,000	**Cost Share Funding:** 1998: $31,579 1999: $328,421 2000: $0

Project Objective: The overall goals are to develop the science and engineering basis needed to: 1) advance scientific fundamentals of $Cu(InGa)(SeS)_2$, CdTe and thin Si materials and processing, 2) improve the performance and manufacturability of thin film solar cells made from these materials, and 3) effectively transfer laboratory results to first time manufacturing. The objectives are to develop improved techniques for growth semiconductor thin films over large areas at high rates, provide detailed characterization of these materials and devices, and to assist industry in transferring laboratory results to economical manufacturing processes while maintaining high efficiencies.

Approach/Background: IEC will develop an in-line evaporation process for the deposition of $Cu(InGa)Se_2$ thin films and characterize the effect of deposition temperature on $Cu(InGa)e_2$ films and devices. $Cu(InGa)(SeS)_2$ films with bandgaps from 1.3 to 1.9 eV will be deposited by alloying with S and characterized. IEC will improve TCO/CdS/CdTe devices with thin CdS layers by altering the TCO or device processing. Stability tests will be performed on a variety of differently deposited CdTe devices and interpreted in terms of back contact and doping. IEC will optimize a-Si p-layers, including microcrystalline layers, deposited by plasma CVD; and explore the growth of doped polycrystalline Si thin films by hot wire CVD.

Status/Accomplishments: The in-line process for evaporation of $Cu(InGa)Se_2$ has been validated by the demonstration of a device with 14.9% efficiency and the development of a model for the flux delivery to the substrate as it moves through the deposition zone, which enables the compositional gradients in the films to be controlled. $Cu(InGa)Se_2$ films deposited at 480°C, below the glass softening point, were shown to have the same grain size as films deposited at 550°C but poorer device performance. A method for making thin film $CuIn(SeS)_2$ with uniform or graded compositions has been developed and quantitatively analyzed and it was shown that S incorporation into Cu-poor films is much smaller than into Cu-rich films.

For conditions typically used to process CdS/CdTe solar cells, the bulk and grain boundary diffusion coefficients and activation energies were determined, and the effects of $CdCl_2$ and O_2 concentrations were quantified. Processing strategies were developed to control junction quality as both window and absorber layer thicknesses are reduced. Accelerated stressing of CdS/CdTe solar cells under a range of applied bias conditions has identified three degradation modes: increased recombination; formation of a blocking contact; and a change in the photoconductivity of either the CdS or CdTe.

The deposition chemistry of thin Si films by hot-wire CVD has been characterized and a process to deposit boron-doped polycrystalline Si films with resistivities of 1-100 Ω-cm was developed. Analysis of a-Si p-i-n solar cells on ZnO or SnO_2 substrates showed that that the lower V_{oc} and FF observed with a ZnO contact is caused by an increase in the junction recombination rather than by a blocking or high resistance ZnO/p contact.

Contract #: ZAK-8-17619-33

Status/Accomplishments (continued): IEC has continued to work closely with several thin film PV companies, to support national Thin Film Partnership Teams in all programs, and to assist other groups in the Thin Film Partnership by providing materials and characterization and completing devices incorporating materials from the other groups.

Planned FY 2001 Activities: The in-line evaporation process for $Cu(InGa)Se_2$ deposition will be optimized to control flux delivery and film composition for fabrication of state-of-the-art solar cells. Sulfur incorporation into $Cu(InGa)Se_2$ films with different relative Cu and Ga compositions will be characterized. Modified processing of TCO and CdS films and devices will be utilized to improve TCO/CdS/CdTe solar cells with thin CdS layers. New back-contacting schemes for CdTe solar cells, developed in-house or by other groups, will be stress tested and analyzed. Microcrystalline Si:C:O:H p-layers will be incorporated into p-i-n solar cells. A process will be developed to deposit larger grain doped Si films by hot-wire CVD for incorporation into devices. IEC will continue to support national Thin Film Partnership Teams in all programs, and continue to support other groups with device fabrication incorporating their materials and characterization.

Major Reports Published in FY 2000:
R.W. Birkmire, J.E. Phillips, W.N. Shafarman, E. Eser, S.S. Hegedus, B.E. McCandless, (2000), “Optimization of Processing and Modeling Issues for Thin Film Solar Cell Devices Including Concepts for the Development of Polycrystalline Multijunctions,” 107 pp., NREL/SR-520-28783, Golden, CO: National Renewable Energy Laboratory (Annual Report for period 8/24/98 – 8/23/99).

Major Articles Published in FY 2000:
NCPV Program Review, Denver, CO, April 16-19, 2000:
- R. Aparicio, R. Birkmire, A. Pant, M. Huff and M. Mauk, “Thin Polycrystalline Silicon films by HWCVD.”
- G.M. Hanket, P.D. Paulson, W.N. Shafarman and R.W. Birkmire, “Deposition of $Cu(InGa)Se_2$ by Inline Evaporation.”
- S.S. Hegedus, B.E. McCandless and R.W. Birkmire, “Analysis of Stress-Induced Degradation in CdS/CdTe Solar Cells.”

16^{th} European PVSEC, Glasgow, Scotland, May 1-5, 2000:
- B.E. McCandless and R.W. Birkmire, “Diffusion in CdS/CdTe Thin Film Couples.”
- R. Aparicio, R. Birkmire, A. Pant, M. Huff, T.W.F. Russell and M. Mauk, “Process Analysis and Modeling of Thin Silicon Film Deposition by Hot-Wire Chemical Vapor Deposition.”

28^{th} IEEE PVSC, Anchorage, Alaska, September 17-22, 2000:
- M.W. Haimbodi, E. Gourmelon, P.D. Paulson, R.W. Birkmire and W.N. Shafarman, “$Cu(InAl)Se_2$ Thin Films and Devices Deposited by Multisource Evaporation.”
- B.E. McCandless and R.W. Birkmire, “Influence of Window and Absorber Layer Processing on Device Operation in Superstrate thin Film CdTe Solar Cells.”
- G.M. Hanket, P.D. Paulson, U. Singh, S.T.Junker, R.W. Birkmire, F.J. Doyle III, E. Eser and W.N. Shafarman, “Fabrication of Graded $Cu(InGa)Se_2$ Films by In-line Evaporation.”
- S.S. Hegedus, B.E. McCandless and R.W. Birkmire, “Analysis of Stress-Induced Degradation in CdS/CdTe Solar Cells.”
- S.S. Hegedus, R. Kaplan, G. Ganguly and G.S. Wood, “Characterization of the SnO_2/p and ZnO/p Contact Resistance and Junction Properties in a-Si p-i-n Solar Cells and Modules.”

R.W. Birkmire, "Compound Polycrystalline Solar Cells: Recent Progress and Y2K Perspective," Proc. 11th Int. PVSEC, Sapporo, Japan, September 20-24, 1999, p. 33 (published in *Solar Energy Materials and Solar Cells* **65** (2001) 17-28).

M. Engelmann, B.E. McCandless and R.W. Birkmire, “Formation and Analysis of Graded $CuIn(Se_{1-y}S_y)_2$ Films,” E-MRS 2000 Spring Meeting, Strasbourg, France, May 30-June 2, 2000.

W.N. Shafarman and J. Zhu, “Effect of Substrate Temperature and Deposition Profile on Evaporated $Cu(InGa)Se_2$ Films and Devices,” *Thin Solid Films* **361-362**, 473-477 (2000).

Thin Film PV Partnership

CIS-Type PV Device Fabrication by Novel Techniques

Contract#: ZAK-8-17619-10	**Contract Period:** 6/30/98–10/15/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	International Solar Electric Technology Inc. (ISET) 8635 Aviation Blvd. Inglewood, CA 90301	
	Organization Type: IN	**Congressional District:** 35
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator** . V.K. Kapur **Phone:** 310-216-4427 **Fax:** 310-216-2908 **E-mail:** vkkapur@earthlink.net	
Technical Monitor: H. S. Ullal **Phone:** 303-384-6486 **Fax:** 303-384-6430 **E-mail**: harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** International Solar Electric Technology Inc. (ISET)
	DOE Funding Allocation: 1998: $275,869 2000: $0 1999: $480,658	**Cost Share Funding:** 1998: $10,000 2000: $0 1999: $11,483

Project Objective: The overall objective of this R&D effort is the development of a low-cost non-vacuum deposition technique for the fabrication of high efficiency CIS type devices. The major tasks include improvement of the efficiencies of solar cells fabricated on absorbers grown by the non-vacuum technique, deposition of large bandgap absorbers and fabrication of sub-modules and modules.

Approach/Background: The non-vacuum technique developed at ISET is a "particle deposition" method. In this approach sub-micron size particles with a fixed Cu/III metallic ratio are employed in the formulation of an ink or a paste. The ink is then deposited on the Mo/glass substrate in the form of a thin precursor layer. The precursor is annealed at elevated temperatures (>400 °C) to form a well fused and continuos Cu-III-VI_2 absorber. The technique offers excellent Cu/III uniformity ratio throughout the absorber layer since this ratio is fixed in the ink which is the source material.

Status/Accomplishments: We have successfully applied this non-vacuum technique using water based inks to fabricate over 13% efficient solar cells. The water based inks consist of nanoparticles of precursor materials in which the Cu/III ratio is fixed. The precursor layers of inks can be applied to a metallized substrate using a variety of coating techniques such as knife edge coating , roller coating or an ink jet printing process. Each of these coating processes requires adjusting the rheology of the ink. So far we have focused on using the knife edge coating process for which generally low viscocity (2 –10 cp) inks work well. However, for other coating processes require modifying viscocity as well as the surface tension of the ink.

To open the bandgap of the absorber layer, the selenized layers are treated with H_2S gas .Though we were able to obtain V_{oc} as high as 530 mV , we still need to optimize the sulfidation process to increase the V_{oc} values to about 600 mV. This process optimization is being continued with an objective of obtaining solar cells with conversion efficiency approaching 15%.

This patented process of ISET works very well for fabricating CIGS solar cells on lightweight flexible metallic substrates.

Planned FY 2001 Activities

- During the year 2001 we will focus our efforts in surface modifications of the absorber layer to achieve efficiencies approaching 15% in our devices.
- We will also continue evaluating various coating processes that may be suitable for processing large area modules.
- We will evaluate alternative schemes of integration of modules. These schemes may require printing of contacts on the active devices. Thus this approach will require evaluating a variety of contacting inks that may be suitable for CIGS/CdS /ZnO solar cells. The focus in this activity will be to make sub-modules with efficiency > 10%.

Contract#: ZAK-8-17619-10

Major Reports Published in FY 2000:
'CIS Type PV Device Fabrication by Novel Techniques', Phase –II Annual Technical Report for the Period July 1, 1999 - June 30, 2000.

Major Articles Published in FY 2000:
Non-vacuum thin-film Process for $CuInSe_2$ Solar Cells, 'Photovoltaics for the 21st Century', Proceedings Vol. 99-11, The Electrochemical Society Inc. Pennington, NJ .08534.

Thin Film PV Partnership

Research on Improved Amorphous Silicon and Alloy Materials and Devices Prepared Using ECR Plasma Techniques

Contract #: XAF-8-17619-30	**Contract Period:** 7/1/98–10/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Iowa State University Ames, Iowa 50011 **Organization Type**: CU	**Congressional District:** 3
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Vikram Dalal **Phone:** 515-294-1077 **Fax:** 515-294-9584 **E-mail:** vdalal@iastate.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $ 70,000 1999: $222,346 2000: $212,636	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The objectives of this subcontract are to: develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States. This will be carried out within the context of the research and development sub-Teams established by the NREL/EPRI Thin Film Partnership. The work is focussed on developing higher, performance, more stable a-Si and a-(Si,Ge)solar cells using innovative plasma deposition technology. Ultimately the goal of the Amorphous Silicon Team is to achieve 15% stable thin-film modules by 2005.

Approach/Background: The approach is to use controlled ECR plasma technology to deposit a-Si and a-(Si,Ge) solar cells. In particular, plasma conditions such as radical chemistry and ion bombardment will be varied to study their influence on material and device properties and stability. Both substrate and superstrate type cells will be made.

Status/Accomplishments: The following results were achieved:

- Good quality a-Ge:H materials and cells were grown using controlled reactive chemical plasma deposition with high hydrogen dilution. The defect densities in the a-Ge:H material, measured using space charge limited current and subgap absorption spectroscopy, were quite low, in the range of $5x10^{16}/cm^3$-eV. The devices showed quantum efficiencies extending to almost 1000 nm. Alloys of other compositions, in the Tauc gap range of 1.2-1.4 eV were also made, and showed good properties. This is the first time ever that any group has succeeded in making good cells at such low bandgaps.
- Studies were made on the influence of ion energies, ion flux and momentum transfer on the properties of a-(Si,Ge):H. It was found that having a high ion flux impinging on the substrate was very important in improving the properties of the material and devices. On the other hand, high ion energies tended to degrade the material properties. Heavier ions, such as He, were found to be beneficial in improving material properties.
- Good quality a-Si devices were made at high growth rates approaching 10 A/sec, using a combination of H and Ar. It was found that H dilution of Ar was critical in improving materials and devices, probably because H is important for improving the chemical reactivity of the surface and subsurface regions, whereas Ar is useful in decomposing silane efficiently. Increasing the growth rate is an important industrial milestone which can significantly reduce the cost of the final product, provided quality can be maintained.
- Microcrystalline Si was investigated as a PV material. The cells were made using the ECR reactive plasma growth technique. A novel buffer layer was developed to improve the performance of the cell.
- Microcrystalline Si cells were fabricated on polyimide substrates. This is the first time ever that anyone has made microcrystalline cells on polyimide. This development should allow industry to fabricate such cells using a roll-to-roll method, thereby lowering the cost of the product.
- Two M.S. and two Ph.D. students in Electrical Engineering were graduated, doing their research supported in part on NREL funding.
- Using careful optical emission spectroscopy, we were able to identify the GeH peak in the spectrum of Germane deposition. This is the first time ever that this peak has been seen in the deposition of (Si,Ge) alloys, and should be invaluable for controlling the deposition plasma.

Contract #: XAF-8-17619-30

Planned FY 2001 Activities:

- Understand the chemistry of deposition with a view of increasing the growth rate of a-(Si,Ge) devices to 3-5 A/sec while maintaining quality**.**
- Make a-(Si,Ge) devices at higher growth rates (3-5 A/sec).
- Improve the buffer layer in devices

Major Articles Published in FY 2000:

J. Shinar, R. Shinar, D. Williamson, S. Mitra and V. Dalal , "Microstructure and hydrogen dynamics in hydrogenated amorphous (Si,C)" Phys. Review B.60, 15875(1999).

K. Erickson and V. L. Dalal, " Growth of microcrystalline Si and (Si,Ge) films on plastic substrates", J.Non-Cryst. Solids, 266, 685(2000).

V. L. Dalal, S. Haroon, Zhiyang Zhou, T. Maxson and K, Han, "Influence of plasma chemistry on the properties of a-Si,Ge:H alloys", J.Non-Cryst. Solids, 266,675(2000).

J. Herrold and V. L. Dalal, " Growth and properties of microcrystalline (Ge,C)", J.Non-Cryst. Solids., 270, 255(2000).

R. Estwick and V. L. Dalal, "Quantum efficiency in a-Si cells", Proc. of MRS, 507, 37 (1999).

J. Herrold and V. L. Dalal, "Growth and properties of (Ge,C)", Proc. of MRS 507, 561(1999).

R. Shinar, J. Shinar, D. Williamson, S. Mitra, H. Kavak and V. L. Dalal, "Microstructure and hydrogen dynamics in a-(Si,C):H", Proc. Of MRS, 507, 329(1999).

Thin Film PV Partnership

Atmospheric Pressure Chemical Vapor Deposition of CdTe for High Efficiency Thin Film PV Devices

Contract#: ZAK-8-17619-03	**Contract Period:** 1/26/98–3/25/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	ITN Energy Systems, Inc. 8130 Shaffer Parkway Littleton, CO 80127	
	Organization Type: IN	**Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator** P. Meyers **Phone:** 303-285-5135 **Fax:** 303-285-5179 **Email:** pmeyers@itnes.com	
Technical Monitor: Ullal, H.S. **Phone:** 303 384-6486 **Fax:** 303 384-6430 E-mail: harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** ITN Energy Systems, Inc.
	DOE Funding Allocation: 1998: $198,310 1999: $241,721 2000: $293,137	**Cost Share Funding:** 1998: $28,033 1999: $17,500 2000: $17,500

Project Objective: Overall objective is improved thin film CdTe PV manufacturing technology with increased power conversion efficiency. Tasks required to accomplish the overall goal are grouped into 1) development of deposition apparatus and procedures which enable control of film growth over large area and 2) development of advanced measurement and analytical procedures which provide useful and effective device characterization.

Approach/Background: CdTe deposition by Atmospheric Pressure Chemical Vapor Deposition (APCVD) employs the same reaction chemistry as has been used to deposit 16% efficient CdTe PV films (Close Spaced Sublimation or CSS) but employs forced convection rather than diffusion as a mechanism of mass transport. APCVD enables discovery of fundamental mass transport parameters which, through application of established engineering principles, can be used to design high throughput, high yield manufacturing equipment. Device analysis will go beyond conventional one-dimensional device characterization and analysis toward two dimension measurements and modeling.

Status/Accomplishments: After several modifications to the existing APCVD reactor, device quality films were produced and a 10.6% AM1.5 cell was measured at NREL. Film structure as determined by electron microscopy is similar to that obtained by CSS and uniform film quality is obtained over an area of approximately 8 cm X 12 cm. Preliminary one dimensional (within the plane of the film) grain boundary modeling has been demonstrated using AMPS software. A team has been assembled to measure and analyze grain boundary effects in CdTe films and devices.

Planned FY 2001 Activities:
- Demonstrate 15% cell efficiency.
- Develop CdTe-specific two-dimensional model.
- Identify two-dimensional factors affecting device efficiency and demonstrate their effects through analysis of a working device.
- Demonstrate 50 cm^2 aperture area mini-module with 10% efficiency.

Major Reports Published in FY 2000:
P. Meyers, R. Kee, C. Wolden, J. Kestner, L. Raja, V. Kaydanov, T. Ohno, R. Collins, and A. Fahrenbruch, “Atmospheric Pressure Chemical Vapor Deposition of CdTe for High Efficiency Thin Film PV Devices”, 20p, NREL/SR-520-28375, Golden, CO: National Renewable Energy Laboratory.

Contract#: ZAK-8-17619-03

Major Articles Published in FY 2000:
P. Meyers and S. Albright, "Technical and Economic Opportunities for CdTe PV at the Turn of the Millenium", Prog. Photovolt: Res. Appl. **8**, 161-169 (2000).

P. Meyers, C. Wolden, J. Kestner, L. Raja, R.J. Kee, "Atmospheric Pressure Chemical Vapor Deposition of CdTe Films", Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK-520-28064, pp.269-270 (2000).

J. Kestner, C. Wolden, P. Meyers, L. Raja, and R. Kee, "Atmospheric Pressure Chemical Vapor Deposition of CdTe – First PV Devices", Proc. *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Thin-Film PV Partnership

In-Situ Sensors for Process Control of $CuInGaSe_2$

Contract#: ZAK-8-17619-08	**Contract Period:** 2/10/98–3/9/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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12441 W. 49th Ave., Suite #2
Wheat Ridge, CO 80033-1927</td><td>ITN Energy Systems
8130 Shaffer Parkway
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<tr><td>Organization Type: IN</td><td>Congressional District: 2</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
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Materials Research Group, Inc., ITN Energy Systems</td></tr>
<tr><td>DOE Funding Allocation:
1998: $90,000
1999: $120,000
2000: $130,000</td><td>Cost Share Funding:
1998: $10,000
1999: $13,333
2000: $14,410</td></tr>
</table>

Project Objective:
Yield and reproducibility issues must be resolved for thin-film $CuIn(Ga)Se_2$ modules to be manufactured at a price fulfilling the technology's low-cost potential. The purpose of this subcontract is to develop in-situ sensors to improve yield, reproducibility, and efficiency of thin-film $CuIn(Ga)Se_2$ (CIGS) modules.

Approach/Background:
In-situ x-ray fluorescence was developed to monitor composition and thickness of deposited layers, and in-situ optical emission spectroscopy has been evaluated as a source of real-time feedback describing deposition plasmas. X-ray fluorescence was examined ex-situ for the initial part of the subcontract, including the investigation of interpretation and equipment issues. Then, an x-ray fluorescence sensor was designed, built, and is currently installed and used in a production environment.

Status/Accomplishments:
A novel, relatively low-cost, x-ray fluorescence sensor was designed and is currently installed in production equipment at Global Solar Energy, LLC. In-situ operation to date indicates that the sensor is a useful indicator of film composition and thickness. Novel elements of the XRF hardware include protection of the sensor from the deposition environment, use of a sensor-to-sample distance appropriate to deposition chambers, and the use of only low-cost components operating at room temperature. Novel aspects of the XRF analysis include real-time CIGS analysis, one-sample calibration that gives valid results over a wide range of compositions, and compensation for variations in substrate location and x-ray tube current drift by using the substrate signal.

Planned FY 2001 Activities:
This program extends five months into FY2001. During that time, several upgrades will be made to the x-ray fluorescence sensor, including establishing maintenance procedures suitable to a production environment, and specifying design improvements for future generations of detectors. Also, a final report will be provided to NREL. This summary will describe the design and operation of the x-ray fluorescence sensor, evaluate the use of optical emission spectroscopy as a real-time sensor, and compare these sensors with others used for CIGS deposition.

Major Reports Published in FY 2000: none.

Major Articles Published in FY 2000:

I.L. Eisgruber, J.R. Engel, R.E. Treece, R.E. Hollingsworth, J. Britt, "In-Situ Measurements of Cu(In,Ga)Se2 Composition by X-Ray Fluorescence", *Proceedings of the 28th IEEE Photovoltaics Specialists Conference*, (2000).

I.L. Eisgruber, J.R. Engel, R.E. Treece, R.E. Hollingsworth, "Results from the Development of a Low-Cost, In-Situ, $CuIn_xGa_{1-x}Se_2$ Composition Sensor Based on X-Ray Fluorescence", *Proceedings of the 2000 National Renewable Energy Laboratory Program Review Meeting*, pp. 255-256, (2000).

High Efficiency, Stable Hot Wire CVD Prepared Amorphous and Polycrystalline Silicon Film Solar Cells

Contract #: ZAK-8-17619-16	**Contract Period:** 4/10/98–4/9/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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Golden, CO 80401</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
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<tr><td rowspan="2">Technical Monitor:
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E-mail: ken_zweibel@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
MVSystems Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $175,000
1999: $403,000
2000: $308,000</td><td>Cost Share Funding:
1998: $20,000
1999: $45,000
2000: $38,500</td></tr>
</table>

Project Objective:
The objective of this R&D contract is to develop a high quality amorphous and micro-crystalline (μc-) Si-based thin film alloy materials by Hot Wire Chemical Vapor Deposition and Pulsed Plasma PECVD techniques and use these materials to fabricate high efficiency PV devices. The goal at the end of the three-year program is to demonstrate (a) micro-crystalline Si solar cell with device efficiency greater than 10%, (b) amorphous silicon solar cell with an efficiency >9% with a gas utilization rate of 25% and a deposition rate of 7A/s using the pulsed plasma technique and (c) develop large area HWCVD depositions with an area of 30cmX30cm.

Approach/Background:
Hot Wire Chemical Vapor Deposition (HWCVD) technique is important because silicon films can be produced as either amorphous or polycrystalline depending on process conditions; the amorphous films have exhibited superior stability compared to PECVD films. A-Si:H solar cells with improved stability have been demonstrated by HWCVD, albeit at lower performance value in comparison with the PECVD approach. Micro-crystalline silicon (μc-Si) thin films in a solar cells configuration of moderate efficiency (approximately 4%) have been reported. MVS intends to explore the potential of the HWCVD deposition approach for both a-Si and μc-Si materials and their use in thin film silicon PV devices.

Pulsed plasma PECVD has shown promise since higher deposition rates can be obtained while at the same time dust emanating from the plasma can be suppressed. High deposition rates and solar cell performance without deterioration in the properties has now been demonstrated by MVS. The technique lends itself to inclusion into the conventional PECVD approach, as no fundamental changes are required. MVS is including this as an option in the sale of PECVD based cluster tools. MVS has already delivered several systems with this option.

Status/Accomplishments:
- Using the HWCVD technique, we have fabricated an amorphous silicon solar cell with conversion efficiency of 8.6%. No further work is contemplated for amorphous based devices.
- Large area HWCVD technique has been developed over an area of 30cmX30cm. No further work at this present time is contemplated as the objectives have been achieved.
- Using the HWCVD technique, we have fabricated proof of concept microcrysatlline Si solar cells, with an efficiency of 3.6%
- Using the Pulsed Plasma PECVD technique, we have developed state of the art amorphous silicon with a deposition rate >7A/s , gas utilization rate >25% . The substrate area was of 30cmX40cm. Uniformity was within +/- 10%.
- Using the Pulsed Plasma PECVD technique, we have fabricated devices of 0.25cm^2 area on substrates of area of 30cmX40cms and have achieved device efficiency >6%, with a gas utilization rate >20% and a deposition rate >7A/s.
- A cluster tool with PECVD and HWCVD was completed.

Contract #: ZAK-8-17619-16

Planned FY 2001 Activities:
- Develop the pulsed Plasma PECVD to achieve an amorphous silicon solar cell with an efficiency exceeding 9%, with a gas utilization rate >25%, and a deposition rate >7A/s.
- Work towards the goal of a uc Si solar cell with an efficiency of 10%.

Major Reports Published in FY 2000:
Second annual technical report submitted to NREL annual, April 2000.

Major Articles Published in FY 2000:
Deposition of device quality amorphous silicon films with a New Hot Wire CVD technique by Scott Morrison, W. Song, K . Coates and Arun Madan, NCPV meeting, p. 203, Denver, 2000.

Deposition of device quality amorphous and micro-crystalline Silicon films with a new Hot Wire CVD technique, by Scott Morrison and Arun Madan, presented at the 28th IEEE PVSC conference, Anchorage, Sept. 2000.

Deposition of device quality amorphous silicon solar cells via the Pulsed PECVD technique by Scott Morrison and Arun Madan, presented at the 28th IEEE PVSC conference, Anchorage, Sept. 2000.

An atomic force microscopy study of the topology of microcrystalline silicon surface by J.J. Gutierrez, D. Adama, C.E. Inlefield, M.C. Delong, P.C. Taylor, Scott Morrison and Arun Madan, APS meeting, Colorado, Oct. 2000.

Characterization of Small Particle Formation in the Preparation of Amorphous Silicon Solar Cells and Determination of the Electric Field Profile in Solar Cells Using Scanning Tunneling Microscopy

Contract #: DAD-8-18653-01	**Contract Period:** 7/1/98–8/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	National Institute of Standards and Technology Boulder, CO, 80309-0440	
	Organization Type: FF	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Alan C. Gallagher **Phone**: 303-497-3936 **Fax**: 303-492-5235 **E-mail:** alang@jila.colorado.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $60,000 1999: $84,000 2000: $105,500	**Cost Share Funding:**

Project Objective: The objectives of this subcontract are to develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States. This will be carried out within the context of two of the research and developments sub-Teams established by the NREL/EPRI Thin Film Partnership. Project Objective: This work will (1) support the National Amorphous Silicon Team with expertise relating to film growth phenomena and nano-size particle formation during deposition of a-Si:H films, and (2) employ a new scanning tunneling microscope (STM) spectroscopic technique to measure the electric field profile in thin-film solar cells. Ultimately the goal of the Amorphous Silicon Team is to achieve 15% stable thin-film modules by 2005.

Approach/Background: Silicon particles inadvertently form within discharges, and deposit into growing a-Si:H films. Measure particle size and density within the discharge and on the substrate, and use this data to model particle growth and escape to the film. The losses in cells occur within many layers and interfaces, and are hard to measure individually. We will measure the apparent potential (AP) versus depth within a cleaved single, tandem and triple cell made from a-Si:H and its alloys.

Status/Accomplishments: We have measured particle growth versus discharge operating time, pressure and power in silane rf discharges, of the type utilized for a-Si:H photovoltaic (PV) deposition. These measurements have elucidated the critical early stages of small particle growth, and the escape of these small particles to the substrate. A full plasma physics and chemistry model has been developed to obtain a more complete understanding of this early particle growth. While some of the particle-growth chemistry is still uncertain, this model fits the data quite well and explains the causes of particle escape and incorporation into the growing PV films. Temperature variations and gradients have a profound effect on particle behavior in the deposition discharges. We have initiated measurements of these influences, which hold promise for controlling particle incorporation into films, for particles greater than 1-2 nm size. These mechanisms can influence initiation of crystallization as well as the properties of amorphous films.

Planned FY 2001 Activities: We will continue to investigate the role of varying but spatially-uniform temperatures, and of temperature gradients, on particle growth and incorporation into films. We may also investigate the plasma conditions that yield crystalline versus amorphous silicon particles. Together with the authors, we have been analyzing the negative-ion growth experiments of Hollenstein and Howling, as these elucidate the causes of the crucial initial cluster growth (from 1-50 Si atoms) in a plasma. Several complications of the experiments require detailed modeling analysis, and these will be developed further to clarify how this growth chemistry occurs and thus how it influences all deposition discharges.

Major Articles Published in FY 2000:

M.A. Childs and A. Gallagher, Small particle growth in silane radio-frequency discharges, *J.Appl. Phys*.**87**,1076-85 (2000).

M.A. Childs and A. Gallagher, Plasma charge-density ratios in a dusty plasma, *J. Appl. Phys*. **87**, 1086-90 (2000).

A. Gallagher, Model of particle growth in silane discharges, *Phys. Rev. E* **62**, 2690-2706 (2000).

Thin Film PV Partnership

Project Management

Contract#: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $670,000
2000: $1,200,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objectives:

- To support the near-term transition to first-time manufacturing and scale-up of thin film a-Si, CIS, CdTe, and film Si;
- To build a technology base upon which these advanced PV technologies can (1) successfully improve manufacturing and (2) continue to progress in terms of performance, reliability, and reduced cost for products meant to compete in the PV marketplace; and
- To sustain innovation to support progress toward ambitious long-term PV cost and performance goals (i.e., 15% modules @ under $\$50/m^2$ and capable of lasting 30 years).

Approach/Background:

FY2000 Research Tasks within the Partnership's National R&D Teams

National Team	FY2000 Major Tasks
CIS	Improved Manufacturability, Lower-Temperature CIGS Deposition on Polyimide, Addition of Sulfur to CIS Made by Selenization, Module Transients and Stability, Two-Junction, CIS-Based Cells
a-Si	Improved Multijunction Efficiencies, Improved Stability, Low-Band Gap Alternatives, Increased Deposition Rates without Loss of Performance
CdTe	Contacts, Thin CdS (improved efficiency), and Cell and Module Stability Testing and Protocols
ES&H	Module Recycling, In-Plant Waste Handling, Toxicity Guidelines, Greenhouse gas reduction

Status/Accomplishments:

Thin films have evolved from laboratory curiosities to a set of technological options with great promise for reaching the long-term DOE and NCPV goals for low cost. Each year, we face familiar challenges: making more efficient cells; making more efficient prototype modules; discovering and optimizing processes for reproducibility and lower cost; assuring scale-up to successful pilot production of new devices and processes; examining cells and modules for degradation mechanisms and optimizing them for stability; developing and implementing new characterization schemes for films, devices, and processes; and maintaining our ongoing commitment to ES&H quality.

During FY2000, we faced challenges and made progress in each of these critical areas:

Prototype Module Efficiency:

A major advance during the year was the achievement of nearly 11% efficiency for a very large (8670 cm^2) CdTe module by BP Solar. This is the second very large module thin film to exceed this level (Siemens CIS is the other). It strengthened BP Solar's effort to commercialize CdTe.

Contract#: DE-AC36-98-GO10337

Status/Accomplishments (continued):

Processes:

In amorphous silicon, speeding up in-line deposition is one of the most critical needs. Both United Solar and BP Solar made progress on this front. United Solar made 10% efficient cells at 6 angstroms/s, about triple prior deposition rates. BP Solar experimented with 3 angstroms/s in their manufacturing line, tripling the prior rate. BP also made progress in terms of reducing materials costs. They improved of germane and silane utilization substantially.

Pilot Production:

All technologies made progress in pilot production and first-time manufacturing. In the most mature technology, amorphous silicon, both BP and USSC added production volume, reaching nearly capacity at their first plants. In addition, United Solar announced a major new facility, 25 MW capacity, to be built in Troy, MI. CdTe followed with some similar progress. BP Solar is finishing shakedown tests of their 5 MW facility in California. Meanwhile, First Solar built and is doing shakedown tests on their 100-MW facility in Toledo, OH. In CIS, both Siemens and Global Solar produced the first commercial CIS modules from their pilot production plants. For the first time ever, all three of these thin films had commercial modules.

Degradation Mechanisms and Stability:

Although a proof-of-concept of inherent stability (except for initial degradation in amorphous silicon) exists for cells and some modules in all the thin films, assuring long-term outdoor reliability is another matter. Module design is a critical factor. But another more subtle one is reproducibility of manufacturing. If the product varies, even slightly, from run to run, then perhaps module stability may vary as well with certain sensitive and sometimes unknown parameters. Efforts were ongoing this year in meeting these challenges.

In summary, FY2000 was an important year, because each of the major thin film options made progress toward successful manufacturing and commercialization. This is an important step in their development and a real transition from the curiosities they once were.

Planned FY 2001 Activities:

During FY2001, we will re-compete the Thin Film Partnership. Current three-year contracts are coming to an end. We expect to release the LOI in the Spring and have the first contracts signed by August 2001.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

H. Ullal, B. Von Roedern, K. Zweibel, "Polycrystalline Thin Film PV Technologies," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

K. Zweibel, "Thin film PV manufacturing: materials costs and their optimization," *Solar Energy Materials and Solar Cells.* **63**, 375 (2000).

CIS and CdTe Based Tandem Solar Cell Studies using AMPS

Contract #: XAF-8-17619-35	**Contract Period:** 10/15/98–2/14/02

<table>
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<tr><td>Directing Organization:
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1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
S.J. Fonash
Phone: 814-865-4931 Fax: 814-865-3018 E-mail: sfonash@psu.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
Phone: 303-384-6480
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E-mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
EPRI (“Special Topic”)</td></tr>
<tr><td>DOE Funding Allocation:
1999: $50,000
2000: $46,567</td><td>Cost Share Funding:
1999: $50,000</td></tr>
</table>

Project Objective: To provide modeling support for the Thin-Film Partnership’s CIS and CdTe PV cell and module development effort using the “AMPS” code previously developed at Penn State University.

Approach/Background: The model will be used to understand the performance limiting mechanisms of polycrystalline solar cells. Penn State will assist with the development of realistic parameter sets used for modeling. Specific emphasis is on assessing the performance of tandem polycrystalline solar cells, where the model is use to predict the performance of multijunction devices based on data obtained on component cells.

Status/Accomplishments: Work was focussed on identifying the factors limiting the performance of CIGS solar cells. The impact of the CdS/interface layer was quantified and the most sensitive bulk and interface parameters were established. It was found that the same percentage of change in certain material parameters in the interface region can have stronger effects on the efficiency than a corresponding change in the bulk region.

Planned FY 2001 Activities: Continue modeling support for CIGS solar cells to understand transient phenomena, the effect of Ga-alloying, and the effect of interface layers. Effort had to be curtailed due to loss of EPRI funding.

Major Reports Published in FY 2000:
Phase 1 Annual Report (unpublished)

Major Articles Published in FY 2000:
H. Zhu, J.D. Cuiffi, and S. Fonash, “AMPS Determination of Key CIGS Solar Cell Material Properties,” *NCPV Program Review Meeting 2000,* April 16-19, 2000, Denver, CO, BK–520-28064, pp.231-232.

Thin Film PV Partnership

Stable a-Si:H Based Multijunction Solar Cells with Guidance from Real Time Optics

Contract #: XAF-8-17619-22	**Contract Period:** 7/17/98–11/16/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	The Pennsylvania State University University Park, PA 16802 **Organization Type**: CU	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Christopher R. Wronski **Phone:** 814-865-0930 **Fax:** 814-863-5341 **E-mail:** crwece@engr.psu.edu	 Robert W. Collins **Phone:** 814-865-3059 **Fax**: 814-865-2326 **E-mail:** rwc6@psu.edu
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $175,000 1999: $159,000 2000: $232,701	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The objectives of this subcontract are to: (i) develop a cost-effective amorphous silicon PV technology, (ii) foster a viable amorphous silicon PV industry in the United States, and (iii) help the U.S. amorphous silicon PV industry to be competitive. These objectives will be met by enhancing performance, stability, and cost-efficiency, e.g., by using higher deposition rates. An important aspect of this effort is to improve the understanding of the details of all mechanisms that limit device performance. The advantages of using new materials preparation and processing schemes, material and device characterization schemes, and device and optical modeling schemes will be documented.

Approach/Background: The approaches that will be adopted to meet these objectives include: (i) the development of preparation and processing schemes for the fabrication of high performance, high stability a-Si:H based multijunction solar cells, applying insights deduced from real time optics and (ii) the detailed characterization and modeling of materials and device structures. In this way, the solar cells will be improved as a result of a fundamental understanding rather than through trial-and-error.

Status/Accomplishments: Real-time spectroscopic ellipsometry (RTSE) and atomic force microscopy (AFM) were used to obtain a broader picture of the previously-established phase diagram for Si:H prepared by plasma-enhanced chemical vapor deposition (PECVD). The phase diagram was extended to include four different growth regimes: (i) a-Si:H with a stable, smooth surface, (ii) a-Si:H with an unstable, rough surface, (iii) mixed-phase (a+μc)-Si:H, and (iv) fully-coalesced (single-phase μc-Si:H) A large parameter space was explored to describe each Si:H phase diagram, specifically including wide ranges of hydrogen dilution values R=$[H_2]/[SiH_4]$ and film thicknesses d_b. In addition, the effect on the phase diagram of an increased rf power was explored in order to establish the nature of films prepared at higher deposition rates. The phase diagrams provided a new understanding of the effect of substrate on subsequent film growth, and the consequent shifting of the phase boundaries were observed for different substrates. Finally, it was demonstrated how such phase diagrams are effective in guiding the deposition of i-layer materials by defining a "window" in which protocrystalline materials with smooth, stable surfaces are obtained.

Systematic studies were carried out correlating the data obtained from RTSE and AFM measurements on these i-layer materials with the corresponding cell structures. The effects of the thickness-dependent phase transitions from a-Si:H to μc-Si:H in the bulk intrinsic layers of p-i-n cells, as well as near the p/i interface, were characterized and quantified. Self-consistent numerical simulation of the cell characteristics of such structures confirmed a change in mobility gap at the a-to-μc transition thicknesses as determined from RTSE and AFM results on films. Having established the requirements for obtaining high-quality materials, studies were carried out on protocrystalline p-i-n and n-i-p structures to establish the nature of the p/i interface and to quantify the contributions of the interface and bulk regions to various solar cell characteristics. It has been demonstrated that a maximum 1 sun V_{oc} for a given bulk material can be correctly extrapolated from bulk dominated J_{sc}-V_{oc} characteristics at low illumination intensities.

Contract #: XAF-8-17619-22

Detailed studies were also carried out on kinetics of light-induced changes on materials deposited by several different institutions: BP Solar, United Solar, Electrotechnical Laboratory, and Penn State University. These studies were carried out at different temperatures (25°C - 100°C) and under 1 sun illumination to a degraded steady state. The significant change in degradation kinetics at different temperatures, combined with the lack of systematic correlation between photoconductivity, subgap absorption, and ESR spin density, indicates that recombination processes cannot be interpreted solely in terms neutral dangling bond defects. The results indicate that the contribution from other defects such as charged defects must be taken into account if meaningful evaluation is to be made of the characteristics of solar cells that incorporate these materials.

Planned FY 2001 Activities: The parameter space within which high quality amorphous and protocrystalline Si materials is obtained will be further explored. The phase diagram concept will be extended to include a wider scope of materials, including those deposited at different temperatures, power densities, reactive gas partial pressures, and excitation frequencies. In all cases, material properties will be correlated with cell characteristics in an effort to develop novel higher stability, efficient solar cell structures. To extend this work, a theoretical mechanism will be developed to provide insights into light-induced defects in a-Si:H. Concurrent device modeling and optical modeling of materials will be carried out to provide a clearer understanding of results. The previously-developed phase diagram for doped amorphous and microcrystalline Si:H films will also be extended and used to guide the optimization of n-i-p cells. In this effort, the limitations imposed on the open-circuit voltage will be elucidated, and the designs for improved tunnel-recombination junctions will be established for multijunction cells. In light of recent studies, it is not clear that the optimum doped layers are prepared in the coalesced single-phase μc-Si:H region of the phase diagram. In particular, protocrystalline doped layers will be developed, studied, and incorporated into devices.

Major Reports Published in FY 2000:
Phase 1 Annual Report, "Stable a-Si:H Based Multijunction Solar Cells with Guidance from Real Time Optics," NREL/SR-520-28809 (August 2000).

Major Articles Published in FY 2000:
Joohyun Koh, A.S. Ferlauto, P.I. Rovira, C.R. Wronski, and R.W. Collins, "Evolutionary Phase Diagrams for Plasma-Enhanced Chemical Vapor Deposition of Silicon Thin Films from Hydrogen-Diluted Silane," *Appl. Phys. Lett.* **75**, 2286 (1999).

R. J. Koval, J. Koh, Z. Lu, L. Jiao, R. W. Collins, and C.R. Wronski, "Performance and Stability of Si:H p-i-n Solar Cells with i Layers Prepared at the Thickness-Dependent Amorphous-to-Microcrystalline Phase Boundary," *Appl. Phys. Lett.* **75**, 1553 (1999).

R. J. Koval, J. Koh, Z. Lu, Y. Lee, L. Jiao, R.W. Collins, and C.R. Wronski, "Kinetics of Light-Induced Changes in P-i-n Cells with Protocrystalline Si:H," Materials Research Society Symposium Proceedings **557**, 263 (1999).

A.S. Ferlauto, J. Koh, P.I. Rovira, C.R. Wronski, and R.W. Collins, "Microcrystalline Silicon Tunnel Junctions for Amorphous Silicon-Based Multijunction Solar Cells," Materials Research Society Symposium Proceedings **557**, 579 (1999).

Z. Lu, L. Jiao, R.J. Koval, R.W. Collins, and C.R. Wronski, "Characteristics of Different Thickness a-Si:H/Metal Schottky Barrier Cell Structures—Results and Analysis," Materials Research Society Symposium Proceedings **557**, 785 (1999).

R. W. Collins, J. Koh, A.S. Ferlauto, P.I. Rovira, Y. Lee, R. J. Koval, and C. R. Wronski, "Real Time Analysis of Amorphous and Microcrystalline Silicon Film Growth by Multichannel Ellipsometry," *Thin Solid Films* **364**, 129 (2000).

R.W. Collins, J. Koh, H. Fujiwara, P.I. Rovira, A.S. Ferlauto, J.A. Zapien, C.R. Wronski, and R. Messier, "Recent Progress in Thin Film Growth Analysis by Multichannel Spectroscopic Ellipsometry," *Applied Surface Science* **154**, 217 (2000).

A.S. Ferlauto, J. Koh, P.I. Rovira, C.R. Wronski, and R.W. Collins, "Modeling the Dielectric Functions of Silicon-Based Films in the Amorphous, Nanocrystalline, and Microcrystalline Regimes," *Journal of Non-Cryst. Solids* **266-299**, 269 (2000).

J. Koh, A.S. Ferlauto, P.I. Rovira, R.J. Koval, C.R. Wronski, and R.W. Collins, "Evolutionary Phase Diagrams for the Deposition of Silicon Thin Films from Hydrogen-Diluted Silane," *Journal of Non-Cryst. Solids* **266-299**, 43 (2000).

J. M. Pearce, R. J. Koval, A.S. Ferlauto, R. W. Collins, C. R. Wronski, J. Yang, and S. Guha, "Dependence of Open Circuit Voltage in Protocrystalline Si:H Solar Cells on Carrier Recombination in p/i Interface and Bulk Regions", *Appl. Phys. Lett.* **77,** 3093 (2000).

C. R. Wronski, L. Jiao, R. Koval, and R. W. Collins, "Recent Advances in Understanding of a-Si:H Based Materials and Performance of Their Solar Cells," Opto-electronic Reviews **8**, (in press).

Optimization of Transparent and Reflecting Electrodes for Solar Cells

Contract #: XAK-8-17619-26	**Contract Period:** 4/15/98–8/14/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	President and Fellows of Harvard College Office of Sponsored Research Holyoke Center 440 Cambridge, MA 02138	
	Organization Type: CU	**Congressional District:** 10
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** R. Gordon **Phone:** 617-495-4017 **Fax:** 617-495-4723 **E-mail:** gordon@chemistry.harvard.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $ 86,000 2000: $166,700 1999: $179,000	**Cost Share Funding:**

Project Objective: The objectives of the program are to develop new higher performance, lower cost transparent conductor layers and diffusion barriers for thin-film solar cells, and to work with manufacturers to scale up their deposition processes for commercial production.

Approach/Background: Atmospheric pressure chemical vapor deposition (APCVD) is a cost-effective process already being used in the production of transparent conductive oxide (TCO) layers in thin-film solar cells. Higher optical transparency and lower electrical resistance of these layers will lead to higher efficiency cells. Diffusion barriers between soda-lime glass and the TCO may also lower its electrical resistance. Efficiency may also be increased by placing buffer layers with high electrical resistance between the TCO and the absorbing layers of a cell.

Status/Accomplishments: The CVD process for zinc stannate developed during the last contract period was improved to provide films with high transparency to visible light and low carbon content. The ratio of zinc to tin in the films was found to increase with distance from the gas inlet to the CVD reactor.

Amorphous silicon solar cells grown on fluorine-doped zinc oxide superstrates showed about 10% higher current collection compared to standard fluorine-doped tin oxide superstrates. However, difficulties were encountered in reproducing high fill factors and in reducing shunts.

Commercial production began for a precursor for CVD of amorphous aluminum oxide that was discovered during a previous NREL contract period. Use of CVD amorphous aluminum oxide as a sodium diffusion barrier between soda-lime glass and fluorine-doped zinc oxide increased its conductivity by about 10%.

Planned FY 2001 Activities:
- Improve the uniformity of the stoichiometric ratio of zinc to tin in CVD zinc stannate films. Assess the potential for using APCVD zinc stannate films in solar cells.
- Reduce the incidence of shunts in amorphous silicon solar cells grown on fluorine-doped zinc oxide and improve the reproducibility of the fill factors.
- Evaluate the diffusivity of sodium through CVD amorphous aluminum oxide films.

Major Reports Published in FY 2000: Phase II Annual Report (unpublished)

Major Articles Published in FY 2000:
R. G. Gordon, “Criteria for Choosing Transparent Conductors,” Materials Research Society Bulletin 25, 52-57 (2000).

R. G. Gordon, K. Kramer and H. Liang, “Chemical Vapor Deposition of Fluorine-doped Zinc Oxide,” U. S. Patent 6,071,561 (2000).

R. G. Gordon, K. Kramer and H. Liang, “Chemical Vapor Deposition of Aluminum Oxide,” U. S. Patent 6,037,003 (2000).

Thin Film PV Partnership

Numerical Modeling as a Tool for Analyzing Thin-Film Solar Cells

Contract #: XAK-8-17619-36	**Contract Period:** 12/7/98–4/6/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Purdue University 1285 Electrical Engineering Building West Lafayette, IN 47907-1285	
	Organization Type: CU	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J.L. Gray **Phone:** 765-494-3390 **Fax:** 765-494-3393 **E-mail:** grayj@ecn..purdue.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $37,000 2000: $31,967	**Cost Share Funding:**

Project Objective: To provide modeling support for the Thin-Film Partnership's CIS and CdTe PV cell and module development effort using the ADEPT (A Device Emulation Program and Tool) code previously developed at Purdue University.

Approach/Background: A simulation code, ADEPT, previously developed at Purdue University will be used to simulate CIS and CdTe solar cells. Emphasis is on developing a user-friendly interface and on integrating the various versions of ADEPT developed over time at Purdue University. Specifically, these versions include capabilities for modeling 2D and 3D structures, complex recombination and trapping mechanisms, and the ability to model time dependent behavior, both transient and sinusoidal steady-state. The integration of these versions will allow not only the simulation of cell performance, but of a variety of electronic and optical characterization measurements, as well. The software platform chosen for this integration is MatLab^{TM}, which will allow for relatively easy customization of "ADEPT" for specific applications.

Status/Accomplishments: Several steps needed for the integration of the various versions of "ADEPT" into a common MatLab^{TM} framework (i.e. MatLab^{TM} toolbox) have been accomplished. An input file parser has been written for MatLab^{TM} so that input files from a previous version of ADEPT (written in FORTRAN) can be used. A new 2D discretization method, based on the 1D Scharfetter-Gummel discretization has been formulated. Also, a preliminary parameter study of the effect of several properties of the interface in CdS/CdTe solar cells has been completed. Work is progressing towards integrating the various versions of ADEPT (written in both C and FORTRAN) into the MatLab^{TM} environment. Some code is being translated in to MatLab^{TM} script, while other routines will be called directly from MatLab^{TM}.

Planned FY 2001 Activities: Development of the MatLab^{TM} toolbox will continue, with a beta version of the MatLab^{TM} ADEPT toolbox expected to be released early in 2001. Testing and refinement of the new 2D discretization method will also continue and work to extend it to 3D will begin. 2D simulations will be used to investigate models of grain boundaries. ADEPT will be used to model sevveral types of characterization measurements employed to examine the properties of CIS and CdTe solar cells.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Thin Film PV Partnership

Photocharge Transport and Recombination Measurements in Amorphous Silicon Films and Solar Cells by Photoconductive Frequency Mixing

Contract #: XAK-8-17619-24	**Contract Period:** 4/20/98–8/19/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Jeffrey Mazer **Phone**: 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Regents of the University of California 405 Hilgard Ave. Los Angeles, CA 90024-1406 **Organization Type**: CU	**Congressional District**: 29
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Braunstein, R. **Phone:** 310-825-1841 **Fax:** 310-206-5668 **E-mail:** braunstein@physics.ucla.edu	
Technical Monitor: JB. von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $43,500 2000: $44,300	**Cost Share Funding:**

Project Objective: The objective of this project is to directly measure the transport properties of amorphous silicon layers used in solar cells and to improve the understanding how these properties change under light-soaking and as the deposition conditions are altered.

Approach/Background: By employing our well established photomixing technique, analysis of the transport properties of amorphous silicon layers and devices are performed. The deduction of the transport parameters directly from photomixing measurements will be attempted. UCLA will work on improving the theories of transport phenomena in disordered materials. Films of interest to the NREL/EPRI amorphous silicon team will be measured and light-soaked as needed. The photomixing measurements enable one to determine the drift mobility and lifetime of electrons. In addition, the electric field dependency of the drift mobility enable us to determine the range and the depth of the long range potential fluctuations that determine the transport properties under annealed and light soaked conditions.

Status/Accomplishments: Employing the above photomixing technique, the following topics were explored with the indicated results:

- Photomixing measurements were performed on a-Si:H samples prepared by the "uninterupted′ growth / annealing method" supplied by Guanglin Kong of the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China. These samples were prepared by varying the substrate temperature at a constant SiH_4.
- Initial photomixing experiments on single films with coplanar and perpendicular contact geometry allowed a measurement of the relative mobility in the respective geometries..
- Comparison of the initial transport properties of films and devices subsequently fabricated from the initial films show that the photomixing results on both structures scale with each other.
- Charge transport properties in the transition from amorphous to microcrystalline produced by MV Systems. show the effect of the transition from amorphous to microcrystalline structure on the transport properties.
- Hydrostatic pressure dependence of charge transport measured by photomixing show an elastic and an inelastic effect of pressure on the transport properties of a-Si:H.
- Photoconductivity measurements on TCO reveal a dc photoresponse; however the conductivity of the films were too high to apply a sufficient bias for the determination of the mobility by photomixing.

Contract #: XAK-8-17619-24

Planned FY 2001 Milestones:

- High deposition rate prepared a-Si:H by HWCVD will be studied: transport properties in both the annealed and light soaked states will be measured to study the effect of deposition rate with respect to substrate temperature, deposition pressure and silane flow rate. Samples prepared at different times will be studied.
- Charge transport properties near and above the transition from amorphous to microcrystalline silicon (MV Systems Inc.) will be studied with respect to filament temperature and H-dilution.
- Transport properties of HWCVD produced a-SiGe:H (0%-40% Ge).will be studied on NREL samples.
- Transport properties of PECVD a-SiGe:H (0%-40%Ge) on samples provided by BP Solar.will be studied.
- Transport properties of low bandgap a-(Ge,Si) H alloys across the entire range of Ge concentration (0-100%Ge) will be studied on samples which have been prepared using low pressure, reactive ECR plasma deposition with high H dilution and ppm B-doping supplied by Vik Dal.
- Photomixing measurements on microcrystalline films deposited by the Pulsed PECVD technique with varying amounts of hydrogen dilution, and substrate temperature produced by MV SYSTEMS Inc. will be studied.

Major Reports Published in FY 2000: Phase II Annual Report, draft received.

Major Articles Published in FY 2000:

A. Kattwinkel, R. Braunstein, and Q. Wang, "Transition from Hydrogenated Amorphous Silicon to Microcrystalline Silicon" MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999).

.J. Liebe , A. Kattwinkel, K.Baerner, G. Sun, S. Dong, R.Braunstein, "Determination of the Gap Density Differences in Hydrogenated Amorphous Silicon and Si/Ge," Materials Science and Engineering A282(2000) 158-163.

S.R.Sheng, G. Sun., J.Liebe, A.Kattwinkel, R.Braunstein, B.P.Nelson, B. von Roedern, K. Baerner, "Electronic Properties of Hydrogenated Amorphous Silicon-Germanium Alloys and Long-Range Potential Fluctuations":submitted to Materials Science and Engineering A.

Thin Film PV Partnership

Commercialization of CIS-Based Thin-Film PV

Contract #: ZAK-8-17619-19	**Contract Period:** 9/25/98–11/24/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Siemens Solar Industries 4650 Adohr Lane Camarillo, CA 93010	
	Organization Type: IN	**Congressional District:** 23
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dale E. Tarrant **Phone:** 805-388-6328 **Fax:** 805-388-6580 **E-mail:** dalet@solar.siemens.com	
Technical Monitor: H.S. Ullal **Phone:** 303-384-6486 **Fax:** 303-384-6430 **E-mail**: harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Siemens Solar Industries
	DOE Funding Allocation: 1999: $795,354 2000: $917,823	**Cost Share Funding:** 1999: $795,353 2000:$917,824

Project Objective: The primary objectives of this subcontract are to scale-up substrate size and to increase production capacity of the baseline SSI CIS-based module process while introducing SSI's first CIS-based products. An additional mid- to longer-term objective is to advance CIS based thin-film technology thereby assuring future product competitiveness by improving module performance, cost per watt produced, and reliability. These combined objectives are pursued to fabricate efficient and stable thin-film modules made by scaleable, manufacturable, low-cost techniques.

Approach/Background: SSI is applying systematic research, development, production and business methodologies to a carefully planned substrate size and capacity scale-up of CIS-based thin-film technology. These methodologies include Statistical Process Control (SPC), Analysis of Variation (ANOVA), and Design of Experiments (DOE) --- approaches widely recognized as appropriate for manufacturing businesses. SSI is also conducting research and development on longer-term issues in support of SSI's ongoing commitment to improve this technology. SSI is independently and in conjunction with TFPPP team activities pursuing improved understanding of processes, devices, and materials. SSI's role in advancing mid- to longer-term CIS technology emphasizes issues related to commercialization of CIS technology and assured future product competitiveness.

Status/Accomplishments: Siemens Solar is the first company in the world to start production of PV modules based on CIS thin-film technology. This is a major milestone in the development of PV. First available as 5-Watt and 10-Watt modules in 1998, R&D Magazine recognized the significance of this event by awarding the prestigious R&D 100 Award to the Siemens Solar family of CIS solar modules. This award is shared by NREL, the California Energy Commission and SSI.

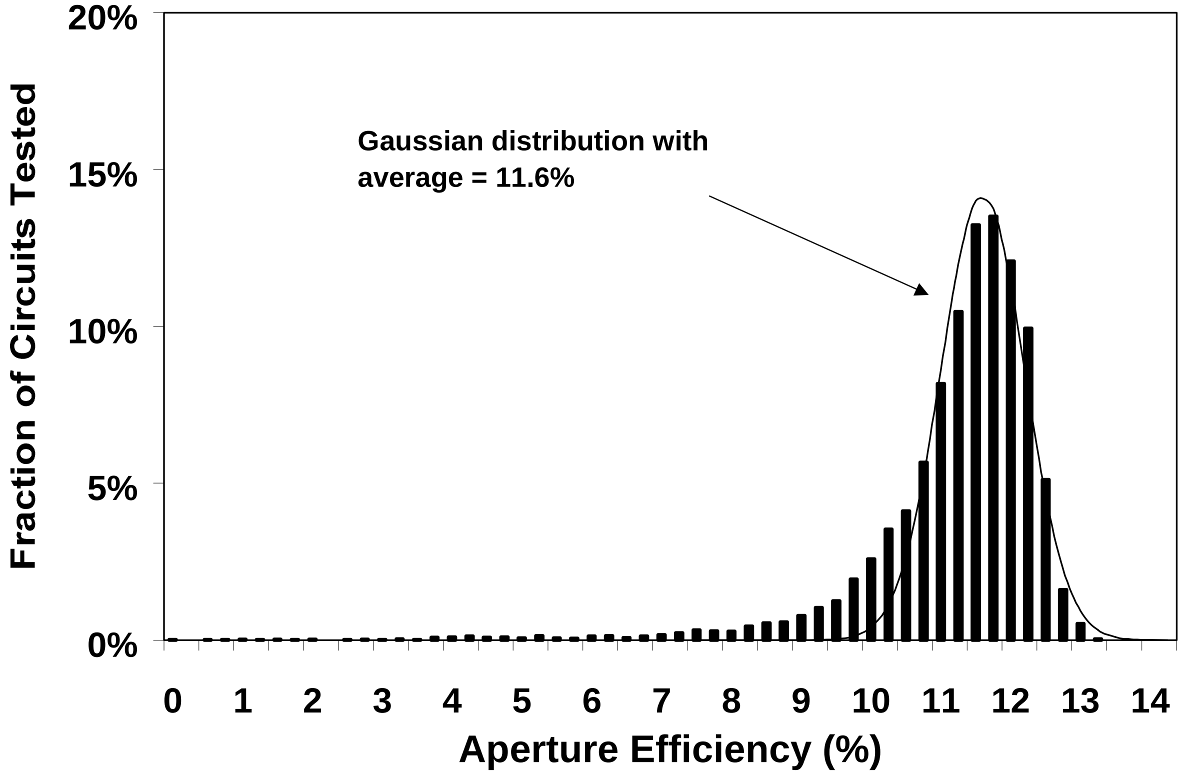
Deliverables for the first subcontract phase were defined as 900-cm^2 (~1-ft^2) CIS-based commercial modules with AM 1.5 aperture-area efficiency of 10%. The specification for these commercial modules is most closely matched by the 10-Watt "ST10" module. However, activities during the first subcontract period led to the availability of larger commercial products with higher efficiencies than anticipated at the time the deliverables were defined. SSI expanded the CIS product line in 1999 to include 20-Watt "ST20" modules and 40-Watt "ST40" modules. Samples of these commercial products were delivered to NREL during the first subcontract phase. Also during the first subcontract phase, a record breaking efficiency of more than 12% was verified by NREL for an ST-40 module. Achieved in advance of DOE milestone for the year 2000, SSI accomplishments demonstrate that CIS meets and should continue to meet the DOE goals.

During this subcontract phase, SSI delivered 20 ST-40 large area modules all with efficiencies over 11% to meet the defined subcontract deliverables of large area modules with efficiencies of over 10%. Also during this subcontract period, the average efficiency based on a Gaussian fit to the main portion of the circuit plate efficiency distribution has increased from 10.8% prior to this subcontract to 11.6% for this subcontract period (figure below). This improvement is particularly notable since it was achieved along with an over 300% increase in production volume.

No one major process improvement is responsible for this demonstrated increase in average efficiency accomplished while simultaneously increasing volume. Instead, these advancements are due to continuous improvement of all process along with particular attention during this subcontract phase to process research for two critical processes – CIS formation in new large area reactors and the quality of molybdenum deposited in new high capacity sputtering equipment. Judicious application of manufacturing engineering disciplines (statistical process control, analysis of variation and design of experiments) has led to a clear definition of near term yield issues. Process development has improved adhesion, decreased breakage, addressed control of raw materials, and decreased failures associated with patterning.

Contract #: ZAK-8-17619-19

Further R&D of CIS processes for part size and capacity scale-up with particular emphasis on the CIS formation process will be critical for near-term and long-term advancements. Remaining R&D challenges are to scale processes to even larger areas, to reach higher production capacity, to demonstrate in-service durability over even longer times, and to advance the fundamental understanding of CIS-based materials and devices with the goal of further efficiency improvements for future products.



Planned FY 2001 Activities: The primary goals of this subcontract are to scale the substrate size from approximately 900 cm^2 (~1 ft^2) to approximately 4000 cm^2 by the middle of the Phase II, and to achieve pilot production rates of 500 kW per year by the end of Phase III. Deliverables for the subcontract include CIS-based products and representative modules delivered to the NREL Module Testing Team for outdoor testing and evaluation. SSI will continue mid-term and longer-term thin-film R&D with the goals of:

- Assuring future product competitiveness
- Improving module performance
- Reducing cost per watt
- Assuring product reliability

Major Reports Published in FY 2000:
D. Tarrant, R. Gay, "Thin-Film Photovoltaic Partnership Program – Commercialization of CIS-Based Thin-Film PV, Phase I Annual Technical Status Report," (June 2000) NREL/SR-520-28597.

Major Articles Published in FY 2000:
J. Ulfert Rühle and Robert D. Wieting, "Characterizing and Controlling Cu/(In+Ga) Ratio During CIS Manufacturing," 28th IEEE Photovoltaic Specialists Conference, Anchorage, Alaska, September 17-22, 2000.

P. Johnson, L. Olsen, K. Ramanathan, J. Sites, D. Tarrant, "Effects Of Buffer Layers On SSI CIGSS-Absorber Transient I-V And C-V Behavior," 28th IEEE Photovoltaic Specialists Conference, Anchorage, Alaska, September 17-22, 2000.

Robert R. Gay and Franz H. Karg, "Experience with Manufacturing CIS Products", Euroconference "Photovoltaic Devices: Thin Film Technology," Berlin (Teltow), Germany, March 31 - April 5, 2000.

Dale E. Tarrant and Robert R. Gay, "Early Experience with Manufacturing CIS Products," National Center for Photovoltaics, Program Review Meeting, April 16-19, 2000, Denver, Colorado.

Thin Film PV Partnership

Electroabsorption and Transport Measurements and Modeling Research in Amorphous Silicon Based Solar Cells

Contract #: XAK-8-17619-23	**Contract Period:** 3/24/98–7/23/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Syracuse University Department of Physics Syracuse, NY 13244-1130	
	Organization Type: CU	**Congressional District:** 25
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Eric A. Schiff **Phone:** 315-443-3901 **Fax:** 315-443-9103 **E-mail:** schiff@physics.syr.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $75,000 1999: $130,000 2000: $116,500	**Cost Share Funding:**

Project Objectives: The primary objective of this project is to improve the understanding of the open-circuit voltage of amorphous silicon based solar cells, for which the open-circuit voltages achieved to date are only about 60% of the electrical bandgap. Secondary objectives include determining ultimate limits to photocarrier transport in amorphous silicon based materials, and development of infrared electromodulation spectroscopy as a characterization technique for critical doped-layer interfaces in cells.

Approach/Background: This project involves an integrated program of experimental measurements, computer simulations, and analytical modeling directed at an understanding of the open-circuit voltage in amorphous silicon based solar cells. The experimental approach to understanding open-circuit voltages (V_{OC}) will emphasize built-in potential (V_{bi}) estimates using electroabsorption techniques. In conjunction with this experimental work a program of computer modeling emphasizing the open-circuit voltage will be carried through, with a particular emphasis on marrying the modeling with the best available parameters from experiments at Syracuse University and elsewhere. Transport measurements will emphasize determination of hole and electron drift-mobilities in advanced materials and devices using the photocarrier time-of-flight technique.

Status/Accomplishments: [A] A "thermionic emission" model was proposed for the effect of non-ideal doped layer interfaces upon the open-circuit voltage in amorphous silicon based cells. [B] Measurements of infrared spectrum due to doped layer interfaces in amorphous silicon cells were completed. The possibility of dopant complexing was evaluated, and the surprisingly large variability in the spectra for cells from different labs was documented. [C] Hole drift-mobilities in materials showing superior properties were studied.

Planned FY 2001 Activities: (i) Modeling studies seeking better understanding of the open-circuit voltage in a-Si:H based cells; (ii) Open-circuit voltages will be explored using polymer hole conductors instead of thin-film semiconductors as the *p*-layer; (iii) Hole drift-mobility measurements on samples of "edge" materials (amorphous silicon materials deposited very close to conditions yielding microcrystalline structure) will be measured; (iv) Infrared optical properties of interfaces will be further explored.

Major Reports Published in FY 2000:
E.A. Schiff, J. Lyou, N. Kopidakis, P. Rao, And Q. Yuan, "*Electroabsorption and Transport Measurements and Modeling Research in Amorphous Silicon Based Solar Cells,"* Phase I Annual Report, NREL/SR-520-27665 (December 1999)

Major Articles Published in FY 2000:
J.-H. Lyou, N. Kopidakis, E. A. Schiff, "Charge Modulation Spectra in Phosphorus-Doped a-Si:H," *J. Non-Cryst. Solids* **266-269**, 227-231 (2000).

N. Kopidakis and E. A. Schiff, "Hydrogen-mediated models for metastability in a-Si:H: role of dihydride bonding," *J. Non-Cryst. Solids* **266-269**, 415-418 (2000).

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Major Articles Published in FY 2000 (continued):

L. Jiang, J. H. Lyou, S. Rane, E. A. Schiff, Q. Wang, and Q. Yuan, “Open-Circuit Voltage Physics in Amorphous Silicon Solar Cells,” in *Amorphous and Heterogeneous Films – 2000*, edited by H. M. Branz, R. W. Collins, S. Guha, H. Okamoto, and M. Stutzmann (Materials Research Society, Symposium Proceedings Vol. 609, Pittsburgh, 2000), *in press.*

Kai Zhu, J. H. Lyou, E. A. Schiff, R. S. Crandall, G. Ganguly, S. S. Hegedus, “Interfacial Optical Spectra in Amorphous Silicon Based pin Solar Cells,” in *Proceedings of the 28th IEEE Photovoltaics Specialists Conference (Anchorage, September 2000)*, in press.

Thin Film PV Partnership

High-Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology

Contract#: ZAK-8-17619-09	**Contract Period:** 3/6/98–3/5/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	United Solar Systems Corp. 1100 West Maple Road Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** S. Guha **Phone:** 248-362-4170 **Fax:** 248-362-4442 **E-mail:** sguha@uni-solar.com	
Technical Monitor: K. Zweibel **Phone:** 303-384-6441 **Fax:** 303-384-6430 **E-mail**: ken_zweibel@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** United Solar Systems Corp.
	DOE Funding Allocation: 1998: $892,000 1999: $879,000 2000: $868,000	**Cost Share Funding:** 1998: $892,000 1999: $879,000 2000: $868,000

Project Objective: To obtain high efficiency amorphous silicon (a-Si) alloy multijunction cells and modules with low manufacturing cost and high reliability. The program goal is to obtain 12% stable modules that will qualify IEEE-Std 1262-1995 reliability testing.

Approach/Background: Using a spectral-splitting, triple-junction structure, we have achieved world-record stabilized total-area cell and aperture-area module efficiencies of 12.0% and 10.2%, respectively. We are also operating a production line with an annual capacity of 5 MW using the triple-junction approach. We shall further improve efficiency by optimizing the component cells of the triple-junction structure and lower manufacturing cost by depositing the cells at higher rates. We shall also carry out fundamental studies to improve our understanding of a-Si alloy materials and cells.

Status/Accomplishments:

1. *Fundamental Studies*

We have established that materials and solar cells made near the amorphous-to-microcrystalline transition exhibit better quality and stability. Optimum conditions for growing the material depend on the substrate on which the film is grown and also on the thickness of the film. This “on-the-edge” material has stirred much interest in the scientific community and stimulated many activities in the field.

2. *Cells Deposited at ~1 Å/s Using RF*

- Deposited single-junction top cells (~0.25 cm^2) on stainless steel substrates without back reflector using a-Si alloy at ~1 Å/s and achieved a total-area stabilized cell efficiency of 5.74% measured under global AM1.5 after 1020 hours of one-sun light soaking at 50^o C, the highest obtained for a top cell.
- Deposited single-junction middle cells (~0.25 cm^2) on stainless steel substrates without back reflector using a-SiGe alloy at ~1 Å/s and achieved a total-area stabilized power output of 3.94 mW/cm^2 measured under global AM1.5 with a λ>530 nm filter after 775 hours of one-sun light soaking with an appropriate filter at 50^oC, the highest obtained for a middle cell.
- Achieved V_{oc}>2 V in an a-Si/a-Si double-junction structure using “near transition” deposition conditions. The initial J-V characteristics are: V_{oc} = 2.018 V, J_{sc} = 6.43 mA/cm^2, FF = 0.746 and η = 9.68% for a total area of 0.268 cm^2.
- Achieved initial η = 11.1% in an a-Si/a-Si double-junction structure using “near transition” deposition conditions. The initial J-V characteristics are Voc = 1.958 V, Jsc = 7.70 mA/cm^2, and FF = 0.733 for a total area of 0.268 cm^2.

3. *Cells Deposited at ~3 Å/s Using RF*

- Deposited single-junction top cells (~0.25 cm^2) on stainless steel substrates without back reflector using a-Si alloy at ~3 Å/s and achieved a total-area stabilized cell efficiency of 4.7% measured under global AM1.5 after 1000 hours of one-sun light soaking at 50^oC.
- Deposited single-junction middle cells (~0.25 cm^2) on stainless steel substrates without back reflector using a-SiGe alloy at ~3 Å/s and achieved a total-area stabilized power output of 2.8 mW/cm^2 measured under global AM1.5 with a λ>530 nm filter after 1010 hours of one-sun light soaking with an appropriate filter at 50^oC.
- Deposited single-junction bottom cells (~0.25 cm^2) on optimized back reflector using a-SiGe alloy at 3 Å/s and achieved a total-area stabilized power output of 3.37 mW/cm^2 measured under global AM1.5 with a λ>630 nm filter after 1000 hours of one-sun light soaking with an appropriate filter at 50^oC, which exceeds the milestone of Phase III for a high rate bottom cell.
- Deposited triple-junction cells (~0.25 cm^2) on optimized back reflector at 3 Å/s and achieved a total-area stabilized efficiency of 10% measured by NREL after 1010 hours of one-sun light soaking at 50^oC.

4. *Cells Deposited at ~6-8 Å/s Using MVHF*

- Deposited single-junction top cells (~0.25 cm^2) on stainless steel substrates without back reflector using a-Si alloy at 6-8 Å/s and achieved a total-area stabilized cell efficiency of 5.39% measured under global AM1.5 after 1000 hours of one-sun light soaking at 50°C, which exceeds the milestone of Phase III for a high rate top cell.
- Deposited single-junction middle cells (~0.25 cm^2) on stainless steel substrates without back reflector using a-SiGe alloy at 6-8 Å/s and achieved a total-area stabilized power output of 2.88 mW/cm^2 measured under global AM1.5 with a λ>530 nm filter after 1000 hours of one-sun light soaking with an appropriate filter at 50°C.
- Deposited single-junction bottom cells (~0.25 cm^2) on optimized back reflector using a-SiGe alloy at 6-8 Å/s and achieved a total-area stabilized power output of 2.6 mW/cm^2 measured under global AM1.5 with a λ>630 nm filter after 1000 hours of one-sun light soaking with an appropriate filter at 50°C.
- Deposited triple-junction cells (~0.25 cm^2) on optimized back reflector at 6-8 Å/s and achieved a total-area initial efficiency of 10.2% measured under global AM1.5 spectrum.

5. *Large-area Module Research*

- Deposited array of single-junction top cells (~0.268 cm^2) on stainless steel substrates without back reflector using a-Si alloy over areas greater than 900 cm^2 and achieved an average total-area stabilized cell efficiency measured under global AM1.5 of 5.5% after 1000 hours of one-sun light soaking at 50°C, exceeding the Phase III milestone.
- Deposited array of single-junction middle cells (~0.268 cm^2) on stainless steel substrates without back reflector using a-SiGe alloy over areas greater than 900 cm^2 and achieved an average total-area stabilized power output measured under global AM1.5 with λ>530 nm filter of 3.7 mW/cm^2 after 1655 hours of one-sun light soaking with an appropriate filter at 50°C.
- Deposited array of single-junction bottom cells (~0.268 cm^2) on optimized back reflector substrates using a-SiGe alloy over areas greater than 900 cm^2 and achieved an average total-area stabilized power output measured under global AM1.5 with λ>630 nm filter of 3.4 mW/cm^2 after 1076 hours of one-sun light soaking with an appropriate filter at 50°C.
- Deposited array of triple-junction cells (~0.268 cm^2) on optimized back reflector substrates using optimized component cells over areas greater than 900 cm^2 and achieved an average total-area stabilized efficiency measured under global AM1.5 of 11.6% after 1067 hours of one-sun light soaking at 50°C.
- Achieved 11.9% initial aperture-area (~920 cm^2) efficiency in an encapsulated triple-junction module measured by NREL.

Planned FY 2001 Milestones:

- Triple-junction modules with stabilized aperture-area efficiency of 11.5%.
- Triple-junction cells deposited at 3-5 Å/s showing total-area stabilized efficiency of 11.5%.

Major Reports Published in FY 2000:

S. Guha, (2000), "High Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology." Annual Technical Progress Report, Subcontract No. ZAK-8-17619-09, 49 pp.

Major Articles Published in FY 2000:

S. Guha, "Multijunction solar cells and modules," in *Technology and Applications of Amorphous Silicon*, edited by R. A. Street (Springer, 1999).

A.H. Mahan, J. Yang, S. Guha, D.L. Williamson, "Structural changes in a-Si:H film crystallinity with high H dilution," *Phys. Rev. B* **61**, 1677 (2000).

S. Guha, J. Yang, and A. Banerjee, "Amorphous silicon alloy photovoltaic research--present and future," in *Prog. in Photovoltaics: Research and Applications* **8**, 141 (2000).

S. Guha, J. Yang, A. Banerjee, K. Lord, and B. Yan, "Science and technology of amorphous silicon alloy photovoltaics--accomplishments and challenges," *NCPV Program Review Meeting 2000*, Denver, CO, 16-19 April 2000.

G. Yue, D. Han, G. Ganguly, Q. Wang, J. Yang, and S. Guha, "Characterization for the onset of crystallization of amorphous to microcrystalline silicon by optical spectroscopies," *NCPV Program Review Meeting 2000*, Denver, CO, 16-19 April 2000.

G. Yue, D. Han, J. Yang, and S. Guha, "Thickness and interface layer effects on the amorphous silicon film property studied by various photoluminescence excitation wave lengths," *Mat. Res. Soc. Symp.*, San Francisco, CA, 24-28 April 2000.

K.C. Palinginis, J.D. Cohen, J.C. Yang, and S. Guha, "A critical test of defect creation models in hydrogenated amorphous silicon alloys," *Mat. Res. Soc. Symp.*, San Francisco, CA, 24-28 April 2000.

D.L. Williamson, D.W.M. Marr, B.P. Nelson, E. Iwaniczko, J. Yang, B. Yan, and S. Guha, "Small-angle neutron scattering from device quality a-Si:H and a-Si:D prepared by PECVD and HWCVD," *Mat. Res. Soc. Symp.*, San Francisco, CA, 24-28 April 2000.

J. Yang, K. Lord, S. Guha, and S.R. Ovshinsky, "Amorphous silicon alloy solar cells near the threshold of amorphous to microcrystalline transition," *Mat. Res. Soc. Symp.*, San Francisco, CA, 24-28 April 2000.

R. Koval, L. Jiao, X. Niu, Z. Lu, G. Ganguly, J. Yang, S. Guha, R.W. Collins, and C.R. Wronski, "Kinetics of light induced changes in protocrystalline thin film materials and solar cells," *Mat. Res. Soc. Symp.*, San Francisco, CA, 24-28 April 2000.

P.M. Voyles, M.M.J. Treacy, H-C. Jin, J.R. Abelson, J.M. Gibson, J. Yang, S. Guha, and R.S. Crandall, "Comparative fluctuation microscopy study of medium-range order in hydrogenated amorphous silicon deposited by various methods," *Mat. Res. Soc. Symp.*, San Francisco, CA, 24-28 April 2000.

J. Yang, A. Banerjee, K. Lord, and S. Guha, "Status of amorphous silicon alloy solar cells and modules made near the onset of microcrystallinity," *28th IEEE PV Specialists Conference*, Anchorage, AK, 17-22 September 2000.

Properties of Wide-Gap Chalcopyrite Semiconductors for Photovoltaic Applications

Contract #: XAK-8-176193-04	**Contract Period:** 7/16/98–10/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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<tr><td>Organization Type: CU</td><td>Congressional District: 15</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
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Bolko von Roedern
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Electric Power Research Institute.
3412 Hillview Ave., P.O. Box 10412
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<tr><td>DOE Funding Allocation:
1998: $16,000
1999: $40,750
2000: $40,350</td><td>Cost Share Funding:
1998: $32,000
1999: $74,000
2000: $45,000</td></tr>
</table>

Project Objective: The objectives of this project are to obtain fundamental understanding of wide-gap chalcopyrite semiconductors and photovoltaic devices. Information to be obtained includes significant new fundamental materials data necessary for accurate modeling of single and tandem-junction devices, new information on the basic materials science of wider-gap chalcopyrite semiconductors to be used in next-generation devices, and practical information on the operation of devices incorporating these materials.

Approach/Background: Thin-film epitaxial and polycrystalline layers of $Cu(In,Ga)(S,Se)_2$ are being produced and characterized. Deposition uses a hybrid sputtering and evaporation method shown previously to produce high-quality epitaxial layers of $Cu(InGa)Se_2$ (CIGS). Experiments have focused on growth and characterization of epitaxial single crystals of (220)/(204) orientation. Recent record solar cell results have shown this orientation of CIGS to have potential for improved performance. During this year we have conducted studies aimed at understanding the fundamental mechanisms by which the improved performance may result. We have characterized the layers using a wide array of state-of-the-art optical, electrical, microchemical and microstructural analysis available at the University of Illinois. These techniques were also provided to assist members of the National CIS Team of which, through this contract, we are a member. Further, we have produced solar cells from the (220)/(204) oriented materials as well as materials produced with other orientations and have begun to determine the factors limiting performance of the devices based on analysis of the materials and device results.

Status/Accomplishments: Single crystal (220)/(204)-oriented single crystal epitaxial layers were deposited on (110)-oriented GaAs substrates with little or no diffusion of Ga from the substrate. Ga was added from the Cu-Ga alloy sputtering target. The (220) film growth mode was found to be unique. The surface consists of equal fractions of the two close packed (112)-oriented planes. These electronically-distinct surfaces had a very significant effect on the electrical properties of the resulting epitaxial layers. Electrical measurements showed a 20X reduction in carrier (hole) concentration with a major change in hole mobility. A growth model was proposed that accounts for the changes and explains the in-plane mobility decrease as resulting from scattering of carriers by point defect platelets. Solar cells were produced based on all three major orientations of CIGS single crystals. The devices showed up to 9% efficiency. A detailed model calculation using the AMPS computer code showed that the results were consistent with the record results in that a 20X reduction in carrier concentration, as observed, could account for the improved device results in the highest performance devices. However, in lower-performance devices the mobility decrease could be more significant than the hole concentration decrease. A small increase in deep-level point defects could also account for the decreased performance. In addition, a number of materials analyses were conducted for CIGS team members and the PI participated in the CIGS team meetings.

Planned FY 2001 Milestones: Continue characterization of CIS based devices in term of defects. Deposit thin films in the presence of surface Na concentrations and determine the effect of this surface layer on device results. Continue quantitative modeling of devices produced at the University of Illinois and elsewhere to develop an optimized set of model parameters. Continue to work with the national CIGS team performing analysis of materials and modeling device results.

Contract #: XAK-8-176193-04

Major Articles Published in FY 2000:
D. Liao and A. Rockett, "(110)-Oriented Cu(In,Ga)Se_2 -- Evidence That It May Improve Solar Cell Performance", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

M. Bodegård, O. Lundberg, J. Kessler, A. Rockett and L. Stolt, **"**HIGH VOLTAGE Cu(In,Ga)Se_2 DEVICES WITH Ga-PROFILING FABRICATED USING CO-EVAPORATION", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

D. Liao and A. Rockett, "Growth and Characterization of (110)-oriented Epitaxial Cu(In,Ga)Se_2 on GaAs (110)", Thin Solid Films, in press.

Invited Talks in 2001:
A. Rockett, "Basic Research Opportunities in Photovoltaics", NCPV Program Review Meeting, Denver, CO, March, 2000

A Rockett, "Deposition and Characterization of CuInSe2 For Solar Cell Applications", Swedish Vacuum Society, August, 2000

A. Rockett, "Basic Research Opportunities in Photovoltaics", Mexican Vacuum Society Annual Symposium, September, 2000

A. Rockett, "Deposition and Characterization of CuInSe2 For Solar Cell Applications", University of Maryland, Thin Films Modeling and Growth Group Seminar Series, November, 2000

Tutorial Lecture:
A Rockett and R. Ahrenkiel, "Analysis of Solar Cell Materials", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Thin Film PV Partnership

Search for Factors Determining the Photodegradation in High-Efficiency a-Si:H-based Solar Cells

Contract #: XAK-8-17619-11	**Contract Period:** 1/28/98–5/12/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of North Carolina at Chapel Hill Dept of Physics & Astronomy Chapel Hill, NC 27599-3255	
	Organization Type: CU	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Daxing Han **Phone:** 919-962-5002 **Fax:** 919-962-0480 **E-mail:** daxing@physics.unc.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $101,250 1999: $136,750 2000: $141,000	**Cost Share Funding:**

Project Objective: The objective of this work is to develop improved understanding of carrier collection and open-circuit voltage limitations of a-Si:H-based solar cells. These limitations will be described in terms of transport properties and recombination losses via midgap and tail-state defects. The work will verify or disprove the role of hydrogen diffusion as the cause of the metastability.

Approach/Background: Study of a-Si:H-based materials and devices using the following techniques: (1) Electroluminescence (EL) spectroscopy, (2) Photoluminescence (PL) energy and excitation wavelength dependence; (2) Photothermal Bending Spectroscopy (PBS) as an innovative technique to characterize the complex photodegradation mechanisms; (4) Nuclear Magnetic Resonance (NMR) and MQ NMR to study the hydrogen microstructure and its dynamics.

Status/Accomplishments: UNC has contributed detailed PL-evaluations of nip solar cells in which the i-layer grows before and after microcrytallinity. When the i-layer is made just before the onset of microcrytallinity, the PL peak energy blue shifts, meanwhile, the solar cell shows the highest Voc. PL spectroscopy is more sensitive than Raman and X-ray to detect the H-dilution and thickness effects on the i-layer microstructures. The optical and electronic properties as well as the photo-induced defects of a-Si:H deposited by hot-wire CVD are similar to that of PE-CVD films. Whereas, the photocurrent is not degraded as much as that in PE-CVD films and the Fermi-level position moves upwards instead downwards upon light soaking. A proton NMR study on ~1 μm-thick film deposited on quartz substrates has succeeded and information related to film orientation is obtained.

Planned FY 2001 Activities: (1) Combined both PL and EL studies searching for the correlation between i-layer properties and the solar cell performance; (2) Complete the NMR study on thin film structures in several groups of films deposited by PE- and HW-CVD techniques; (3) Electronic states and H-microstructures of high growth rates films by PL and NMR studies.

Major Reports Published in FY 2000:
Daxing Han, Annual Technical Report of 01/16/99-01/15/2000, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000:

Daxing Han, Guozhen Yue, J. D. Lorentzen, Jing Lin, H. Habuchi, and Qi Wang, “Optical and electronic properties of microcrystalline silicon as a function of microcrystallinity”, J. Appl. Phys. **87**, 1882 (2000).

Jonathan Baugh, Daxing Han, Qi Wang and Yue Wu, “DIAMAGNETIC SUSCEPTIBILITY OF MICRON THICK A-SI:H FILMS MEASURED VIA PROTON NMR: A PROBE OF STRUCTURAL ORDER”, MRS-2000.

Daxing Han, Jonathan Baugh, Guozhen Yue, and Qi Wang, “Light-induced Structural Changes and their Correlation to Conductivity Changes in Intrinsic Hydrogenated Amorphous Silicon Films”, Phys. Rev. B **62**, 7169 (2000).

Guozhen Yue, Daxing Han, D.L. Williamson, Jeffrey Yang, Kenneth Lord and Subhendu Guha, “Electronic states of intrinsic layers in n-i-p solar cells near amorphous to microcrystalline silicon transition studied by photoluminescence spectroscopy” APL **77**, 3185 (2000).

Thin Film PV Partnership

Identifying Electronic Properties Relevant to Improving Stability in a-Si:H Based Cells and Overall Performance in a SiGe:H Based Cells

Contract #: XAF-8-17619-05	**Contract Period:** 1/16/98–5/15/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of Oregon Eugene, OR 97403	
	Organization Type: CU	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J.D. Cohen **Phone:** 541-346-4775 **Fax:** 541-346-3422 E-mail: dcohen@oregon.uoregon.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $ 97,600 1999: $134,432 2000: $132,198	**Cost Share Funding:**

Project Objective: The objectives of this subcontract are to: develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States. This will carried out within the context of two of the research and developments sub-Teams established by the NREL/EPRI Thin Film Partnership. This effort will focus on the characterization of the electronic properties of a Si:H and a-SiGe:H films obtained from a variety of outside sources, most of which will be compared with the performance of companion p-i-n cells. Ultimately the goal of the Amorphous Silicon Team is to achieve 15% stable thin-film modules by 2005.

Approach/Background: To characterize the properties of these a Si:H and a-SiGe:H alloys using junction capacitance spectroscopic techniques, including drive-level capacitance profiling, transient photocapacitance and transient junction photocurrent spectroscopies, modulated photocurrent methods. On some occasions, ESR spectroscopy will also be employed to help identify the charge state of deep defects under investigation.

Status/Accomplishments: The detailed study of low Ge fraction a-Si,Ge:H alloys produced at United Solar Systems Corp. was continued. This set of six samples with Ge fractions near 2, 5, 7, 10, 13, and 20at.% were examined most extensively using the modulated photocurrent (MPC) method to monitor metastable changes in both Si and Ge dangling bonds. It was found that: (1) Both types of defects increased with light exposure at different rates; however, their sum exhibited nearly $t^{1/3}$ creation kinetic. (2) The annealing behavior indicated a simple correlation between the two types of defects which implied a global mechanism underlying the annealing. (3) One specific experiment was carried out to test the "hydrogen collision" model of deep defect creation proposed by Howard Branz. Our experimental result appears to contradict one key aspect of that model.

Sub-band-gap spectra of these rf glow discharge United Solar a-Si,Ge:H samples were obtained along with such spectra of a few a-Si,Ge:H samples produced by dc glow discharge at BP Solar and hot-wire CVD a-Si,Ge:H produced at NREL. We deduced smaller optical gaps for the NREL HWCVD samples at a given Ge content than for the United Solar material. The BP Solar a-Si,Ge:H samples exhibited gaps intermediate between those of the other series of samples for a given Ge concentration. For the United Solar a-Si,Ge:H material we also compared film and device performance for three of the compositions (5, 13, and 20at.%). Films and devices were characterized, degraded side by side and characterized again. A clear inverse correlation was found between the fill factor of the cells and the deep defect density of the films, particularly once the defect density exceeded about 7×10^{15} cm^{-3}.

Atomic force microscopy (AFM) and Kelvin force microscopy (KFM) were used to image the surface morphology of three United Solar a-Si:H samples: one standard sample deposited without hydrogen dilution, and two highly hydrogen diluted samples, lying near the edge of the amorphous/microcrystalline phase boundary. These latter two samples differed only in thickness (a 1.0µm film and a 1.3µm film). It had previously been established from X-ray diffraction analysis that United Solar hydrogen diluted films deposited under such conditions exhibited a small microcrystalline component when the thickness exceeded one micron. The AFM images revealed distinct surface "bumps" on the hydrogen diluted films, but not on the standard film. Moreover, the bumps were denser and larger for the 1.3µm film. The KFM images over the same region indicated that these bumps exhibited a 0.25 volt higher contact potential difference compared to the background. This identified them unambiguously as crystalline-like regions. These measurements thus clearly add to our understanding of the film morphology at the onset of microcrystallinity in a-Si:H samples.

Contract #: XAF-8-17619-05

Planned FY 2001 Activities: First, work will continue on the low Ge fraction a-Si,Ge:H alloys in order to further elucidate the mechanisms of light-induced defect creation. In particular, the correlation between Si and Ge defects will be compared under thermal annealing and light-induced annealing. Second, several series of high growth rate a-Si:H samples will be characterized and, in several cases, comparisons will be made between film and device behavior. These series of samples will include high growth rate samples from BP Solar, ECD (vhf glow discharge material), and ultra-high deposition rate HWCVD samples from NREL.

Major Reports Published in FY 2000:
Phase I annual report, NICH Report No. SR-520-28050 (March 2000)

Phase II annual report, draft version received.

Major Articles Published in FY 2000:
Y. Lubianiker, Y. Tan, J.D. Cohen, and G. Ganguly, "Amorphous silicon deposited at high growth rate near the onset of crystallinity", J. Non-Cryst. Solids **266-269**, 450 (2000).

Y. Lubianiker, J.D. Cohen, G. Lubarsky, Y. Rosenwaks, J. Yang, and S. Guha, "Structural and electronic properties of optimized a-Si:H films", J. Non-Cryst. Solids **266-269**, 253 (2000).

K. C. Palinginis, J. David Cohen, J.C. Yang, and S. Guha, "Defect bands in a-Si,Ge:H alloys with low Ge content", J. Non-Cryst. Solids **266-269**, 665 (2000).

K.C. Palinginis, J.D. Cohen, J.C. Yang, and S. Guha, "A critical test of defect creation models in hydrogenated amorphous silicon alloys", Mat. Res. Soc. Symp. Proc., in press.

Thin Film PV Partnership

Advanced Processing Technology for CdTe and High Band Gap CIGS Solar Cells

Contract #: ZAF-8-17619-29	**Contract Period:** 5/26/98–8/22/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of South Florida (USF) 4202 E. Fowler Ave. Tampa, FL 33620	
	Organization Type: CU	**Congressional District:** 11
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D.L. Morel and C.S. Ferekides **Phone:** 813-974-2508 and 813-974-4818 **Fax:** 813-974-5250 **E-mail:** morel@eng.usf.edu and ferekide@eng.usf.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: EPRI (Special Topic)
	DOE Funding Allocation: 1998: $172,461 1999: $278,941 2000: $313,940	**Cost Share Funding:** 1998: $66,316 1999: $123,544

Project Objective: The objectives of this work are to develop improved solar cell processing schemes for CdTe and CIGS based solar cells which are capable of further enhancing the performance and long-term stability and to reduce the manufacturing costs of commercial thin-film photovoltaic modules. Important aspects of the research will be to develop improved understanding and insights to how process modifications affect device performance. CIGS cells with wide band gaps of the absorber layer will be produced and evaluated as suitable candidates for CIS-based tandem devices.

Approach/Background: For both CdTe and CIGS based technologies we will fabricate and evaluate complete device structures. Although some devices will be fabricated on substrates such as 7059 glass for evaluative purposes, most devices will use soda lime glass, the industry standard. The process approaches, which we will develop, will be consistent with the realities of manufacturability. Stability testing of select devices will also be conducted under appropriate simulation conditions to relate any observed instabilities to process parameters.

Status/Accomplishments: Various processing schemes and materials are being investigated in the area of thin film CdTe solar cells: 1-Transparent conductors/front contacts/window layers: Cadmium oxide prepared by MOCVD has been utilized as an alternative front contact (i.e. replaced SnO_2) and devices with high Voc's and ff's have been prepared. Zinc selenide (ZnSe) has been used as the window layer (this material has a larger bandgap than CdS). However, the performance of CdTe/ZnSe cells to-date remained in the 10-11% range. Work on all-CSS devices has continued with emphasis on understanding and improving the quality of CSS-CdS films prepared on soda lime glass substrates. Critical processes/processing parameters (that include heat treatments) have been identified and devices on soda lime glass can be routinely produced with state of the art Voc's and ff's. Work on SnO_2 and the role of bi-layer structures has also been carried out in order to understand the influence of the front contact on device performance and also develop robust baseline processes. 2-Vapor chloride treatment: In an effort to simplify the cell fabrication procedures for manufacturing CdTe/CdS cells treated in vapor CdC_2 (instead of the typical wet process) have been investigated. This process, although not completely robust yet, it has produced Voc's in the 830-840 mV range and ff's above 70%. 3-Back contact: A considerable effort is being focused on identifying new back contact materials/processes that will yield efficient and stable devices. Copper-based approached that include Cu_xTe alloys and ZnTe/Cu_xTe bi-layers have been successfully implemented. Copper-free contacts have in some instances produced very encouraging results and ff's have reached the 70% mark. 4-Stability studies: In an effort to identify and eliminate possible degradation mechanisms CdTe/CdS solar cells are being stressed under various conditions. To-date devices have been exposed to temperatures up to 120ºC in the dark for over 2000 hours. Additional cells have been light soaked under simulated AM1.5 conditions at 70ºC for over 2000 hours. Most of the evidence suggests that the back contacts in these devices are not the primary source for the observed changes in performance.

Progress with CIGS devices is being greatly aided by use of AMPS simulations. The simulations have been particularly helpful in sorting out photocapacitance data that is being used to identify the defects controlling recombination. Much of the defect structure associated with our 2-step solid source selenization process is related to improper Ga incorporation. Correlation of these Ga based defects with processing is also being accomplished. Using these results we have been able to devise processing schemes that

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Status/Accomplishments (continued):
accomplish effective Ga incorporation. This has resulted in one-for-one increases in Voc with increasing band gap, an important advancement for our processing approach.

These techniques are also being applied to high band gap CGS. In this case the controlling mechanisms seem to be related to balancing overall compensation rather than to a single entity. Using feedback from defect measurement and AMPS simulation we have achieved improvement in both Voc(>700 mV) and Jsc(>15 mA/cm^2) in these devices. However, we have not completely separated surface and bulk optimization as we have in CIGS to advance overall performance. This is the focus of our current efforts.

A new reactor has been constructed and is now in operation. The first devices have just been completed. This reactor will allow much greater control over our process in a mode that is a prototype for large scale production. Our current processes including the new insights described above are currently being transferred to this reactor.

Planned FY 2001 Activities: In the area of CdTe we plan to continue the activities discussed in the status section above. Emphasis will be placed on (a) expanding the current set of stress conditions in our stability studies, (b) investigate new back contact materials as well as continue optimization of the most promising ones identified to-date, (c) investigate new processing techniques for a simplified back contact, (d) improve the robustness of the vapor $CdCl_2$ treatment, (e) optimize the operation of the newly installed CdTe-CdS deposition system, and (f) continue work on the role of bi-layer front contacts.

In the CIGS area emphasis will be placed upon transferring process recipes to the new reactor. This will then allow more efficient optimization of overall performance using all of the improvements in process detail that we have developed. The main limitation for CGS devices remains low Voc's. We will complete experiments aimed at determining which parts of the device structure are defective and limiting Voc. New ideas for eliminating this weakness will be implemented.

Major Reports Published in FY 2000:
Phase I Annual Report, NREL/SR-520-28796 (8/2000, 55 pages)

Major Articles Published in FY 2000:

C. S. Ferekides, D. Marinsky, V. Viswanathan, B. Tetali, V. Palekis, P. Selvaraj, and D. L. Morel, "High Efficiency CSS CdTe Solar Cells", Proceedings of the European Materials Conference, E-MRS, Strasbourg, June, !999.

B.R.Tetali, V.Viswanathan, Z.Zhao ,"Thermal Effects on CdS/CdTe Solar Cells", presented at the Student Poster Competition of 28th Annual Symposium of the Florida Chapter of the American Vacuum Society, March 13-14, 2000, Orlando, Florida.

P. Panse, H. Sankaranarayanan, , R. Narayanaswamy, M. Shankaradas, Y. Ying, C. S. Ferekides and D. L. Morel, "Ga Incorporation Mechanisms in CIGS Solar Cells", Proceedings of the NCPV Program Review Meeting, Denver, April, 2000.

V. Viswanathan, B. Tetali, Z. Zhao, V. V. Komin, V. Palekis, N. Rao, D. L. Morel, and C. S. Ferekides, "A Novel Cu-Free Back Contact for CdS/CdTe Thin film Solar Cells", Proceedings of the NCPV Program Review Meeting, Denver, April, 2000.

Z. Zhao, V. Komin, V. Viswanathan, D. L. Morel, and C. S. Ferekides ,"Application of tin-doped cadmium oxide films in CdTe/CdS solar cells", Presented at the 28th IEEE Photovoltaic Specialists Conference, September 15-22, 2000, Anchorage, Alaska.

V. Viswanathan, B.Tetali, P.Selvaraj, S. Jagannathan, D.L. Morel, and C.S. Ferekides, "Ni_2P – A Promising Candidate for Back Contacsts to CdS/CdTe Solar Cells", Presented at the 28th IEEE Photovoltaic Specialists Conference, September 15-22, 2000, Anchorage, Alaska.

V. Komin, V. Viswanathan, B.Tetali, D.L. Morel, and C.S. Ferekides, "Investigation of Deep Levels in Cdte/Cds Solar Cells", Presented at the 28th IEEE Photovoltaic Specialists Conference, September 15-22, 2000, Anchorage, Alaska.

P. Panse, H. Sankaranarayanan, R. Narayanaswamy, M. Shankaradas, Y. Ying, C. S. Ferekides and D. L. Morel, "Evaluation and Modeling of Junction Parameters in Cu(In,Ga)Se Solar Cells", Proceedings of the 28th IEEE PVSC, Anchorage, 09/2000.

M. Shankaradas, Y. Ying, H. Sankaranarayanan, P. Panse, C. S. Ferekides and D. L. Morel, "Photocapacitance Analysis of Defect Mechanisms in Cu(In,Ga)Se Solar Cells", Proceedings of the 28th IEEE PVSC, Anchorage, 09/2000.

Thin Film PV Partnership

High Efficiency Thin-Film Cadmium Telluride and Amorphous Silicon-Based Solar Cells

Contract #: ZAF-8-17619-14	**Contract Period:** 3/4/98–5/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	The University of Toledo 2801 W. Bancroft Toledo, OH 43606 **Organization Type**: CU	**Congressional District:** 9
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** A.D. Compaan (P.I.) **Phone:** 419-530-4787 **Fax:** 419-530-2723 **Email:** adc@physics.utoledo.edu	X. Deng (co-P.I.) **Phone:** 419-530-4782 **Fax:** 419-530-2723 **E-mail:** dengx@physics.utoledo.edu
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $253,500 1999: $278,118 2000: $305,240	**Cost Share Information**: The University of Toledo **Cost Share Funding:** 1998: $174,435 1999: $177,086 2000: $201,736

Project Objectives: To develop improved solar cell processing schemes for CdTe-based and for a-Si:H-based solar cells which can further enhance the performance and long-term stability of these devices and/or reduce the manufacturing costs of commercial thin-film photovoltaic modules based on these devices.

Approach/Background: The CdTe-based cell effort is focused on the use of planar magnetron sputtering, including reactive sputtering, for deposition of the active semiconductor layers (CdS, CdTe, and ZnTe) as well as for the electrode/contact structures. Pulsed laser deposition is used for exploratory work. The a-Si:H-based effort utilizes both RF and VHF plasma-enhanced chemical vapor deposition (PECVD), as well as a hot-wire process for deposition of a-Si:H, a-Si:Ge:H, and polycrystalline and nanocrystalline forms of these materials. Devices are tested by current-voltage, quantum efficiency, and photovoltage measurements. The cell fabrication efforts are supported by characterization studies which include photoluminescence, Raman scattering, optical absorption, SEM, EDS, x-ray diffraction, Hall effect, conductivity, and capacitance-voltage measurements. Laser scribing facilities with Nd:YAG and XeCl excimer lasers are used for submodule fabrication and collaborative work.

Status/Accomplishments:

- Comparatively studied the performance of a-SiGe solar cells and properties of a-SiGe single layer films deposited using a wide range of H dilution.
- Comparatively studied the performance of a-SiGe solar cells and properties of a-SiGe single layer films with different Ge contents.
- Fabricated a-Si based solar cells on ultra-thin stainless steel substrate (7.5 micron) and obtained equivalent performance and yield as on the regular SS substrates (127 micron).
- Comparatively studied the performance of a-Si based solar cells on SS substrates and on SnO_2-coated glass substrates.
- Studied the performance of p-layers deposited under various deposition conditions for n-i-p type solar cells.
- Performed an analysis for the component cell current matching within a triple-junction solar cell.
- Completed the installation of a unique hot-wire deposition system and deposited hot-wire n-i-p solar cells.
- Implemented a diode-array spectrograph system and utilized optical emission spectroscopy to help optimize the reactive sputtering of N-doped ZnTe for CdTe back contact structures.
- Identified the photoluminescence signatures of various defect states in CdTe related to Cd vacancies, Cu_{Cd} acceptors, Cu-V_{Cd} complexes and donor-acceptor pairs, and related these states to instabilities in the hole concentration at room temperature.
- Fabricated superstrate ITO/CdS/CdTe cells on Mo substrates with efficiencies above 7.5%.
- Collaborated in studies of EXAFS of Cu in CdTe which indicate the existence of a Cu-Te bond length of 2.62 Å or 6.7% shorter than the CdTe bond in agreement with recent theoretical calculations.
- Performed laser scribing of submodule prototypes on our own films and for collaborators.

Contract #: ZAF-8-17619-14

Planned FY 2001 Activities:

- Effort will be placed on further development of copper-free back contacts to CdTe cells utilizing reactively sputtered interfacial layers.
- Photoluminescence studies will correlate changes in PL signals from both CdTe and CdS with changes in cell performance during stressing. These will include spatial nonuniformities in PL.
- Effort will be made to achieve doping of CdTe with reactive sputtering.
- Laser scribing efforts will continue in collaboration with other groups and small submodules will be fabricated of RF sputtered material.
- Effort will be made to further improve the stable efficiency of a-Si/A-SiGe/a-SiGe triple-junction solar cells.
- Studies will be made in depositing a-Si, a-SiGe and poly-Si, using hot-wire CVD and VHF PECVD.
- The deposition "phase diagram" between amorphous and microcrystalline films as a function of H-dilution, rf power, and substrate temperature will be explored.

Major Reports Published in FY 2000:

Compaan, A. D.; Deng, X.; Bohn, R. G. (1999). High Efficiency Thin Film CdTe and a-Si Based Solar Cells: Annual Technical Report, March 4, 1998 - March 3, 1999. 68 pp.; NICH Report No. SR-520-27666. [Full manuscript available at http://www.nrel.gov/docs/fy00osti/27666.pdf]

Major Articles Published in FY 2000:

D. Grecu and A.D. Compaan, "Photoluminescence Study of Cu Diffusion and Electromigration in CdTe, Appl. Phys. Lett. **75**, 361-363 (1999).

A.D. Compaan, J.R. Sites, R.W. Birkmire, C.S. Ferekides, and A.L. Fahrenbruch, "Critical Issues and Research Needs for CdTe-Based Solar Cells," *Electrochemical Society Symposium Proceedings*, vol. 99-11, "Photovoltaics for the 21st Century" Seattle, WA, May, 1999.

Y.L. Soo, S. Huang, S. Kim, G. Kioseoglou, Y.H. Kao, A.D. Compaan, D. Grecu, and D. Albin, "Effects of heat treatment on diffusion of Cu atoms into CdTe single crystals," Appl. Phys. Letts. **76**, 3729 (2000).

D. Grecu, A.D. Compaan, D. Young, U. Jayamaha, and D.H. Rose, "Photoluminescence of Cu-doped CdTe and related stability issues in CdS/CdTe solar cells," J. Appl. Phys. **88**, 2490 (2000).

X.B. Liao, J. Walker, and X. Deng, "Effect of buffer layers in narrow bandgap a-SiGe solar cells," in *Amorphous and Heterogeneous Silicon Thin Fims—Fundamentals to Devices*, MRS Symp. Proc. **557**, 779 (1999).

X. Deng, H. Povolny, S. Han and P. Agarwal, "Ultra-lightweight amorphous silicon solar cells deposited on 7.5µm thick stainless steel substrates", in Proceedings of 28th IEEE Photovoltaic Specialist Conf. (2000).

H. Povolny, P. Agarwal, S. Han and X. Deng, "Comparison study of a-SiGe solar cells and materials deposited using different hydrogen dilution", in Amorphous and Heterogenous Silicon Thin Films—2000, ed. by H. Branz, R. Collins, S. Guha, H. Okamoto and M. Stuztzmann, 2000.

X. Deng, P. Agarwal, H. Povolny and S. Han, "Amorphous silicon germanium solar cells and thin films deposited using different hydrogen dilution", in Proceedings of NCPV Program Review Meeting—2000, A13 (2000).

G. Yue, X. Deng, G. Ganguly and D. Han, "Electro- and Photo-Luminescence Spectra From a-Si and a-Si:Ge p-i-n Solar Cells", *Journal of Non-Crystalline Solids*, **266**, 1119 (2000).

X. Deng and X.B. Liao, S. Han, H. Povolny and P. Agarwal, "Amorphous silicon and silicon germanium materials for high efficiency triple-junction solar cells", *Solar Energy Materials & Solar Cells*, **62**, 89 (2000).

Thin Film PV Partnership

Characterization of Amorphous Silicon Thin Films and PV Devices

Contract #: XAK-8-17619-13	**Contract Period:** 1/14/98–5/13/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	University of Utah Salt Lake City, UT 84112	
	Organization Type: CU	**Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** P. Craig Taylor **Phone:** 801-581-8751 **Fax:** 801-581-4246 (or 801-581-4801) **E-mail:** craig@physics.utah.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $63,400 1999: $91,596 2000: $92,463	**Cost Share Funding:**

Project Objective: The objective of the research is to characterize the defects, impurities and metastabilities in hydrogenated amorphous silicon (a-Si:H), in hydrogenated amorphous silicon-germanium alloys (a-Si_xGe_{1-x}:H) and in other related alloys of importance to photovoltaic devices. Of special interest is to develop an understanding of the degradation of a-Si:H and related alloys and to pursue options to eliminate this degradation.

Approach/Background: Various optical and magnetic resonance techniques are employed to examine the role of defects , impurities and metastabilities in a-Si:H and related alloys. Optical techniques include photothermal deflection spectroscopy to measure low levels of optical absorption, photoluminescence and photoluminescence excitation spectroscopy, and various modulated optical spectroscopies. Magnetic resonance techniques include electron spin resonance and optically detected magnetic resonance. Measurements are made on individual films and on device structures.

Status/Accomplishments: We have performed detailed kinetic experiments using electron spin resonance (ESR) and light-induced ESR (LESR) at low temperatures. These measurements are difficult due to saturation of the LESR signal as a result of long spin-lattice relaxation times. To solve this problem, we have employed a second-harmonic detection technique that effectively eliminates this difficulty and allows for detailed kinetic experiments to be performed, even for small ESR spin densities. The improvement in effective signal-to-noise ratio can be several orders of magnitude at low temperatures. Whereas the standard detection of ESR results in a signal proportional to the derivative of the absorption, the second harmonic detection results in a line shape that roughly approximates the resonant absorption component. We have shown that below approximately 300 K the production of silicon dangling bonds depends on the temperature and that the production below approximately 100 K is at most half as efficient as at 300 K. In addition, the dangling bonds produced by up to 10 hours of irradiation below 100 K are unstable and anneal essentially completely at 300 K. The existing kinetic models that attempt to explain the S-W effect are not robust enough to explain this complex behavior. We have also shown that low temperature experiments that measure the production of silicon dangling bonds must take great care to remove the long-lived carriers trapped in localized band-tail states. These carriers are very difficult to remove optically.

In spite of a number of attempts over the last 20 years [5,6], no similar LESR has been detected in a-Ge:H. In the last two quarters we have observed LESR in a-Ge:H, and we attribute the signals to holes and electrons trapped in the valence- and conduction-band tails, respectively. The observation of LESR in a-Ge:H allows the recombination kinetics and doping mechanisms in this amorphous semiconductor to be compared with those observed in a-Si:H and therefore allows potentially universal features to be identified.

The presence of molecular hydrogen in a-Si:H has been an important issue for many years. However, both the concentration and the local environment of H_2 are controversial due to the difficulty of detecting ortho-molecular hydrogen (o-H_2) directly. We have employed a new way to measure the concentration and to investigate the local environments of o-H_2 in a-Si:H by ^{1}H NMR. This method is to measure the dipolar echoes instead of the free induction decays. We have found that the concentration of molecular hydrogen in a-Si:H is much higher than previously believed. Most o-H_2 molecules do not participate in the spin-lattice relaxation of bonded hydrogen. Two o-H_2 environments exist, one in which the molecules are essentially isolated and one in which the molecules are clustered. Part, but not all, of the 4 kHz narrow line at room temperature is due to o-H_2 molecules. Finally, the o-H_2 lineshape in HWCVD samples suggests a more ordered structure for the Si lattice than in typical PECVD samples.

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In summary, major accomplishments include (1) the first observation of optically induced ESR in a-Ge:H, (2) the first direct measurement (ESR of silicon dangling bonds) of the kinetics of degradation of a-Si:H at temperatures below 100 K, and (3) the determination that an order of magnitude more molecular hydrogen exists in various samples of a-Si:H than was previously thought. In conjunction with our previous results on low-temperature LESR in a-Si:H, the first accomplishment shows that the decay of optically excited band tail electrons and holes at low temperatures is a universal feature of tetrahedrally-coordinated amorphous semiconductors. The determinations of molecular hydrogen concentrations in both PECVD and HWCVD samples show clearly that there are distinct differences between these two types of a-Si:H. In particular, the HWCVD samples with low hydrogen concentrations also have low molecular hydrogen concentrations and possess a more ordered local silicon network.

Planned FY 2001 Activities: We will continue our studies of the low temperature kinetics for the growth and decay of band-tail carriers and of the low-temperature production of silicon dangling bonds in a-Si:H. We will expand these studies to include hydrogenated amorphous germanium (a-Ge:H) and silicon-germanium alloys. We are also continuing the characterization of p-i-n solar cells grown in our three-chamber, load-locked PECVD system and will test the stability of cells employing sulfur in the i-layers. Our nuclear magnetic resonance (NMR) measurements of HW and PECVD samples of intrinsic and doped a-Si:H will also continue. We will test the hypothesis that the decay of dipolar order in the hydrogen system is due to cross-relaxation with electrons trapped at Si dangling bonds and with electrons and holes trapped in band tail states.

Major Reports Published in FY 2000:
P. C. Taylor, Phase 2 Annual Technical Progress Report NREL (2000).

Major Articles Published in FY 2000:
W. Xu, S. L. Chen, and P. C. Taylor "Photoluminescence in Hydrogenated Amorphous Silicon Alloyed with Selenium," Homage Book - Andrei Andriesh (INOE&INFM Publishing House, Bucharest, 1999), M. Popescu, ed., p. 45-52; also Rom. Rpts. in Phys. **51** (2000).

B. Yan, N. Schultz, A. L. Efros, and P. C. Taylor "Universal Distribution of Residual Carriers in Tetrahedrally-Coordinated Amorphous Semiconductors," Phys. Rev. Lett. **84**, 4180 (2000).

F. C. Marques, P. C. Taylor, and M. M de Lima, Jr "Light-Induced Electron Spin Resonance in Amorphous Hydrogenated Germanium," Appl. Phys. Lett. **74**, 3797 (1999).

T. Su, S. L. Chen, P. C. Taylor, R. S. Crandall and A. H. Mahan "NMR Study of Ortho-Molecular Hydrogen in Hydrogenated Amorphous Silicon," MRS Symp. Proc. **557**, 293 (1999).

N. Schultz and P. C. Taylor "Low Temperature Kinetics for the Growth and Decay of Band-tail Carriers and Dangling Bonds in Hydrogenated Amorphous Silicon," MRS Symp. Proc. **557**, 353 (1999).

A. A. Andreev, V. G. Golubev, A. V. Medvedev, A. B. Pevtsov, N. A. Feoktistov, V. F. Masterov, S. B. Aldabergenova, and P. C. Taylor "Observation of Fine Structure in the Photoluminescence Spectrum of an Er^{3+} Ion in an Amorphous Silicon Matrix," JETP Letters **70**, 797 (1999).

T. Su, P. C. Taylor, R. S. Crandall, and A. H. Mahan "Ortho-molecular Hydrogen in Hydrogenated Amorphous Silicon," Appl. Phys. Lett. **76**, 565 (2000).

F. C. Marques, P. C. Taylor, and M. M. de Lima, Jr "Optically Excited Paramagnetic Centers in Amorphous Hydrogenated Germanium," J. Non-Cryst. Solids **266-269**, 717 (2000).

N. Schultz, B. Yan, A. L. Efros, and P. C. Taylor "Recombination Kinetics of Long-Lived Carriers in a-Si:H at Low Temperatures," J. Non-Cryst. Solids **266-269**, 372 (2000).

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R. M. Mehra, J. Baveja, L. P. Purohit, R. Jumar, A. V. Singh, P. C.. Mathur, and P. C. Taylor "Optical Properties of Large Band Gap Se- and S-doped Amorphous Hydrogenated Silicon," J. Non-Cryst. Solids **266-269**, 708 (2000).

T. Su, S. Chen, P. C. Taylor, R. S. Crandall, and A. H. Mahan "Molecular Hydrogen in Hydrogenated Amorphous Silicon: New Evidence from NMR," Phys. Rev. B **62**, 12849 (2000).

Thin Film PV Partnership

Alternative Window Schemes for $CuInSe_2$-Based Solar Cells

Contract #: XAF-8-17619-06	**Contract Period:** 12/29/97–2/28/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail:** Jeffrey.Mazer@ee.doe.gov	Washington State University (WSU) Pullman, WA 99164-3140	
	Organization Type: CU	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** L.C. Olsen **Phone:** 509-372-7221 **Fax:** 509-372-7100 **E-mail:** lolsen@tricity.wsu.edu	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $138,700 1999: $120,875 2000: $125,777	**Cost Share Funding:**

Project Objective: The objective is to develop window alternatives (replacing CdS) for $Cu(In,Ga)Se_2$ solar cells to meet the DOE goal set for the 2005 to achieve commercial, low-cost, 15% efficient thin-film photovoltaic modules.

Approach/Background: The approach is to optimize MOCVD-deposited alternative window layers and obtain state of the art $Cu(In,Ga)Se_2$ solar cells. Emphasis is placed on investigations of ZnO, ZnSe and ZnS compounds as replacements for CdS, and on optimization of the complete process of cell fabrication. In particular, approaches to growth of window layers compatible with subsequent processing steps including TCO and collector grid deposition that yield stable, efficient solar cells are being investigated.

Status/Accomplishments: Efforts concentrated on four areas: investigation of cells based on CIGSS and ZnO buffer layers grown by MOCVD; fabrication of a complete solar cell using an alternative buffer layer, TCO, collector grids and MgF_2 AR coating with all processes beginning with the buffer layer being done at WSU; electrical and physical characterization of MOCVD ZnO buffer layers; and proof of concept studies of ZnS buffer layers. Discussions of key results in these three areas follow.

CIGSS Cells Based On MOCVD ZnO Buffer Layers --A procedure was developed for growth of resistive MOCVD ZnO buffer layers onto CIGSS material that yields cells with efficiencies greater than 12%. Previous work with SSI CIS and NREL CIGS substrates involved the use of a two step process with hydrogen as a carrier gas. This past year's work determined that a modified procedure gives better results for the SSI CIGSS material. Instead of hydrogen, nitrogen is used as a carrier gas and although the sample is heated to 250°C, no film growth occurs until the sample is cooled to 100°C. An additional modification of our ZnO growth procedure involves adding water to the THF precursor. This process consistently yields very resistive ZnO films with the resistivity being greater than 10,000 ohm-cm. After growth of the ZnO buffer layers, CIGSS cells were completed by depositing n-ZnO TCOs and Ni/Ag or Ni/Al collector grids. Although several cells were completed with efficiencies over 11 %, NREL determined that one cell had a total area efficiency of 12.7 % (active area efficiency of approximately 13.4 %). Values of other cell parameters included J_{sc} = 33.0 mA/sq cm, V_{oc} = 0.577 Volts and FF 66.55 %. Besides the respectable efficiency, the value of open circuit voltage is An important step in cell fabrication process conducted at WSU has been an etching step prior to buffer layer growth. In particular, after cleaning CIGSS material received from SSI, substrates are etched with a 10% solution of KCN. Studies were carried out to compare cells fabricated with and without the KCN etch step. Results clearly established that inclusion of the etching step resulted in improved cell results. As a result, studies were conducted to understand the effect of the KCN etch using XPS profiling and Raman spectroscopy. The XPS investigations determined that one significant effect of the etch is to remove oxygen from the surface that is bonded to selenium as SeO_2. Plots of Raman shift versus wavenumber for etched and non-etched CIGSS material were essentially identical. This result is in contrast to previous Raman studies carried out for SSI CIS material which clearly established that KCN removed Cu-Se precipitates. In conclusion, these studies suggest that removal of oxygen from the surface or near surface regions is the main effect of the KCN etch. Furthermore, it is postulated that removal of oxygen leaves Se free to occupy Se vacancies that exist in grain boundaries near the surface, thereby reducing shunting effects of inverted grain boundaries.

<u>Fabrication Of Complete Solar Cells With Alternative Buffer Layers</u> – The use of a new RF magnetron sputtering system to deposit conducting n-ZnO to serve as a TCO was implemented. The system has two targets, an intrinsic ZnO target and a Al-doped ZnO .

target. Procedures were developed for depositing a bilayer TCO. Typical film thicknesses used to establish a TCO consist of 300 to 400 Å of intrinsic ZnO followed by 4000 Å of conductive ZnO. Sheet resistance values for TCO layers are typically10 to 20 ohm/sq. After developing the TCO capability, efforts concentrated on complete fabrication of cells beginning with deposition of a ZnO buffer layer on SSI CIGSS substrates. Specifically, cell fabrication includes the following steps all carried out at WSU: (1) Clean a CIGSS substrate followed by a KCN etch; (2) Grow a 500 Å to 800 Å ZnO buffer by MOCVD; (3) Sputter deposit a bilayer TCO with a sheet resistance between 10 and 20 ohms/sq; (4) Deposit a collector grid comprised of 500 Å of Ni followed by 2.5 µm of Ag; (5) Deposit 1000 Å of MgF_2 for an AR coating. Several cells were completed with efficiencies greater than 10 %. The best result to date was achieved with a 0.45 cm^2 cell which exhibited the following properties: J_{sc} = 36.1 mA/sq cm, V_{oc} = 0.540 Volts, FF = 0.546 and an efficiency = 10.7 %. Clearly, improved values of FF must be achieved. However, the key objective of developing a capability at WSU for completing cells beginning with the buffer layer deposition has been accomplished.

Electrical And Physical Characterization Of MOCVD ZnO Buffer Layers -- In addition to the two-step approach to growing ZnO buffer layers discussed above, a one-step process has also been utilized. The one-step approach involves raising the sample directly to 100°C and growing 500 Å to 800 Å of ZnO Solar cells with efficiencies greater than 12 % have been fabricated with two-step buffer layers, while cells with one-step buffer layers exhibit very poor performance. XRD studies have determined that both types of films are crystalline. Characterization of ZnO buffer layers grown on CIS substrates with spectroscopic ellipsometry has revealed the major difference between the two types of films. Optical absorption in a one-step ZnO films is characterized by a very soft electron band edge, suggesting a high density of interband states. Two-step films, on the other hand, are characterized by a very abrupt electron band edge. Based on these studies, it appears that one-step films lead to ZnO-CIS interfaces characterized by high interface densities and high electron recombination, whereas two-step films lead to high quality ZnO-CIS interfaces. It is further concluded that subjecting the CIS substrate to 250°C in the two-step process results in removal of impurities that allows the growth of a ZnO film with low interband state densities, as well as low ZnO-CIS interface state densities.

Proof Of Concept Studies With ZnS Buffer Layers -- Two methods are being investigated for growth of ZnS buffer layers, namely, chemical bath deposition (CBD) and MOCVD. MOCVD growth of ZnS is accomplished by reacting a zinc adduct with hydrogen sulfide. Initial studies indicate that cells with ZnS buffer layers several hundred angstroms and greater exhibit low values of photocurrent, apparently due to a barrier formed at the ZnS/CIGSS interface. Studies are underway with thin ZnS buffer laeyers. Investigations of CBD ZnS buffer layers are also underway. ZnS films were deposited onto CIGSS substrates by decomposition of thiourea in alkaline solution containing a suitable complexing agent. The best cell fabricated to date exhibited the following characteristics: J_{sc} = 29.3 mA/sq cm, V_{oc} =0.491 Volts, FF= 0.569 and a total area efficiency of 8.2 %.

Planned FY 2001 Activities: (1) Continue cell fabrication and characterization of cells based on SSI CIGSS with alternative buffer layers, which will include ZnO, ZnSe and ZnS. This effort will also be extended to other sources of CIS-related alloys. (2) Carry out studies comparing ZnO, ZnSe and ZnS buffer layers grown by MOCVD and CBD. (3) Place an increased emphasis on studies concerning understanding the role of buffer layers in cell performance. These investigations will include XPS and SIMS profiles, and spectroscopic ellipsometry and Raman studies of Buffer-Layer/CIS structures carried out in collaboration with researchers at PNNL. These efforts will be conducted in parallel with device simulation studies using AMPS 1D and PC 1D computer codes.

Major Reports Published in FY 2000:

L.C. Olsen, “Alternative heterojunction Partners for CIS-Based Solar Cells,” 35 pp. NREL/SR-520-27930, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000:

L.C. Olsen , G. J. Exarhos , Phil Lei and F. W. Addis. “Characterization of MOCVD ZnO Buffer Layers for CIS Solar Cells,” American Vacuum Society 46th International Symposium, Seattle, WA, 25-29 October 1999.

L. C. Olsen, G. J. Exarhos, Peter Eschbach, Phil Lei and F. W. Addis, “Characterization of MOCVD ZnO Buffer Layers for CIS Solar Cells With Spectroscopic Ellipsometry,” Under Review for publication in The Journal of Vacuum Science and Technology.

L. C. Olsen , F. W. Addis, L. Huang and Peter Eschbach, CVD ZnO Buffer Layers for SSI CIGSS Solar Cells, Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK-520-28064. Pp. 237-238 (2000).

L. C. Olsen, F.W. Addis, Liang Huang, Peter Eschbach and G. J. Exarhos, “ CIGSS Solar Cells Based On CVD ZnO Buffer Layers,” 28th IEEE PV Specialists Conference, Anchorage, AK, 17-22 September 2000.

Thin Film PV Partnership

Identifying and Overcoming Degradation Mechanisms in CdTe Solar Cells

Contract #: AAK-7-17619-15	**Contract Period:** 7/27/98–9/26/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E-mail**: Jeffrey.Mazer@ee.doe.gov	Weizmann Institute of Science Rehovot, Israel	
	Organization Type: ZZ	**Congressional District:** N/A
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** David Cahen, Gary Hodes, Konstantin Gartmsan **Phone:** 972-8934-2246 **Fax:** 972-8934-4139 **E-mails:** david.cahen@weizmann.ac.il, gary. hodes@weizmann.ac.il, konstantin.gartsman@weizmann.ac.il	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E-mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $34,000 2000: $132,000 1999: $127,000	**Cost Share Funding:**

Project Objective: Develop improved understanding of the mechanisms leading to degradation of CdTe solar cells during their use; suggest and test various ways to reduce such degradation.

Approach/Background: We check the assumption that atomic migration of contact constituents is involved in device degradation. To do this we need to identify and measure such atom mobility. For this purpose several techniques that have been used by us for single crystals are adapted for use with polycrystalline thin films. These include the p/n junction motion and transient ion drift (capacitance decay). Subsequently new ways to make contacts as well as ways to prevent atom motion will be explored and their efficacy tested by some of the above-mentioned techniques. Prominent among these will be CdTe surface modifications.

Status/Accomplishments: Stress – testing of samples, supplied by NREL and First Solar, including complete cells, continued. The scientific literature concerning stability of CdTe/CdS cells was reviewed and scrutinized for indications of atom mobility. In this way we found unexplained differences between modules and cells, possibly between encapsulated and air-exposed systems. We have, therefore, suggested that particular attention be paid to the action of air, probably with water, on and in cells. Another result of this effort was a comprehensive model for Cu-assisted cell degradation, which should now be tested experimentally by the appropriate R&D teams.

Both LBIC and EBIC were used to distinguish between stressed and unstressed cells. From these we could confirm our earlier hypothesis that decrease in charge separation efficiency is correlated with increase in electrical heterogeneity of the cell.
After treating cells without back contact with a series of simple organic compounds, whose dipole is varied systematically, we find, *grosso modo*, such systematics in the electronic behaviour and electrical characteristics of these cells, suggesting significant porosity of the CdTe film.

$NiTe_2$ rather than NiTe or a Ni-P material, was found to be the product of a *modified* electroless Ni:P deposition process. Such back contacts were further optimized, with special attention being given to stability,

Planned FY 2001 Activities:
Further measurements on stressed and unstressed cells are planned to detect the diffusion of other contact-related species, such as Hg, including photoluminescence.

SIMS analysis (S. Asher, NREL).on samples investigated by LBIC, will be done, to assert the cause for the diffusion front that was discovered.

We continue our efforts on electrical measurements of single grains and single grain boundaries to better understand factors that limit and, eventually to improve cell efficiency and stability. These efforts employ scanning probe and electron microscopies with sub-micrometer resolution manipulators, to check models for Cu-assisted degradation, as well as to characterize the effect of chemical treatments on the grain bulk and surface. The treatments concern organic molecular as well as inorganic ones. These investigations will include adsorption of a wider variety of molecules than used hitherto. As part of these efforts we will need to characterize the effect of molecule adsorption on the electronic properties of single-crystal p-CdTe (which will be prepared in-house), and on cells, completed here by applying the appropriate back contact.

Further characterization of the $NiTe_2$ back contact is planned, especially the identification of contaminants in the $NiCl_2{\cdot}6H_2O$ solution which affect the behavior of the deposited contact. Co will also be studied in place of Ni.

Major Reports Published in FY 2000:
D. Cahen, K. Gartsman, G. Hodes, O. Rotlevy, I. Visoly-Fisher, and K. Dobson, Overcoming Degradation Mechanisms in CdTe Solar Cells, NREL/SR-520-27932, 02/2000.

Major Articles Published in FY 2000:
K. Dobson, I. Visloy-Fisher, G. Hodes, D. Cahen, "Performance and Stability of CdTe/CdS Thin-Film Solar Cells", *Sol. En. Mater. Sol. Cells*, **62**, 295-325 (2000);

O. Rotlevi, K. Dobson, D. Rose, and G. Hodes, Electroless Ni and $NiTe_2$, "Ohmic Contacts for CdTe/CdS PV Cells", *Thin Solid Films*, in press.

Photovoltaic Environmental, Health and Safety Assistance Center

Contract #: Project #: PV-1516	**Contract Period:** 10/1/99-9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	Brookhaven National Laboratory Building 830 Upton, NY 11973-5000 **Organization Type**: FF	**Congressional District**: 1
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator** Vasilis M. Fthenakis **Phone:** 631-344-2830 **Fax:** 631-344-4486 **E-mail:** vmf@bnl.gov	
Technical Monitor: A. Bulawka **Phone**: 202-586-5633 **Fax**: 202-586-5127 **E-mail:** Alec.Bulawka@ee.doe.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1994: $400,000 1998: $300,000 1995: $380,000 1999: $300,000 1996: $300,000 2000: $300,000 1997: $300,000	**Cost Share Information**: **Cost Share Funding:**

Project Objective: Assist the safe and environmentally friendly operation of photovoltaic facilities and products, extending from R&D to manufacturing and deployment. The specific objectives of the Center are to help in preventing accidents, reduce EH&S occupational and public risks, and reduce environmental and safety related costs. These objectives are paramount to the economic viability and public acceptance and support of PV systems.

Approach/Background: The BNL Center conducts the following types of activities: 1) It provides direct support to DOE Headquarters, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory (SNL) to ensure that the operations of their facilities and those of their contractors are operated in an environmentally responsible manner. 2) It conducts EH&S audits, safety reviews and incident investigations, as needed. 3) It assists the photovoltaic industry to identify and examine potential EH&S barriers and hazard control strategies for new photovoltaic material, process and application options before their large-scale commercialization. To facilitate the application of knowledge derived from the above activities, BNL hosts workshops, tutorials and symposia, uses electronic mail and a web page, and publishes articles in the peer-reviewed literature (155 publications up-to-date).

Status/Accomplishments: In FY 2000, we handled several requests for assistance and information from the industry, universities, and the public; we visited First Solar's new plant at Perrysburg, Ohio and assisted them on environmental and material handling issues; we visited BP Solar, Fairfield, CA and assisted them on site-specific EH&S issues and issues related to California regulations; we compiled and reviewed domestic and international environmental regulations affecting PV manufacturing and disposal; reviewed recent studies on the explosiveness of silane and developed a software tool for evaluating the safety of silane handling systems; and modeled CO_2 emissions reduction for various scenarios of market penetration. We published the proceedings of the workshop "Lead-free Solder Technology Transfer", two journal papers, and a conference paper.

Planned FY 2001 Activities:
Task 1: *Identify and characterize EH&S issues related to new technologies, processes, materials and applications.* We will continue conducting EH&S research related to new photovoltaic and conducting materials, tried by the industry in their pursuit of the 5-year and 20-year roadmap milestones. In FY 2001, we plan to examine potential EH&S issues related to the production of dye-sensitized solar cells, contributing to a 200l milestone in the 5-year program roadmap.

Task 2: *Hazard Management:* Our studies on safety and loss prevention will continue to ensure that today's PV facilities are protected in the most efficient and vigilant way. These activities are pivotal in preserving the safe and environmentally friendly nature of the PV industry as it moves towards multi-hundred-megawatt manufacturing (a 2003 program milestone). This task is leveraged by hazard management research in the semiconductor and chemical industries. In FY2001 BNL will participate at the Semiconductor Safety Association (SSA) Risk Assessment and Risk Management conference, and the American Institute of Chemical Engineers (AIChE) Loss Prevention Symposium. In the environmental area, we will evaluate options available to the PV industry on substitution and mitigation of greenhouse and ozone-depletion gases. Also, our studies regarding waste management options for PV manufactures and vendors in California will continue.

Contract #: Project #: PV-1516

<ins>*Task 3*</ins>*: Industry Outreach*: a) Directly assist PV production facilities to run safely and friendly to the environment. In FY 2001, we will continue interactions with BP Solar, First Solar and Siemens Solar on issues previously identified, and we plan to visit other PV facilities and assist them on site-specific issues. b) If additional funding is available, we propose: 1) to make our facility visits/ EH&S audits more comprehensive by engaging multi-disciplinary teams of experts instead of the current practice of one-person visits; 2) to expand the industry outreach effort with visits to university laboratories, which handle hazardous materials (e.g., silane); 3) to present on-site basic EH&S tutorial during these visits. c) Efforts will be made to enhance industry collaboration on EH&S and other "common ground" areas (e.g., material supplies, material utilization, waste minimization), following last year's example of industry collaboration on Pb-free solder technology transfer.

<ins>*Task 4*</ins>*. Assist DOE, NREL and Sandia on PV EH&S Issues* as needed. The PV EH&S Assessment and Assistance Center has interactions with the Thin-Film Partnership, DOE-SBIR, Million Roof Program, and PVMat projects.

<ins>*Task 5*</ins>*. Information dissemination.* a) The results of Tasks 1 and 2 will be disseminated with new publications, e-mail and the web. b) Answers to inquiries about EH&S information and assistance from the industry, and inquires regarding PV EH&S issues and environmental benefits from the public, media and the investor's community. In addition to the above activities, in FY2001, BNL will contribute to a project focusing on California PV EH&S conducted by EPRI with support from the California Energy Commission.

Major Reports Published in FY 2000:

Fthenakis V., Proceedings of the Pb-free Solder Technology Transfer Workshop, October 19, 1999, Vail, CO, Brookhaven National Laboratory, BNL-67536.

Fthenakis V., Regulations Affecting PV Disposal, Recycling and Transboundary Movement of Spent PV Modules, Brookhaven National Laboratory, Progress Report, September 2000.

Major Articles Published in FY 2000:

Fthenakis V.M. and Moskowitz P.D., Photovoltaics: Environmental, Safety and Health Issues and Perspectives, Progress in Photovoltaics, Millennium Issue, 8, 27-38, 2000.

Fthenakis V.M., A Review of Recent Silane Explosion Tests, NCPV 2000 Program Review Meeting, April 17-19, 2000, Denver, CO.

Fthenakis V.M., End-of Life Management and Recycling of PV Modules, Energy Policy Journal, 28, 1051-1058, 2000.

Technology Development

PV Manufacturing R & D

Cost Reduction and Manufacture of the SunSine™ AC Module

Contract#: ZAX-8-17647-03	**Contract Period:** 4/21/98–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	Applied Power Corp., Ascension Technology Division 1210 Homann Drive Lacey, WA 98503	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** E. Kern **Phone:** 781-684-6101 **Fax:** 781-890-2050 **E-mail:** ekern@ascensiontech.com Miles Russell **Phone:** 781-684-6102 **Fax:** 781-890-205 **E-mail:** mrussell@ascensiontech.com Gregory Kern **Phone:** 303-417-1418 **Fax:** 303-417-1423 **E-mail:** gkern79725@aol.com	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6490 **E-mail**: holly_thomas@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Applied Power Corp., Ascension Technology Division
	DOE Funding Allocation: 1998: $144,280 2000: $313,699 1999: $154,232	**Cost Share Funding:** 1998: $ 61,834 2000: $274,856 1999: $(17,657)

Project Objective: Applied Power Corp./Ascension Technology's (APC/AT) objectives are to achieve: 40-50% reduction in inverter manufacturing costs, a 40% or more reduction in inverter size from 169 to 100 square inches; a 4% increase in peak inverter efficiency from 87 to 91% at full power; as well as UL listing, FCC certification, and export certifications. They will also establish a production capability of 5,000 SunSine™ inverters/year through manufacturing improvements and production line design improvements; 0.10% failures at time of installation/turn-on; a 5 year warranty; and reach a rating of 250 W_{ac} at PTC for the SunSine™ AC Module Rating.

Approach/Background: The objective of this subcontract over its two phases is to continue to improve the manufacturability and reliability of the SunSine™ AC Module and address design improvements in order to reduce the cost to manufacture the SunSine™ inverter by 40-50% per unit. This work will also boost its performance and enhance its marketability by adding customer-valued features. AT will accomplish these advancements by reductions in the die-cast aluminum enclosure and base plate; utilizing soft switching for cost reduction and performance gains; optimizing the circuit board and components for performance gains and size reduction; and streamlined testing.

Status/Accomplishments:
In Oct 1999, the first prototype SunSine AC Module was delivered to NREL to begin outdoor testing. Initial tests of inverter efficiency indicated 91.0%, right on target for the project objectives. The die-cast aluminum enclosure design was completed, prototyped, and placed into production. Two patent applications, one relating to the design of the die cast enclosure, the other to the power electronics desing and a factory calibration procedure, were filed. UL Listing and FCC Class B EMI testing of the revised SunSine AC Module was completed. The SunSine AC Module was approved to the New York Standardized Interconnect Requirements by the New York Department of Public Service, which is a more rigorous standard. Pilot production of an initial 110 units was nearly completed. Of these, 28 were installed at the University of Texas, Houston Science Center, others were installed with Portland Power (Oregon).

Planned FY 2001 Activities:
During this fiscal year, AP/AT will: 1) complete pilot production and begin regular production of the SunSine; 2) complete Revision G of the power board; 3) complete the Highly Accelerated Lifetime Testing (HALT) to simplify manufacturing, improve reliability and reduce costs; and 4) submit the revised SunSine AC PV Module for testing at SNL and NREL.

Major Reports Published in FY 2000:
E. Kern and Greg Kern, (March 2000), "Cost Reduction and Manufacture of the SunSine AC Module – Annual Report," 16 pp. NREL/SR-520-27982, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000:
J. Hoffner, M. Palani and E. Kern, "A PV window Awning System on the University of Texas Houston Health Science Center Using AC Modules," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Cost Reductions in High Volume EFG PV Module Manufacturing Line

Contract #: ZAX-8-17647-10	**Contract Period:** 8/5/98–2/4/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	ASE Americas 4 Suburban Park Drive Billerica, MA 01821-3980	
	Organization Type: IN	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Kalejs **Phone:** 978-947-5993 **Fax:** 978-663-7555 **E-mail:** jkalejs@asepv.com	
Technical Monitor: Martha Symko-Davies **Phone**: 303-384-6528 **Fax**: 303-384-6490 **Email:** martha_symko_davies@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: ASE Americas
	DOE Funding Allocation: 1998: $168,000 1999: $972,801 2000: $667,668	**Cost Share Funding:** 1998: $182,000 1999: $1,046,557 2000: $838,734

Project Objective: The objective of this PVMaT subcontract over its 3-year duration is to advance ASE Americas' PV manufacturing technologies in order to lower costs of ASE manufacturing systems through development of improved larger diameter EFG tube and thinner wafer production, process integration, Statistical Process Control implementation, data systems implementation, and ISO9000 and ISO14000 implementation.

Approach/Background: ASE Americas will meet these objectives by:

- Developing processes which can be scaled-up to high volumes in manufacturing
- Developing the growth of larger diameter EFG tubes with improved productivity and production of solar cells from the resulting wafers
- Improving crystal growth, laser cutting and wafer etching technology to obtain higher cutting speeds and stronger EFG wafers, and cell processing for improved efficiencies.
- Investigate Flexible Manufacturing through the development of large-area EFG wafers, continuous improvement, and advanced module manufacturing.

Status/Accomplishments:

- Electrical yield loss reduction of 10% demonstrated on manufacturing line relative to Phase I baseline.
- Modifications have been completed to crystal growth, laser cutting system and etching processes, to produce lower stress and stronger EFG wafers. New etch equipment for improving wafer strength and reducing chemical waste is undergoing initial testing and being brought on line in manufacturing
- Rapid Thermal Anneal (RTA) processing developed at Georgia Tech for increasing EFG solar cell efficiency using oxide formation, back surface fields, silicon nitride and gettering.
- Design, construction, and installation of advanced laser wafer laser-cutting system for cutting up to 2 in/s *with reduced damage* has been completed.

Cost Reductions in High Volume EFG PV Module Manufacturing Line

- A solar cell processing sequence has been devised and solar cells of 13% efficiency have been made on 150 µm thick wafers up to 6 cm x 6 cm in area cut from EFG cylinders
- Initial analysis of field test samples for new module encapsulation technology has been completed.
- Evaluation has been completed for reliability and quality performance of the AC module in field tests.

Contract #: ZAX-8-17647-10

Planned FY 2001 Activities:

- Demonstrate manufacturing chemical waste, mechanical and electrical yield loss reduction of 10% each
- Achieve a 9% module manufacturing cost reduction
- Complete installation of TPM on 75% of most critical process stations
- Complete ISO9000 and ISO14000 compliance implementation and begin certification
- Complete a design review of large diameter EFG growth performance and processing of solar cells and document large area cell performance as commercial product
- Complete design review on new Georgia Tech processes for increasing EFG solar cell efficiency
- Complete integration of crystal growth processes**,** advanced laser cutting technology, and etching processes, to produce lower stress and stronger large EFG wafers for manufacturing
- Complete identification of manufacturing process schematic for full-scale manufacturing of new encapsulation process.
- Complete evaluation of ability of the AC module to be released as a commercial product.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

Roy, B. Mackintosh, J. P. Kalejs, Q.-S. Chen, H. Zhang and V. Prasad, "A numerical model for inductively heated cylindrical silicon tube growth system", J. Crystal Growth 211(2000) pp 365-371.

J.-W. Jeong, M. D. Rosenblum, J. P. Kalejs and A. Rohatgi, "Hydrogenation of defects in EFG Al-enhanced plasma enhanced CVD Silicon Nitride multicrystalline silicon" J. Appl. Phys. 87(2000) pp. 7551-7557.

B.R. Bathey, J. Cao, R.M. Giancola, M.J. Kardauskas, M.D. Rosenblum and J.P. Kalejs, ASE Americas, Inc., Billerica, MA, "R&D Toward a 15+% Efficiency Solar Cell Manufacturing Line for Multicrystalline Silicon Wafers," *proc. 28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

B.H. Mackintosh, M.P. Ouellette, M.D. Rosenblum and J.P. Kalejs, ASE Americas, Billerica, MA; and B.P. Piwczyk, Xinetics, Inc., Devens, MA, "100 Micron Thick Multicrystalline Si Wafers and Cells from Large Diameter EFG Cylinders," *proc. 28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

J.W. Jeong and A. Rohatgi, Georgia Institute of Technology, Atlanta, GA; M.D. Rosenblum and J.P. Kalejs, ASE Americas, Inc., Billerica, MA, "Lifetime Enhancement in EFG Multicrystalline Silicon," *proc. 28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

I. Tarasov and S. Ostapenko, University of South Florida, Tampa, FL; and J.P. Kalejs, ASE Americas, Billerica, MA, "Defect Monitoring Using Scanning Room_Temperature Photoluminescence in Crystalline Silicon Solar Cells," *proc. 28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

M.D. Rosenblum, R.L. Brown, R. Gonsiorawski and J.P. Kalejs, ASE Americas, Inc., Billerica, MA, "ISO 14000 Introduction in the Photovoltaic Industry," *proc. 28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

PV Manufacturing R & D

Silicon-Film™ Solar Cells by a Flexible Manufacturing System

Contract #: ZAX-8-17647-01	**Contract Period:** 4/16/98–5/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	AstroPower, Inc. Solar Park Newark, DE 19716-2000	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Rand and J. Culik **Phone:** 302-366-0400 x136 **Fax:** 302-368-6474 **E-mail:** jimrand@AstroPower.com	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6490 **E-mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: AstroPower, Inc
	DOE Funding Allocation: 1998: $874,734 2000: $985,785 1999: $1,005,352	**Cost Share Funding:** 1998: $890,479 2000: $1,021,979 1999: $1,058, 659

Project Objective: The objective of this subcontract is to advance the Silicon-Film™ solar cell manufacturing process to reduce solar-cell and module cost, expand production capacity, and develop a manufacturing system for a 50-MW fully integrated manufacturing plant that will produce a variety of panel and module products.

Approach/Background: AstroPower will meet these objectives by developing several flexible solar cell manufacturing processes capable of handling large-area Silicon-Film™ sheets at high speeds and generating solar cells of various sizes in a manufacturing-friendly environment. These in-line Silicon-Film™ processes will include chemical surface etching, impurity gettering, junction diffusion, and contact metalization.

Status/Accomplishments:

- Completed production-level testing of new oxide-etch system, and transferred system to the AstroPower production line. New system was so successful that a second, larger system was specified, purchased and commissioned.
- Improved oxide-etch system solution chemistry to accelerate process and reduce etch time.
- Completed detailed design, specification, and purchase of prototype silicon-etch system.
- Developed new 8" Silicon-Film™ solar cell product (designated as APx-8 solar cell). Product used in new family of AstroPower modules ranging from 50W to 220W.
- Completed changes in cell production line allowing processing of 8" wafers.
- Widened process window on continuous emitter diffusion process.
- Designed and installed new high temperature chambers for belt furnaces.
- Optimized front contact metallization firing process for Silicon-Film™ solar cells.
- Developed post-metallization forming gas anneal process.
- Initiated development of improved in-house metallization ink.
- Developed and implemented surface cleanliness analysis technique.
- Completed an investigation of batch wet chemical processes.
- Assembled higher capacity continuous Silicon-Film™ sheet production machine capable of 3 m/min throughput.
- Completed design and prototyping of large-area roof top module.
- Completed development and testing of residential roof-top solar electric system that includes all necessary components for assembling a code-compliant system.
- Designed, constructed, and commissioned module tester for larger-area laminates and modules.
- Designed, constructed, and commissioned cell tester for larger-area cells incorporating new low-cost, large-area light source simulator.

Contract #: ZAX-8-17647-01

Planned FY 2001 Activities:

- Develop continuous in-line silicon-etch system and transfer process to AstroPower Silicon-Film™ manufacturing line.
- Move new APx-8 solar cell to full-scale production.
- Develop new contact metallization process options for Silicon-Film™ solar cells.
- Develop production-scale silicon nitride anti-reflection coating system for Silicon-Film™ solar cells.
- Demonstrate production of Silicon-Film™ sheet production at 3.0 m/min.
- Complete design of AstroPower 50 MW/yr Silicon-Film™ manufacturing line.

Major Reports Published in FY 2000:

J.S. Culik, J.A. Rand, J.R. Bower, J.C. Bisaillon, J.R. Cummings, K.W. Allison, I. Goncharovsky, R. Jonczyk, S.D. Ressler, P.E. Sims, R.B. Hall, and A.M. Barnett, "Silicon-Film Solar Cells by a Flexible Manufacturing System", PVMaT Phase II Annual Subcontract Report, February 1, 1999 - January 31, 2000, NREL/SR-520-28547, (August 2000).

Major Articles Published in FY 2000:

S. Ressler, J. Culik, J. Bower, C. Dunne, and J. Rand, "Large-Area Roof-Mount Silicon-Film™ Module and Grid-Connected Rooftop System Design," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

J.C. Bissaillon, J.R. Cummings, J.S. Culik, J.D. Lesko, P.E. Sims and J.A. Rand, "Non-Traditional Light Sources for Solar Cell and Module Testing", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

I. Goncharovshy, J.S. Culik, G.A. Addison, P.E. Sims, and J.A. Rand, "PVMaT Enabled In-Line Chemical Processing of Silicon-Film Solar Cells" NCPV Program Review Meeting, Denver, 16-19 April 2000.

PV Manufacturing R & D

Improvements in Polycrystalline Silicon PV Module Manufacturing Technology

Contract #: ZAX-8-17647-05	**Contract Period:** 5/4/98–9/3/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	BP Solar 630 Solarex Court Frederick, MD 21701 **Organization Type**: IN	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Wohlgemuth and S. Shea **Phone:** 301-698-4375 **Fax:** 301-698-4201 **E-mail:** Wohlgej@bpsolar.com	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6490 **E-mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $470,000 2000: $873,342 1999: $928,235	**Cost Share Information**: BP Solar **Cost Share Funding:** 1998: $489,184 2000: $892,014 1999: $879,837

Project Objective: The objective of this subcontract over its three year duration is to advance the of BP Solar PV manufacturing technology in order to design and implement a process which produces polycrystalline silicon PV modules that can be sold profitably for $2.00 per peak watt or less and which increases the production capacity of the Frederick plant to at least 25MW/year.

Approach/Background: BP Solar will meet these objectives by:

- Developing a process to produce solar-grade silicon feedstock from commercial grade H_2SiF_6 that can be sold profitably for less than $15/kilogram in large quantities to industrial Silicon PV manufacturers.
- Improving the control of their casting process to increase yields and improve material quality through a new automated casting control system.
- Reducing their wire saw center-to-center cut distance to less than 450μm in production.
- Developing glycol-based slurry system that doesn't require organic cleaners and eliminates generation of hazardous waste.
- Developing a method to recycle a significant fraction of their silicon carbide grit.
- Demonstrating and implementing a cost-effective, robust cell process that produces a minimum average cell efficiency of 15% and improves the cell line electrical yield.
- Developing and qualifying an encapsulation system that meets technical and reliability requirements and can be laminated and cured in less than 6 minutes in the present BP Solar laminators,
- Refining three specific production line process areas for improved product and materials handling to increase production line yield and reduce labor,
- Improving process measurement and control in their production line and reduce rework through the implementation of an improved information system.

Status/Accomplishments:

- Completed fabrication of pilot facility for production of solar-grade silicon from SiF_4.
- Designed and constructed laboratory prototypes of ceramic handling and slip dispensing equipment.
- Completed transfer of SiC recycling process to BP Solar production line.
- Completed installation of oil recycle equipment and transferred to BP Solar production line.
- Completed wire saw process optimization on BP Solar production line.
- Identified candidate methods for detecting cracks in wafers and finished cells.
- Completed cost analysis for reductions in consumable costs by at least $0.05/wafer.
- Completed design and development of prototype ultrasonic doper.
- Completed environmental testing of cells from new ultrasonic doper and implemented onto BP Solar production line.
- Completed design, fabrication, and installation of production silicon-nitride deposition system.
- Identified candidate method for in-line, non-destructive testing of cell interconnects.
- Selected two candidate fast cure encapsulant formulations for environmental and outdoor testing.

Contract #: ZAX-8-17647-05

Planned FY 2001 Activities:
- Demonstrate silicon production from SiF_4 and Na.
- Complete implementation of controls and monitoring procedures to assure casting process remains in control and optimized.
- Complete transfer of silicon nitride process to BP Solar production line.
- Complete transfer of new edge isolation process to BP Solar production line.
- Complete qualification and transfer of fast cure encapsulant to BP Solar module production line.

Major Reports Published in FY 2000:

J. Wohlgemuth, "PVMaT Improvements in the Solarex Photovoltaic Module Manufacturing Technology", Annual Subcontract Technical Report, 4 May 1998- 3 May 1999, NREL/SR-520-27643, (January 2000)

J. Wohlgemuth, and S. Shea, "PVMaT Improvements in the Solarex Photovoltaic Module Manufacturing Technology", Annual Subcontract Report, 5 May 1999- 15 June 2000, NREL/SR-520-29459, (December 2000)

Major Articles Published in FY 2000:

A. Cuevas, M. Kerr, D. Macdonald, C. Samundsett, A. Sloan, A. Leo, M. Mrcarica, S. Winderbaum, and S. Shea, "Evidence of Impurity Gettering by Industrial Phosphorus Diffusion," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

J.P. Galica and N. Sherman, "Results to Date - Development of New EVA-based Encapsulants, Faster-Curing and Flame Retardant Types", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

J.P. Galica and N. Sherman, "Development of Low-Cost Faster-Curing Encapsulants for Terrestrial PV Modules", 18th E. C. Photovoltaic Solar Energy Conference, Glasgow, Scotland, 1-5 May 2000.

Production of Solar Grade (SoG) Silicon by Refining of Liquid Metallurgical Grade (MG) Silicon

Contract #: ZAX-8-17647-13	**Contract Period:** 6/10/98-4/19/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Crystal Systems, Inc.
27 Congress Street
Salem, MA 01970</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Chandra Khattak
Phone: 978-745-0088 Fax: 978-744-5059 Email: khattak@crysys.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Martha Symko-Davies
Phone: 303-384-6528
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E-mail: martha_symko_davies@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Crystal Systems, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $143,500 2000: $420,000
1999: $386,500</td><td>Cost Share Funding:
1998: $61,500 2000: $172,623
1999: $156,705</td></tr>
</table>

Project Objective: The objective of this PVMaT program is to produce solar grade (SoG) silicon feedstock by refining metallurgical grade (MG) silicon in the liquid state so that this material can be used as feedstock for ingot processes such as the Heat Exchanger Method (HEM) for photovoltaic applications. It is intended to continue this technology development in larger scale using thermo-chemical refining techniques and reduce metallic impurities and Boron (B) and Phosphorous (P) in MG silicon to less than 1 ppma at the 450-kg level.

Approach/Background: The approach is based on thermo-chemical refining of metallurgical grade (MG) silicon using the Heat Exchanger Method. The reduction of most impurities to less than one ppma level was demonstrated with approximately 3-kg charge of MG silicon with this approach. The present program focuses on the development of equipment and procedures for upgrading MG silicon to the SoG level consistent with theoretical analysis and experimental results. Prototype experiments will be carried out with up to 450-kg charge size. The projected production cost of SoG silicon is less than $20/kg.

Status/Accomplishments: Commercially available metallurgical grade (MG) silicon contains several impurities that need to be reduced to produce solar grade (SoG) silicon feedstock. Most of the impurities have low segregation coefficients and therefore can be removed using directional solidification of the melt. The two impurities, B and P, have high segregation coefficients. Therefore, it is necessary to remove B and P prior to directional solidification. The segregation coefficients of B and P are 0.8 and 0.35, respectively. This means that B will be least affected by directional solidification. The most economic approach for removing B and P is to develop a simple refining step prior to directional solidification. CSI has emphasized developing refining steps involving stirring of the bath using a neutral gas such as argon, reaction with reactive gases, varying the moisture content of these gases, and reaction with various slag chemistries, etc. Special attention was paid to removing B and P with emphasis on B removal and evaluating the scalability of the refining steps. The effort concentrated on starting with commercially available MG silicon. Experiments with 1-kg charge size reduced B and P to 1.8 ppma and 7.5 ppma, respectively. The charge size was increased with a goal of maintaining B and P to <10 ppma. For a 100-kg charge (Run #MG3-14), B and P were reduced to 5.5 and 11 ppma, respectively. Refining was carried out for charge sizes up to 150 kg. The B and P concentrations were reduced to 8.6 and 6.3 ppma, respectively for a 140-kg charge (Run #MG3-16). Beside B and P all other impurities were reduced to below 0.1 ppma.

The effectiveness of the simple B reduction process developed was confirmed by using heavily B-doped high purity silicon that contained 10 times the B concentration that of MG silicon. Such silicon is available as reject and scrap from the semiconductor industry, but it cannot be used, with its present B doping, as feedstock for the photovoltaic industry. The simple B reduction process developed by CSI could be used with this silicon and thereby develop a new source of high-purity feedstock for the interim until MG silicon can be effectively developed to produce SoG silicon.

Theoretical analysis was carried out and a model was developed to estimate the B removal rate using experimental parameters. The experimental program was focused on achieving more effective refining within a segment rather than on achieving the lowest B and P concentrations. Based on this data, it was calculated that the projected refining time for reducing B concentration in commercially available MG silicon to <1ppma can be approximately 2-15 hours depending on assumptions in the model.

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Status/Accomplishments (continued): In order to scale up the charge sizes without increasing the crucible or furnace size, it is necessary to add feedstock to the crucible after the initial charge is molten. This procedure of hot loading the melt was carried out to show that MG silicon feedstock can be added to the molten bath of silicon. This procedure was demonstrated with a 300-kg charge. The crucible used for this experiment was a 69-cm square-cross-section crucible with a diagonal of approximately 98 cm. If a 100-cm diameter round crucible is used, it will fit in the current HEM furnace. An ingot of the same height as the 300-kg charge but in the 100 cm diameter crucible will be approximately 500 kg. It was demonstrated that such a charge of 500-kg can be refined using present procedures in the existing furnace.

An effective and simple approach has been developed to refine B in commercially available MG silicon. With current procedures, this approach is scalable to large charge sizes. Refining experiments have been carried out up to 150 kg. Hot loading procedures for adding feedstock to molten silicon have been developed and demonstrated for charges up to 300 kg. With an appropriate crucible, charge sizes up to 500 kg can be refined using the current HEM furnace. The projected refining times for removing B from commercially available MG silicon to <1 ppma can be carried out using this simple approach in 2-15 hours. The P reduction has also been demonstrated and <10 ppma has been achieved. Other impurities have been reduced to <0.1 ppma. The approach is consistent with producing SoG silicon at a production cost of less than $20/kg.

Planned FY 2001 Activities: CSI is continuing R&D efforts to improve the effectiveness of B removal so that the refining times can be reduced. CSI is focusing on reducing B concentration to <1 ppma so that the material can be used as feedstock for silicon ingot growth and for use in solar cell applications. A process to further reduce the P concentration during refining shall be developed using slagging additions to the melt. CSI shall refine and characterize MG silicon from charges of 300-450 kg and demonstrate economic feasibility of the project. The refined material will be distributed to the photovoltaic industry for evaluation.

Major Reports Published in FY 2000:

C. P. Khattak, D. B. Joyce, and F. Schmid, "Production of Solar Grade (SoG) Silicon by Refining Liquid Metallurgical Grade (MG) Silicon," *Annual Report, NREL/PVMaT Phase 5A, Subcontract No. ZAX-8-17647-13 (Phase I),* 32 pp. *(*1999).

Major Articles Published in FY 2000:

C. P. Khattak, D. B. Joyce and F. Schmid, "Production of Solar Grade Silicon by Upgrading MG Silicon in Charges up to 140 Kg," *NCPV Program Review Meeting 2000*, 16-19 April 2000, Denver, CO, (2000).

C. P. Khattak, D. B. Joyce, M. A. Wilkinson and F. Schmid, "Refining Molten Metallurgical Grade Silicon for Use as Feedstock for Photovoltaic Applications," *16th European Photovoltaic Solar Energy Conference and Exhibition*, Glasgow, Scotland, May 1-5, 2000 (in press).

C. P. Khattak, D. B. Joyce and F. Schmid, "Production of Solar Grade Silicon by Upgrading MG Silicon in Sizes up to 140 kg," *10th NREL Workshop on Crystalline Silicon Solar Cell Materials and Processes,* Copper Mountain, CO, August 13-16, 2000.

C. P. Khattak and F. Schmid, "Production of Multicrystalline Silicon Ingots by HEM for Photovoltaic Applications," *2nd International School on Crystal Growth Technology,* Zao, Japan, August, 2000.

C. P. Khattak, D. B. Joyce and F. Schmid, "Upgrading Metallurgical Grade (MG) Silicon for Use as Solar Grade Feedstock," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000 (in press).

PV Manufacturing R & D

Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy Manufacturing Technology

Contract #: ZAX-8-17647-09	**Contract Period:** 6/22/98–10/21/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Energy Conversion Devices 1675 West Maple Road Troy, MI 48084 **Organization Type:** IN	**Congressional District:** 12
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. Ellison **Phone:** 248-362-4780 **Fax:** 248-362 0012 **E-mail:** time@ovonic.com	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax:** 303-384-6490 **E-mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $333,000 2000: $830,854 1999: $942,000	**Cost Share Information**: Energy Conversion Devices **Cost Share Funding:** 1998: $567,000 2000: $839,302 1999: $709,990

Project Objective: The objective of this subcontract over its three year duration is to advance Energy Conversion Devices' PV manufacturing technologies in order to support the PVMaT cost-reduction and capacity-increase goals with the development of manufacturing technologies which allow a 25-30% reduction in module cost ($/W) and a 60% increase in manufacturing capacity (MW/year) over the United Solar 4th Quarter 1997 annualized manufacturing capacity.

Approach/Background: Energy Conversion Devices, Inc. will meet these objectives by:

- Developing, fabricating and installing a new substrate heating system and temperature sensor system designed to achieve more accurate temperature controlling and monitoring for the production of high-efficiency solar cells,
- Developing, fabricating, and installing a set of in-line real-time material quality monitoring systems for the United Solar Systems production machines,
- Demonstrating the feasibility of using Zn metal targets in the DC sputtering process to prepare ZnO layers for high performance back-reflectors for incorporation of the process into United Solar's 5-MW amorphous silicon (a-Si) module production line,
- Redesigning the internal hardware for the a-Si intrinsic layer deposition chambers used in the 5-MW United Solar's production line, and
- Developing, fabricating, installing and testing new Pinch Valve technology to allow loading and unloading rolls of web without letting up the deposition chambers to atmospheric pressure.

Status/Accomplishments:

- Completed development, testing, and implementation of new substrate heating system in the United Solar 5 MW production equipment with resulting increased run times, decreased cost, and improved cross-web temperature uniformity.
- Completed development of ZnO Reflectometer to measure the precise online adjustment of ZnO thickness in the production.
- Completed bench testing and design of 3rd generation PV Capacitive Diagnostic (PVCD) system to accurately measure voltage vs. time, VOC, the quantity Q/C, and Fill Factor in the take-up chamber.
- Completed design and initiated bench testing of 2nd generation back-reflector Scatterometer to measure both specular and diffuse reflectance in the 5 MW back-reflector machine.
- Demonstrated production of solar cells using new reactive ZnO sputtering process which demonstrated the same conversion efficiency as those made using ceramic ZnO targets. This process will be transferred to United Solar's 25 MW production line after further data collection.
- Demonstrated a ±5% i-layer deposition uniformity over 80% of the cathode area in the pilot roll-to-roll machine at deposition rates between 2.9 and 4.3 Å/s (up to 2.2 times faster rate than currently used in production).
- Demonstrated improved i-layer quality resulting in a 4 % increase in single-junction a-Si cell efficiencies over those obtained in production.
- Completed the prototype development, fabrication and installation of a new Pinch Valve technology for testing in United Solar's 5 MW and 25 MW production equipment.

Contract #: ZAX-8-17647-09

Planned FY 2001 Activities:

- Complete testing of rolling thermal couple concept testing in 5 MW production equipment, and transfer to new 25 MW production line.
- Initiate on-line collection and evaluation of Voc data using 3rd Generation PVCD on 5 MW production equipment.
- Complete bench-scale assessment of new photo-diode array scatterometer, and install in 5 MW production equipment for testing.
- Conduct evaluation of 3rd generation deposition geometry hardware in pilot roll-to-roll machine.
- Complete design, fabrication, and installation of improved 3rd generation deposition geometry hardware in 5 MW production equipment to evaluate long term reliability.
- Modify and qualify both software and operating procedures for incorporation of new pinch valve technology into United Solar production line.

Major Reports Published in FY 2000:

M. Izu, "Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology", Annual Subcontract Technical Status Report, 22 June 1998 - 21 June 1999, NREL/SR-520-27535, (November 1999).

T. Ellison, "Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology", Phase II Annual Subcontract Report, June 1999 - August 2000, NREL/SR-520-29288, (November 2000).

G. Bondarenko, J. Doehler, T. Ellison, E. Haggard, M. Izu, S. Jones, R. Kopf, A. Kumar, A. Myatt, J. Call, S. Guha, K. Hoffman, M. Lycette, G. Pietka, M. Walters, J. Yang, "ECD's PVMaT Progam: Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology", NCPV Program Review Meeting (April 2000).

Major Articles Published in FY 2000:

T. Ellison, R. Kopf, W. Messing, and T. Bernard, "Non-Contacting PV Capacitive Diagnostic (PVCD) System for Real Time in-situ Analysis, QA/QC, and Optimization," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Continuous, Automated Manufacturing of String Ribbon Si PV Modules

Contract #: ZAX-8-17647-07	**Contract Period:** 5/21/98-7/20/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	Evergreen Solar 211 Second Ave Waltham, MA 02154	
	Organization Type: IN	**Congressional District**: 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Jack Hanoka **Phone:** 781-890-7117 **Fax:** 781-890-7141 **E-mail:** hanoka@evergreensolar.com	
Technical Monitor: Martha Symko-Davies **Phone**: 303-384-6528 **Fax**: 303-384-6490 **E-mail**: martha_symko_davies@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Evergreen Solar, Inc.
	DOE Funding Allocation: 1998: $363,500 2000: $1,009,189 1999: $977,929	**Cost Share Funding:** 1998: $155,786 2000: $ 432,509 1999: $419,112

Project Objective: Continue to advance Evergreen Solar's (ESI) PV technology to achieve a multi-megawatt crystalline silicon manufacturing line, which is highly automated and virtually continuous.

Approach/Background: Exploit ESI's unique and innovative technology in the areas of silicon ribbon growth, cell making, and module manufacturing. Focus on crystal growth, cell manufacturing, module lay-up and factory layout and automation. Use developments in this project to further the objective of a high-throughput automated production line.

Status/Accomplishments: A completely redesigned String Ribbon crystal growth machine has been built, debugged, and will be the basic platform we will use in our new factory. This new design has a number of important features. These include simplification of the water cooled shell, a better frame design, a more compact packaging of the electronics, a single PLC to tie together all the control functions, a more tightly sealed system, a more accurate puller design, a feeder design wich reduces any possiblity of contamination, and a more general base plate design which will allow for further advances such as a lower cost hot zone and the growth of 10 cm. wide ribbon. At present, this machine will produce 8 cm. wide ribbon with a 30% higher growth speed than our earlier furnaces which grew 5.6 cm. wide ribbon. The result here is a doubling of throughput per machine over our earlier furnaces. This new machine was built at a 20% lower capital cost than the previous machines. It is designed to be more operator friendly and it is capable of significant automation. A major step in this direction has been the development of a full feedback automated thickness measurement and control. Another such step has been automatic freeze detection. The upgraded PLC could, in the future, feed data into a central computer. Also, the string reel feed mechanism has been redesigned such that the frequency with which reels of string need to be changed has been reduced by a factor of at least ten.

In the solar cell area, progress has been made in both machines for automation and in the overall process. A number of machines have been developed and built which will allow us to have a highly automated cell line with a minimum of both batch and wet chemistry steps. In the design of these machines, the following underlying principles were used: generic PLCs , vision systems, gantry systems, and rotary tables. The entire cell area is based on the movement of specially designed and bar coded plastic boxes that can readily be transported and handled by robots. Under these guidelines, new machines for contact application, diffusion load and unload, and integrated testing with front cell binning and tabbing have been developed. Several significant developments in solar cell processing were made this year. These include a method of incorporating hydrogen passivation which could have automated loading and unloading, a method and machine for continuous, belt type operation of diffusant glass removal, and the demonstration of a possibility of eliminating all wet chemical etch steps between growth and diffusion with the consequent elimination of the need for plastic carriers.

In the module manufacturing area, a new method has been developed for soldering individual cells and for forming cell strings which should provide much higher yields than that presently used.

Fraunhofer USA Center for Manufacturing at Boston University was utilized to lay the groundwork for ESI's move to a new multi-megawatt facility. They assisted with the factory layout, process flow, and buffer requirements so that we can properly exploit the latest advances in manufacturing science.

Contract #: ZAX-8-17647-07

Status/Accomplishments (continued):
Overall, the project is on schedule, and should reach its completion date as scheduled.

Planned FY 2001 Activities: The principal activity will be in integrating all the new machines and processes in the new multi-megawatt factory and then demonstrating their efficacy in terms of the typical production metrics such as materials costs, yields, machine uptime, and throughput.

Major Reports Published in FY 2000: Second Annual Report prepared under this subcontract. Submitted to NREL in June, 2000.

Major Articles Published in FY 2000:
R.E. Janoch, et al, "PVMaT Funded Manufacturing Advances in String Ribbon Technnology", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

A.P.Anselmo et al, " Automation of the String Ribbon Process", Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO.

PV Manufacturing R & D

Specific PVMaT R&D in CdTe Product Manufacturing

Contract #: ZAX-8-17647-06	**Contract Period:** 5/8/98–11/7/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">First Solar, LLC.
1702 North Westwood Ave.
Toledo, OH 43607</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 9</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
A. McMaster
Phone: 419-872-7661 Fax: 419-534-2794 E-mail: amcmaster@firstsolar.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Richard Mitchell
Phone: 303-384-6479
Fax: 303-384-6490
E-mail: richard_mitchell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Solar Cells, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $554,000 2000: $754,572
1999: $840,167</td><td>Cost Share Funding:
1998: $249,714 2000: $382,404
1999: $378,764</td></tr>
</table>

Project Objective: The objective of this subcontract over its three-year duration is to continue the advancement of the First Solar manufacturing technologies in order to: develop high-throughput, low-cost processes for the lamination, potting and laser scribing portions of the First Solar's CdTe module manufacturing line; improve acceptance of First Solar products into existing and new markets and improve the acceptance and variety of the First Solar product line to provide an opportunity to penetrate market segments other than those which are served by its standard frameless, 60cm x 120cm module; and establish a safety, health and environmental program which will place First Solar in a leadership position relative to comparable businesses both within and outside of the photovoltaic industry.

Approach/Background: First Solar will meet these objectives by:

- Developing low-cost lamination processes with throughputs raised from 18 modules/hour to at least 30-modules/hour while simultaneously reducing labor costs by 50% and lowering capital requirements by a factor of four.
- Developing high-throughput, low cost potting by increasing potting line throughput by a factor of at least four, reducing labor costs by at least a factor of ten, and increasing overall quality.
- Developing improved laser scribing techniques and equipment by engaging industry experts and vendors to implement state-of-the-art techniques and automation.
- Certifying First Solar modules according to IEEE 1262 and UL 1703 in three successive, evolutionary steps depending on product changes due to market demand and product changes.
- Refining and improving environmental, health and safety programs including use of external industry experts leading to ISO 14,000 certification and implementation of best-demonstrated-practices of world class programs.

Status/Accomplishments:

- Adopted new UL-listed mounting method replacing previously problematic polyurethane mounting pads.
- Developed new "Cord-Plate" contact termination method, replacing potted polyurethane termination "pigtails."
- Completed modifications to production potting process, including improvements in methodology and resource allocation.
- Completed testing of improved module lamination processes including standard pressure, thermal, and vacuum lamination with EVA, and selected EVA method for use on the First Solar production line.
- Completed design, fabrication and installation of high-throughput solar finishing line.
- Developed novel, single-laser scribing system and implemented in production, exceeding FY 2000 milestone. This completely automated system is up to 10 times faster and shows a 15-fold improvement in registration of consecutive laser-scribe lines than existing laser scribing systems.
- Completed and passed UL 1703 qualification testing of PVMaT improved modules.
- Completed over thirty different review activities covering First Solar Environmental, Health and Safety (EHS) program and published a report covering the results.
- Completed industry survey to determine additional needs in pursuing ISO 14000 certification.

Contract #: ZAX-8-17647-06

Planned FY 2001 Activities:
- Complete demonstration of First Solar rapid laser-scribing process and its performance in production.
- Complete encapsulation design review for modified module and resolve remaining design issues.
- Complete IEEE 1262, IEC 1215, and UL1703 qualification testing on First Solar's modified module.
- Complete allocation and assignment of capital and personnel resources for ISO 14000 project and initiate certification activities.
- Complete design, development, and testing of alternative module encapsulation, replacing glass with combination of polymer and metal, and complete an evaluation of its performance.
- Complete comprehensive review of First Solar PVMaT Environmental, Safety, and Health programs.

Major Reports Published in FY 2000:
J. Bohland, K. Kormanyos, G. Faykosh, V. Champion, S. Cox, M. McCarthur, T. Dapkus, K., Kamm, and M. Flis, "Specific PVMaT R&D in CdTe Product Manufacturing", Annual Subcontract Technical Report, 5 May 1998 - 4 May 1999, NREL/SR-520-27574, (February 2000).

M. McMaster, "Specific PVMaT R&D in CdTe Product Manufacturing", Phase II Annual Subcontract Technical Report - May 1999 - September 2000, NREL/SR-520-29292, (November 2000).

Major Articles Published in FY 2000:
D. Rose, R.C. Powell, U. Jayamaha, M. Maltby, D. Giolando, A. McMaster, K. Kormanyos, G. Faykosh, J. Klopping, and G. Dorer, "R&D of CdTe-Absorber Photovoltaic Cells, Modules, and Manufacturing Equipment: Plan and Progress to 100 MW/YR," presented at the 28th IEEE Photovoltaic Specialists Conference, Anchorage, AK, September 2000; to appear in the IEEE Conference Record.

J. Bohland and Ken Smigielsi, "First Solar's CdTe Module Manufacturing Experience; Environmental, Health and Safety Results," ibid.

Manufacturing Cost and Throughput Improvements for CIGS-based Thin Film PV Modules

Contract #: ZAX-8-17647-11	**Contract Period:** 7 /7/98–11/6/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Global Solar Energy
12401 W. 49th Avenue
Wheat Ridge, CO 80033</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 2</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
R. Wendt and S. Wiedeman
Phone: 303-285-5144 x18 Fax: 520-546-6318 E-mail: rwendt@globalsolar.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Richard Mitchell
Phone: 303-384-6479
Fax: 303-384-6490
E-mail: richard_mitchell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Global Solar Energy</td></tr>
<tr><td>DOE Funding Allocation:
1998: $290,000 2000: $826,004
1999: $788,030</td><td>Cost Share Funding:
1998: $136,471 2000: $301,649
1999: $264,885</td></tr>
</table>

Project Objective: The objective of this PVMaT subcontract over its three-year duration is to improve speed and yield for manufacturing thin-film CIGS PV modules. Areas identified that had the greatest impact on manufacturing yield and speed were: (1) high rate all-laser layer-specific scribing for monolithic integration; (2) eliminating screen printing by development, of commercial ink-jet techniques for high-speed, large-area thin-film PV module fabrication on a flexible substrates; (3) development of uniform, high rate (27 cm/min) absorber deposition with high materials utilization; (4) in-situ measurement and control of CIGS properties ; and (5) the development of a more robust back contact as a replacement for molybdenum to decrease the cost by over 50% and substantially reduce scheduled and unscheduled downtime.

Approach/Background: Global Solar Energy will meet these objectives by:
- Refining the all-laser, multiple-beam, high-speed scribing method for all CIGS PV layers, resulting in 23cm/sec beam translation speeds while achieving high yields using advanced machine vision control.
- Designing and adapting commercial ink-jet printing for module manufacturing to replace screen-printing.
- Integrating ink-jet printing into laser scribing equipment in the manufacturing production line resulting in freedom to generate complex patterns to tailor module performance voltage and current specifications.
- Modifying existing multi-source co-evaporation sources for high-rate CIGS deposition process on a continuous moving flexible substrate in production-based equipment.
- Optimizing source-sequence and relative flux profiles to achieve high efficiency at fast deposition rates.
- Designing, building and integrating Parallel Detector Spectroscopic Ellipsometer (PDSE) into the thin-film CIGS production line.
- Developing algorithms for real-time, full closed-loop control of CIGS thickness and stoichiometry.
- Developing alternative back contacts that are more amenable to high rate production and result in less debris generation.

Status/Accomplishments:
- Integrated new high-speed scribing processes into Global Solar Energy manufacturing equipment, demonstrating robust and repeatable scribing.
- Completed analysis and integration of industrial ink-jet hardware into Global Solar Energy production based equipment for high-speed module manufacturing.
- Completed evaluation of CIGS deposited at increased rates in production-based equipment.
- Completed testing of PDSE in evaluation deposition system and installed in production-based equipment.
- Completed characterization and analysis, and selected alternate back contact material and process, for alternate back-contact deposition on flexible polymer and stainless steel substrates.

Contract #: ZAX-8-17647-11

Planned FY 2001 Activities:

- Complete development of PDSE and X-Ray Florescence (XRF) control algorithms and install and test systems in production roll coater.
- Complete documentation of control limits on stoichiometry achieved with XRF in active control.
- Complete integration of ink-jet process with laser-scribing process on Global Solar Energy manufacturing equipment and evaluate ink-jet process repeatability and control.
- Complete analysis of module losses, such as area loss and shunting, due to new ink-jet process.
- Complete refinement of CIGS deposition parameters to achieve CIGS formation on a web moving at 27 cm/min.
- Complete analysis to determine final Se consumption required to form high-quality CIGS in Global Solar Energy manufacturing equipment.
- Initiate manufacture of completed 27-watt modules using a high-rate deposition processes.

Major Reports Published in FY 2000:

S. Wiedeman, R.G. Wendt, "Photovoltaic Manufacturing Cost and Throughput Improvements for Thin Film CIGS Based Modules", Annual Subcontract Technical Report, 7 July 1998 - 6 July 1999, NREL/SR-520-27590, (February 2000).

R.G. Wendt, S. Wiedeman, "Photovoltaic Manufacturing Cost and Throughput Improvements for Thin Film CIGS Based Modules", Phase 2 Technical Report, July 1999 - August 2000, NREL/SR-520-29283, (November 2000).

Major Articles Published in FY 2000:

J. Britt, S. Wiedeman, D. Mason, and R. Wendt, "High Rate CIGS Processing on Flexible Substrates", presented at the NCPV Program Review, April 2000.

PV Manufacturing R & D

Project Management

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
C. E. Witt Phone: 303-384-6402 Fax: 303-384-6490 E-mail: ed_witt@nrel.gov
Richard Mitchell Phone: 303-384-6479 Fax: 303-384-6490 E-mail: richard_mitchell@nrel.gov
Holly Thomas Phone: 303-384-6400 Fax: 303-384-6490 E-mail: holly_thomas@nrel.gov
Martha Symko-Davies Phone: 303-384-6490 Fax: 303-384-6490
E-mail: martha_symko_davies@nrel.gov</td></tr>
<tr><td rowspan="2">Technical Monitor:
Larry Kazmerski
Phone: 303-384-6600
Fax: 303-384-6601
E-mail: larry_kazmerski@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $1,261,726
2000: $1,139,052</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
- Help the U.S. PV industry improve module manufacturing processes and equipment.
- Accelerate manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems.
- Increase commercial product performance and reliability.
- Enhance the investment opportunities for substantial scale-ups of U.S.-based PV manufacturing plant capacities.

Approach/Background:
- The Project is a government/industry research and development (R&D) partnership between the U.S. federal government (through the U.S. Department of Energy [DOE]) and members of the U.S. PV industry.
- Multi-year projects are being carried out through cost-shared awards made in response to competitive solicitations.
- Each proposal from the U.S. photovoltaic industry is evaluated by panels of experts in the technology, manufacturing, business planning, and applications, including utility executives.
- Funding identified here supports technical management, subcontract administration, fees, and other direct recharges in support of subcontracts awarded under this project and described under the PVMaT Technology Area in this Project Summary.

Status/Accomplishments:
- Completed renewal of on-going PVMaT subcontracts.
- Collected, analyzed, and reported on capacity/cost/recharge data from PVMaT participants.
- See individual subcontract summaries for specific technical accomplishments.
- Released solicitation with emphasis on in-line diagnostics and intelligent manufacturing for larger capacity manufacturing lines.
- Presented papers to promulgate PVMaT results (see below).

Planned FY 2001 Activities: Subcontracts from the FY1998 awards will be continued in FY2001. All except one will be completed. The selected R&D efforts are divided into two parts. PV System and Component Technology includes manufacturing improvements directed toward innovative, low-cost, high-return, high-impact PV products. Efforts in this area address manufacturing R&D generally related to PV system components and aspects other than modules. System components such as inverters, system integration efficiency and design improvements, and the development of processes to produce cheaper solar grade silicon are being pursued. The second area, PV Module Manufacturing Technology, includes, but is not limited to, improvements in module manufacturing processes and the manufacturing, assembly, and integration of systems to build a PV product, as well as the packaging of that product to meet market requirements. Module manufacturing development is a substantial portion (50% or more) of each of the efforts in this area.

Contract #: DE-AC36-99G010337

A new solicitation for Manufacturing R&D was released in late FY2000. This solicitation is entitled "PV Manufacturing R&D - In-Line Diagnostics and Intelligent Processing in Scale-Up Manufacturing". As in previous PVMaT solicitations, it requests Letters of Interest (LOIs) from individual or teamed U.S. PV and related industries to address a range of topics relating to the manufacturing of PV modules, components and systems. It is open to all PV industry entities. And it is designed with the two areas as described above. However, a primary focus is supporting approaches for intelligent processing and larger-scale manufacturing, as identified in the U.S. Photovoltaics Industry Roadmap. The focus of the solicitation stems from the facts that there are many issues and costs associated with translating small prototype-line results to first-time large scale manufacturing due to the complexity of the processes involved for making large area, high volume PV modules. This is further compounded by the lack of the fundamental scientific and engineering base required to properly engineer and operate manufacturing equipment. Awards will be made during the last half of FY01.

Major Reports Published in FY 2000:
See individual subcontract summaries.

Major Articles Published in FY 2000:
Symko-Davies, M., et al., "Decade of PV Industry R&D Advances in Silicon Module Manufacturing," *Proceedings of the 28th at the IEEE PV Specialists Conference*, Anchorage, Alaska, September 15-22, 2000.

Thomas, H., et al., "Progress in Photovoltaic Components and Systems," *Proceedings of the 16th European Photovoltatic Solar Energy Conference and Exihition*, Glasgow, Scotland, U.K., May 1-5, 2000.

Thomas, H., et al., "Testing to Support Improvements to PV Components and Systems," *Proceedings of the 16th European Photovoltatic Solar Energy Conference and Exihition*, Glasgow, Scotland, U.K., May 1-5, 2000.

Witt, C. E., et al., "Terrestrial Photovoltatic Technologies – Recent Progress in Manufacturing R&D," *Proceedings of the 2000 National Heat Transfer Conference*, Pittsburgh, PA, August 20-22, 2000.

Witt, C. E., et al., "Ten Years Of Manufacturing R&D In PVMaT – Technical Accomplishments, Return On Investment, And Where Do We Go Next," *Proceedings of the 28th at the IEEE PV Specialists Conference*, Anchorage, Alaska, September 15-22, 2000.

Manufacturing and System Integration Improvements for One- and Two-Kilowatt Residential PV Inverters

Contract#: ZAX-8-17647-08	**Contract Period:** 7/17/98–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	Omnion Power Engineering Corporation, A Division of S & C Electric company P.O. Box 879, 2010 Energy Drive East Troy, WI 53120 **Organization Type:** IN	 **Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D. Porter **Phone:** 262-642-7200 **Fax:** 262-642-7760 **E-mail:** dporter@omnion.com	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6490 **E-mail**: holly_thomas@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1998: $ 96,000 2000: $(3,211) 1999:$357,404	**Cost Share Information:** Omnion Power Engineering, Division of S&C Electronics **Cost Share Funding:** 1998: $ 41,143 2000: $(1,376) 1999: $153,173

Project Objective: The objective of this subcontract was to produce two inverter products that are easily manufactured, and are suitable for use in residential PV applications. Omnion will finalize designs and evaluate one-kilowatt and two-kilowatt (kW) single-phase inverters for utility-interconnected applications suitable for high-volume production (5,000 units/year). Features of the Series 2500 inverters will include features such as:

- Integrated AC and DC Disconnects to meet NEC and UL Requirements.
- Dedicated access for AC output and DC input terminal wiring.
- Laminated bus plane integrated into printed circuit board.
- Price of less than $.50/watt for the two-kW unit and less than $.75/watt for the one-kW unit.
- An estimated mean-time-between-failure (MTBF) equal to or exceeding 60,000 hours.

Approach/Background: S& C Electric Company (Omnion) was to complete their work in two incrementally-funded phases. Omnion uses a four-step process for designing new products. Step I is product concept, Step 2 is prototype development, followed by pilot production, and full production. During Phase I Omnion was to build prototypes of the Series 2500 one-kilowatt and two-kilowatt inverters and proceed with a pre-production version of the products. The plan was to use the transformerless phase leg topology used by Omnion for its Series 2200, but modified by adding a buck-boost DC/DC converter to broaden the input voltage range from ±180 to ±300 to ±180 to ±400 or so. The broader range would simplify PV system design because of the broader array voltage window.

Status/Accomplishments: S & C Electric Company purchased and named Omnion Power Engineering Company a subsidiary during 1999. In January 2000 the subsidiary was incorporated into S&C Electric Company. The S&C/Omnion subcontract was awarded in 1998 and was terminated by mutual agreement after the purchase, when company priorities changed. No research was done during this fiscal year. Although the intent of subcontract was not completed, the company has stated it is plans to proceed on it own at a later date.

Planned FY 2001 Activities: none

Major Reports Published in FY 2000:
D. Porter, "PVMaT – OMNION Series 3300: Photovoltaic Power Conversion System for Utility Connected Application, Final Report," NREL/SR-520-28820, August 2000.

Major Articles Published in FY 2000: none

PowerGuard® Advanced Manufacturing

Contract#: ZAX-8-17647-12	Contract Period: 6/10/98–10/31/01

Sponsoring Office Code: EE-11	Performing Organization(s)	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	PowerLight Corporation 2954 San Pablo Avenue Berkeley, CA 94710	
	Organization Type: IN	**Congressional District:** 9
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Tom Dinwoodie **Phone:** 510-540-0550 **Fax:** 510-540-0552 **E-mail:** td@powerlight.com	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6490 **E-mail**: holly_thomas@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** PowerLight Corporation
	DOE Funding Allocation: 1998: $275,000 2000: $400,794 1999:$452,623	**Cost Share Funding:** 1998: $310,106 2000: $622,043 1999: $622,823

Project Objective: The objective of this subcontract is to continue the advancement of PowerLight Corporation (PowerLight) PV manufacturing technologies in order to reduce cost, increase manufacturing capabilities and provide PV systems incorporating financing options. PowerLight plans to demonstrate system costs of $3.05/W and complete manufacturing improvements for PowerGuard® tile fabrication capability of 16 MW/yr, and stimulate US PV laminate manufacturing expansion by 2 MW/year.

PowerLight plans to reduce PowerGuard® system costs through 1) improvements in manufacturing technology related to system (non-module) components, 2) product design enhancements, 3) increased production capacity, 4) enhanced system reliability and performance, and 5) strategic alliances to leverage PV module technical improvements and cost reduction.

Approach/Background: Under this planned three-phase subcontract PowerLight Corporation (PowerLight) will address the PVMaT goals of manufacturing improvements directed toward innovative, low-cost, high-return, high-impact PV products. PowerLight incorporates financing, safety and reliability in its building-integrated PV product. The approach is to introduce incremental improvements to their system components and manufacturing processes to reduce Balance of System (BOS) costs to $2.00/W. PowerLight has also selected US strategic partners to achieve additional cost reductions and leverage the PV laminate manufacturing enhancements. Finally, by the end of this subcontract PowerLight expects to expand PV laminate production capacity with a US manufacturer, due to demand for the PowerGuard® product, by approximately 2 MW/yr of laminates, with total PowerGuard® tile fabrication capacity in excess of 16 MW/yr.

Status/Accomplishments: PowerLight Corporation continued efforts to reduce costs, increase production capacity and improve the PowerGuard® PV product. To achieve the 57% production cost reduction, extensive improvements and modifications have been implemented. These include: 1) increased production line throughput of the cement-coated extruded polystyrene (XPS) substrate from 3 minutes/tile to 45 seconds/tile; automation of spacer (surface for mounting PV module on the tile) attachment process to more consistently position spacers with a throughput of 20 seconds/tile and 3) improved methods for placement of the PV module on the spacers, speeding placement from 120 seconds/tile to 50 seconds/tile with better ergonomics and more accurate alignment. The company also developed a new trimming process for handling the completed tiles, reducing the amount of labor required by 75% and improving the overall quality of the tile edge. The company completed design software enabling the Value-added Reseller to specify systems for particular locales in the U.S., Europe and Japan and a standardized manual with packaged systems based upon economical modular increments. This standardized manual is linked with software so the reseller can present a system design visually and develop a complete bill of materials. With site-specific information, resellers can use this manual to specify and order a system for their clients. The company also achieved UL-listing for additional tile configurations utilizing modules from 4 manufacturers (ASE, Siemens, AstroPower and First Solar). The complete PowerGuard® system, including the company's modular source circuit combiner box design has also been UL-listed. Compared to earlier approaches, their standardized combiner box reduces the number of boxes by 75%, materials costs by 60%, labor costs by 80%, and improves reliability. In addition, the PowerGuard® product now has a Class A fire rating when configured with ASE double glass laminates and a Class B fire rating with BP Solar and AstroPower Tedlar®-backed laminates. IEC and IEEE testing is in progress in order to achieve CE listing for the European market. The manufacturing facility, which was dedicated in March, was inspected and complies with all EPA and OSHA requirements. Finally, PowerGuard® systems have been installed in several commercial demonstration projects. The company has noted the improved product quality reduces installation time and improves overall appearance.

Contract#: ZAX-8-17647-12

Planned FY 2001 Activities: During this fiscal year, PowerLight will continue to address the improvement of the PowerGuard^{R} manufacturing process. Specific performance objectives include reducing installed system costs of \$3.05/Wp; assess the performance of dedicated PowerGuard^{R} PV plant capacity of 2 MW/year; produce an installation manual and training program for installing PowerGuard^{R} systems; and finalize UL, International Conference of Building Officials (ICBO), and international listings on PowerGuard^{R} improvements.

Major Reports Published in FY 2000:

M.C, Marshall, T.l. Dinwoodie, C.O. O'Brien, (June 2000) "PowerGuard^{R} Advanced Manufacturing," PVMaT Phase I Technical Report, June 1, 1998 – September 30, 1999," *31pp. NREL/SR-520-28564*, *Golden, CO: National Renewable Energy Laboratory*.

Specific R&D Problems in Product Manufacturing

Contract #: ZAX-8-17647-14	**Contract Period:** 6/22/98–10/21/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Siemens Solar Industries P.O. Box 6032 4650 Adohr Lane Camarillo, CA 93011 **Organization Type:** IN	**Congressional District:** 23
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. Jester **Phone:** 805-388-6500 **Fax:** 805-388-6557 **E-mail:** terry.jester@solar.siemens.com	
Technical Monitor: Richard Mitchell **Phone:** 303-384-6479 **Fax:** 303-384-6490 **E-mail:** richard_mitchell@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1998: $350,000 2000: $772,775 1999: $984,438	**Cost Share Information:** Siemens Solar Industries **Cost Share Funding:** 1998: $350,000 2000: $772,775 1999: $984,438

Project Objective: The objective of this PVMaT subcontract over its three-year duration is to continue the advancement of Siemens PV manufacturing technologies in order to develop and optimize silicon ingot growth, wafer sawing, and solar cell processes (which are necessary to manufacture 125-micron wafers and cells), as well as crystal growth processes for the production of 200-mm diameter Cz silicon ingots. Additionally, Siemens will develop improved modules using the new 200-mm diameter cells, and develop and optimize processes for the reduction, and re-use of waste material from both the Siemens wafer and cell manufacturing processes.

Approach/Background: Siemens Solar Industries will meet these objectives by:
- Developing and integrating new optimized cell fabrication processes into their manufacturing line for the production of 17% efficient, 125-mm cells with a 30% reduction in the cell manufacturing cost.
- Developing a large-area cell production capability for 200-mm diameter, 4.5-watt prototype solar cells and low-cost prototype modules to reduce module manufacturing cost by 20%.
- Initiating Siemens' Environmental, Safety and Health activities directed toward reducing their hazardous waste by over 50% through recycling and re-use of slurry materials in their wire saw process and an over 70% reduction in caustic waste.

Status/Accomplishments:
- Completed development of tooling to handle boat-to-boat transfers on the Siemens Solar Industries production line.
- Demonstrated 16.5% efficient thin Siemens Solar Industries Cz silicon cell production.
- Demonstrated 200-mm diameter wafer and cell fabrication, resulting in new low-cost frameless modules.
- Demonstrated 200-mm diameter 4.0-Watt solar cell.
- Completed report on processes for the production of 200-mm diameter cells and new module design, resulting in a 10% reduction in module manufacturing costs.
- Demonstrated 20% recycling of SiC in wafering.
- Demonstrated a 15% reduction of waste volume in Siemens Solar Industries cell fabrication wet-line process.

Planned FY 2001 Activities:
- Implement "auto-boating" in pilot production of 150-micron wafers.
- Demonstrate manufacturing process for 195-micron thick, 16.5% efficient Siemens Solar Industries Cz silicon solar cells.
- Demonstrate prototype 195-micron thick, 17% efficient Siemens Solar Industries Cz silicon solar cells.
- Complete process development for 200-mm diameter Siemens Solar Industries Cz silicon solar cells.
- Complete design of system to recover 50% of SiC used in Siemens Solar Industries wafering process.
- Complete analysis of the pilot production of 195-micron thick, 17% efficient solar cells contributing to a 30% cost reduction to Siemens Solar Industries cell manufacturing costs.

Contract #: ZAX-8-17647-14

Major Reports Published in FY 2000:

T. Jester, "Specific PVMaT R&D on Siemens Cz Silicon Product Manufacturing", Annual Subcontract Technical Report, 22 June 1998- 21 June 1999, NREL/SR-520-27591, (November 1999).

T. Jester, "Specific PVMaT R&D on Siemens Cz Silicon Product Manufacturing", Annual Subcontract Technical Report, June 1999 - September 2000, in progress.

Major Articles Published in FY 2000:

T.L. Jester, "Specific PVMaT R&D on Siemens CZ Silicon Product Manufacturing," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

K. Knapp, G. Mihalik, T. Jester, "Energy Balances for Photovoltaic Modules: Status and Prospects", Energy Balances for Photovoltaic Modules: Status and Prospects, *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

K. Knapp, T. Jester , "An Empirical Perspective on the Energy Payback Time for Photovoltaic Modules", *SOLAR 2000 Conference*, Madison, Wisconsin, June 16-21, 2000.

K. Knapp, T. Jester, "Initial Empirical Results for the Energy Payback Time of Photovoltaic Modules", European PVSC, Glasgow, Scotland, May 5-12, 2000.

J. Palm, W. Krühler, W. Kusian, A. Lerchenberger A.L. Endrös, G. Mihalik, B. Fickett, and T. Jester, "Characterization of Tri-Crystalline Silicon for Photovoltaic Applications," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

J. Palm, A. Lerchenberger, W. Kusian, W. Krühler and A.L. Endrös, G. Mihalik, B. Fickett, J. Nickerson and T. Jester, "Crystal Growth of Tri-Crystalline Silicon for Photovoltaic Applications", European PVSC, Glasgow, Scotland, May 5-12, 2000.

Post-Lamination Manufacturing Process Automation for Photovoltaic Modules

Contract #: ZAX-8-17647-04	**Contract Period:** 4/15/98-9/14/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Spire Corporation One Patriots Park Bedford, MA 01730-2396	
	Organization Type: IN	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Michael J. Nowlan **Phone:** 781-275-6000 **Fax:** 781-275-7470 **E-mail:** mnowlan@spirecorp.com	
Technical Monitor: Martha Symko-Davies **Phone:** 303-384-6528 **Fax:** 303-384-6490 **E-mail:** martha_symko_davies@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Spire Corporation
	DOE Funding Allocation: 1998: $454,561 1999: $873,695 2000: $905,991	**Cost Share Funding:** 1998: $194,812 1999: $316,574 2000: $382,183

Project Objective: Spire Corporation is addressing the Photovoltaic Manufacturing Technology (PVMaT) project goals of PV module cost reduction and improved PV module manufacturing process technology. New cost-effective automation processes are being developed for PV module assembly after the solar cell lamination process. The development and implementation of these automated systems are expected to result in significant labor cost savings and increased throughput. A reduction in repetitive stress injuries may also be achieved by eliminating product lifting and manual edge trimming tasks.

Approach/Background: The automated processes under development in this program include (1) a module buffer storage system, including conveyor load/unload and module storage, (2) an integrated edge process system, including automated edge trimming, edge sealing, and framing capabilities, (3) a junction box installation system for attaching a junction box, and (4) an integrated module test system that combines high voltage isolation testing, ground continuity testing, and module performance testing. These processes apply to both crystalline and thin film modules. Proof-of-concept prototype systems are being developed and evaluated with module components from several US module manufacturers.

Status/Accomplishments: Two new automated systems were designed, fabricated and tested: a buffer system for dispensing and storing modules, and an integrated test system for measuring module electrical isolation, ground continuity, and performance (I-V measurement with a sun simulator). Two additional systems are now under development: an edge trimmer for removing excess encapsulant and back cover film from module edges after lamination, and an edge sealer and framer for dispensing edge sealant and installing frames on trimmed modules. The development of automated processes for junction box installation is planned.

These systems are designed to be combined to form an automated assembly and testing line. A standard electrical interface protocol (SMEMA) is incorporated in all of these systems, allowing each system to communicate with upstream and downstream automation. All systems are designed to process modules up to 102 cm by 162 cm. The throughput goal for these systems is one module per minute, equivalent to 9.3 MW/year of 75 W modules on a one-shift (40 hour/week) basis.

A production prototype module edge trimming system was designed and fabricated, and is now in the testing phase. Detailed mechanical, electrical, and software designs were completed. The trimmer's main components include module transport conveyors, a module aligner, a module lift, and a robotic edge trimmer. A four axis (x, y, z, and θ) Cartesian robot transports an end-effector with fiber optic sensors for detecting glass edges and a hot knife for trimming excess encapsulant and back cover film from the module edges.

A production prototype module edge sealing and framing system was designed and system fabrication and assembly has begun. The main components include module transport conveyors, a module aligner, a module lift, long and short frame feeders, corner key feeders, corner key presses, hot-melt sealant dispensers, a four-axis Cartesian robot with mechanical grippers for frame transport, and a two-axis frame press.

Contract #: ZAX-8-17647-04

Planned FY 2001 Activities: Process development will be completed for the automated module edge trimming system. Evaluations will be done with module laminates provided by several US module manufacturers. The module edge sealing and framing system will be fabricated, tested, and evaluated with trimmed laminates, frame members, edge sealant, and corner keys.

A junction box Design for Manufacturing analysis will be completed and automated assembly processes will be developed. A production prototype automated junction box installation system will be designed, fabricated, and demonstrated.

Major Reports Published in FY 2000:
M.J. Nowlan, J.M. Murach, S.F. Sutherland, E.R. Lewis, and S.J. Hogan "Post-Lamination Manufacturing Process Automation for Photovoltaic Modules," Annual Technical Progress Report, 15 June 1999 to 14 July 2000, NREL/SR-520-28789.

Major Articles Published in FY 2000:
M.J. Nowlan, J.M. Murach, E.R. Lewis, S.F. Sutherland, and S.J. Hogan "Process Automation for Photovoltaic Module Assembly and Testing," *proc. 28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

M.J. Nowlan, J.L. Sutherland, E.R. Lewis, and S.J. Hogan "Evaluations of an Automated Photovoltaic Module Test System," *proc. 16th European Photovoltaic Solar Energy Conf.*, Glasgow, UK, 1-5 May 2000.

M.J. Nowlan, J.M. Murach, E.R. Lewis, S.F. Sutherland, and S.J. Hogan "Automation for Photovoltaic Module Edge Trimming, Edge Sealing, and Framing," *Program and Proceedings, NCPV Program Review Meeting 2000*, Denver, CO, 16-19 April 2000, BK–520-28064, pp. 87-88 (2000).

PV Manufacturing R & D

Development of a Fully-Integrated PV System for Residential Applications

Contract#: ZAX-8-17647-02	**Contract Period:** 3/27/98–3/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	Utility Power Group, Inc. 21250 Califa Street, Suite 111 Woodland Hills, CA 91367	
	Organization Type: IN	**Congressional District:** 24
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Gil Duran **Phone:** 818-932-9480 **Fax:** 818-9481 **E-mail:** upgpv@aol.com	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6490 **E-mail**: holly_thomas@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Utility Power Group, Inc.
	DOE Funding Allocation: 1998: $237,900 2000: $422,535 1999: $ 279,500	**Cost Share Funding:** 1998: $101,957 2000: $181,086 1999: $119,786

Project Objective: Objectives of this subcontract are to:

- reduce the total installed cost of residential, roof-top-mounted PV power systems;
- increase the reliability of these systems, and;
- expand the technology base which supports increasing US PV power system production capacity.

Utility Power Group (UPG) is working with its lower-tier subcontractor, Trace Technologies, Inc. to achieve a 30% reduction in total non-module related system costs through the development of a PV Array and Power Unit with direct material and direct labor costs below $\$4/ft^2$ and $0.45/W, respectively. The roof-top system will consist of a PV array, a Power Unit with a peak power maximum of 19 kW, and an optional Energy Storage Unit.

Approach/Background: The subcontract consists of two phases. During Phase I, UPG worked with its lower-tier subcontractor Trace Technologies, to design and test prototypes for each of the system elements — the PV Array, Power Unit, and Energy Storage Unit. The work included the design, development and thorough evaluation of prototypes for each element of the integrated residential PV system. Underwriter's Laboratories (UL) and other safety recognitions are planned, and UPG worked closely with UL to ensure the design meets applicable design requirements.

During Phase II, UPG is focusing on the refinement and evaluation of systems installed for beta testing. Each of the system elements will be reviewed, and Highly Accelerated Lifetime testing conducted on the Power Unit as part of the prototype evaluation. The final production prototype will be submitted to UL to apply for listing. By the conclusion of Phase II, UPG will demonstrate a low-cost, reliable, fully integrated residential PV system.

Status/Accomplishments: UPG sold its power engineering to Trace Technologies which became a lower-tier subcontractor. UPG is completing a factory-assembled PV Array Unit and Trace is developing the 12kW Power Unit and Energy Storage Unit. UPG reports an installed cost for the PV Array Unit of $\$3.95/ft^2$. Trace reported an estimated manufacturing cost of $0.25/W for their bipolar, transformerless Power Unit. The Power Unit can operate in a grid-tied or stand-alone configuration when coupled with the 13kWhr capacity Energy Storage Unit. When complete, this fully integrated residential PV system will incorporate advanced power management and storage. UPG's PV Array design can accommodate PV modules from several different manufacturers, either framed or frameless. Their design uses bolts and a rail assembly to attach the factory-assembled panels to the roof. In a test for planned projects for SMUD, UPG reported a crew of 2 installed 1 kW of PV on a test roof in less than 1 hour.

Planned FY 2001 Activities: UPG will complete field testing of the PV Array and Trace Technologies will complete development of the Power Unit's management and control software and deploy the system, with storage, for testing.

Major Reports Published in FY 2000:

R. West, K. Mackamul, G. Duran, (March 2000), "Development of a Fully Integrated PV System for Residential Applications-Phase I Annual Technical Report" 53 pp. NREL/SR-520-27993, Golden, CO: National Renewable Energy Laboratory.

Photovoltaic Module Thermal/Wind Performance Long Term Monitoring and Measurement

Contract #: ACQ-9-29610-01	**Contract Period:** 8/16/99–8/16/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Arizona State University PO Box 873503 Tempe, AZ 85287-3503-	
	Organization Type: CU	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Liang-Jun Ji **Phone:** 480-727-1219 **Fax:** 480-727-1223 E-mail: l.ji@asu.edu	
Technical Monitor: Carl R.Osterwald **Phone**: 303-384-6764 **Fax**: 303-384-6790 **E-mail**: carl_osterwald@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: none
	DOE Funding Allocation: 1999: $27,479 2000: $17,217	**Cost Share Funding:**

Project Objective: The purpose of this work is to aid the development of a consensus standard for rating modules by energy production by measuring the temperature of a group of photovoltaic (PV) modules as a function of wind speed, wind direction, total irradiance and possibly relative humidity. This data will be used to propose, investigate, and evaluate experimental methods for obtaining the ambient temperature and wind speed to module temperature transfer function for an arbitrary module.

Approach/Background: The current draft Institute for Electrical and Electronics Engineers energy ratings standard (IEEE PAR 1479) specifies the hourly irradiances, ambient temperatures, and wind speeds at which a module's maximum power is determined; these results are then integrated over time to obtain the energy produced during several reference days. Because each different module type may have a different thermal characteristic, a method of obtaining the actual module temperature from the ambient data is needed.

A group of modules has been installed for similar measurements at NREL's Solar Radiation Research Laboratory (SRRL) on top of South Table Mountain. The subcontract work will parallel the NREL work, with the exception that it be located in a hot, desert climate. In order to increase the confidence in any results, the measurements will be continued for as long as possible.

Status/Accomplishments: ASU completed the installation of the test modules and began data acquisition in February 2000. Since that time, data collection has proceeded, and the first six months of collected data were delivered in August 2000.

Planned FY 2001 Activities: The extension of this subcontract for FY2001 includes funding for data analysis and publication of results from both NREL and ASU PTL, and for collection of an additional year of wind/thermal data.

Major Reports Published in FY 2000:

L. Petacci and L. Ji, "Photovoltaic Module Thermal/Wind Performance Long Term Monitoring and Measurement, Month-8 Report," Arizona State University Photovoltaic Testing Laboratory, Mesa, AZ, Aug. 2000.

Major Articles Published in FY 2000: none

Accelerated Testing of Materials and Encapsulated PV Cells

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. McMahon (Task Leader) **Phone:** 303-384-6762 **Fax:** 303-384-6790 **E-mail**: tom_mcmahon@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E-mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: N/A
	DOE Funding Allocation: 1999: $831,00 2000: $853,425	**Cost Share Funding:**

Project Objective: This Task is being performed in support of the PV Program to accelerate the development of PV technologies for a 30-yr service life of PV modules as targeted by DOE's *Solar 2000-A Collaborative Strategy*. The principal purposes of this task are (1) to develop and establish adequate accelerated weathering or exposure testing (*AWT/AET*) methodologies for investigating the photo, thermal, and electrical stability of various module technologies and encapsulation materials; (2) to identify by AWT/AET and to mitigate the causes or mechanisms of degradation; (3) to improve the materials, cells, interconnects, encapsulation conditions, and module processing methods; and (4) to collaborate with U.S. PV industry through (1 to 3) to improve reliability and stability.

Approach/Background: The R&D activities include performing AET studies, elucidating the photothermally and/or voltage-bias induced primary and other secondary degradation mechanisms of module materials, and testing new encapsulation materials and methods that are developed either in house, through CRADA/academic collaborations, or by PV manufacturers. The Task employs several AWT/AET methods to investigate the performance stability of a relatively large number of c-Si minimodules that are encapsulated by using various materials (e.g., superstrates, pottants, and substrates) and methods. A voltage-biased damp-heat (at 85^{O}C and 85 %RH) AET method is employed to investigate the performance reliability of commercial thin film a-Si modules. The NREL's high flux solar furnace is also used for studying EVA-laminated c-Si solar cells in collaboration with SNL. A number of analytical methods, including surface/interfacial analysis, and IV/QE measurements are employed to characterize and identify material and cell failure mechanisms resulting from AWT/ALT. Technology transfer is accomplished through presentations at professional meetings, publications of research results, and licensing negotiation of patent of the technology or materials developed.

Status/Accomplishments: We delivered milestones as AOP2000 required. 1) A paper (ref.1) was co-authored with Sandia that concluded that a generalized life test protocol to predict whether-or-not a module will last 30 years is unrealistic and that time would be better spent rank on ordering failure mechanisms. 2) A performance reliability study for c-Si solar cells variously encapsulated with different EVA formulations and super-/substrate materials upon various accelerated exposure testing (AET) conditions showed that electrical degradation of the c-Si solar cells was random and not proportional to the optical loss of superstrate/EVA layers. Delamination, moisture ingress/condensation, and corrosion of tab ribbon/gridlines were observed for cell samples tested in weatherometers. To elaborate the solar cell's electrical degradation mechanisms, we initiated quantitative light/dark I-V curve analysis to extract six parameters--diode quality factors n_1 and n_2, series resistance R_s, shunt resistance $R_{sh,}$ saturation currents Io_1 and Io_2. 3) A study was initiated to develop and better moisture barriers for thin-film and crystalline modules. Goals will be to enable thin-film modules to pass damp heat testing with a polymer-based back sheet, thus reducing the weight of these large modules. 4) Along these lines, hi-voltage damp heat testing results were published quantifying a Na-ion migration problem common to SnO superstrate thin-film modules. 4) Guidance to the Thin-Film Partnership Team activities continues. A paper was co-authored with A. Fahrenbruch explaining the non-ideal behavior found in CdS/CdTe solar cells; this with help in the interpretation of cell degradation. Generally, we provided various technical suggestions on PV encapsulation issues and paper reprints to a number of domestic and international PV community personnel, collaborated with or assisted US PV manufacturers and CRADA partners in photothermal stability tests of new encapsulants, and provided introductory presentations and tours to foreign visitors. We also received a U.S. patent, "Composition and Method for Encapsulating PV Devices," serial no. 6,093,757, for which we participated in technology transfer (licensing) effort. We had six paper publications and made five oral presentations.

Contract #: DE-AC36-98-GO10337

Planned FY 2001 Activities: We will continue to study the performance reliability (photothermal stability) of various encapsulated solar cells (milestone), to investigate the conductivity degradation of EVA encapsulants upon AET (milestone), to improve further the EVA formulations with new stabilizers and ingredients, to improve the performance reliability with new and better super-/substrate materials provided by US companies, and to investigate better edge sealing materials and/or methods. A workshop is planned (key milestone) to bring to the forefront some of these issues, namely, moisture ingress and hi-voltage isolation. It will be held at NREL next March. Additionally, an instrument to measure moisture transmission through candidate backsheet materials is being purchased. We want to be able to establish maximum water vapor transmission rates that can be allowed for backsheet materials and still pass the 1000 hs of damp heat testing. Additionally, thin films of oxides and/or metals are being applied to candidate backsheet materials to reduce permeability to water vapor. We will collaborate with NCPV staff to use atomic force microscopy to study AET effects on Tefzel polymer superstrates (widely used for a-Si modules), carry out instrumentation efforts for in-situ I-V measurements for solar cells and resistance measurements for EVA laminates under AET, and, as usual, continue to collaborate with NCPV, domestic, and international PV community.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:

T. J. McMahon, G. Jorgensen and R. Hulstrom, D. King and M. Quintana, "Module 30 Year Life: What does it mean and is it Predictable/Achievable?,"16th NCPV Program Review Meeting, April 16-19, 2000, Denver, CO.

F. J. Pern and S. H. Glick, "Photothermal Stability of EVA Encapsulants for Photovoltaic Applications: Effects of Formulation, Curing Condition, and Method," Conference proceeding of 3rd Biennial Conference on Polymer Stabilizers and Modifiers, November 8-10, 2000, Hilton Head Island, S. Carolina, pp. 333. (invited paper).

F. J. Pern and S. H. Glick, "Photothermal Stability of Encapsulated Silicon Solar Cells and Encapsulation Materials upon Accelerated Exposures–II," 28th IEEE PVSC, September 17-22, Anchorage, Alaska.

T. J. McMahon and A. Fahrenbruch, "Insights into the Nonideal Behavior of CdS/CdTe Solar Cells," 28th IEEE PVSC, September 17-22, Anchorage, Alaska.

D. L. King, J. A. Kratochvil, M. A. Quintana and T. J. McMahon,"Applications for Infrared Imaging Equipment in Photovoltaic Cell, Module and System Testing," *ibid.*

F. J. Pern and S. H. Glick, "Effects of Accelerated Exposure Testing (AET) Conditions on Performance Degradation of Solar Cells and Encapsulants," 16th NCPV Program Review Meeting, April 16-19, 2000, Denver, CO.

F. J. Pern, "Development of an Accelerated Weathering Protocol using Weatherometers for Reliability Study of Minimodules and Encapsulation Materials," *ibid*.

F. J. Pern and S. H. Glick, "Photothermal Stability of Various Module Encapsulants and The Effects of Superstrate and Substrate Materials Studied for PVMaT Sources," *ibid*.

F. J. Pern and S. H. Glick, "Photothermal Stability of Encapsulated Si Solar Cells and Encapsulation Materials upon Accelerated Exposures," Solar Energy Materials and Solar Cells, **61** (2000) 153-188.

"Issues on Characterizing Optical Degradation of Photovoltaic Module Encapsulant EVA under Interference from Substrate Materials," F. J. Pern and S.H. Glick, Abstract and oral presentation at 42nd Rocky Mountain Conference on Analytical Chemistry, August 2, 2000, Denver, CO.

"Photothermal Stability of Various Module Encapsulants and The Effects of Superstrate and Substrate Materials Studied for PVMaT Sources," F. J. Pern and S. H. Glick, Poster presentation, *ibid.* (Same as the poster presented in the 16th NCPV Program Review Meeting.)

"An Introduction of National Center for Photovoltaics (NCPV) at National Renewable Energy Laboratory (NREL)," J. Pern, SERF Auditorium, to a 40-Chinese delegation on April 25, 2000, The presentation materials later were requested, further processed, and incorporated in a CD for the delegates.

Module and Array Performance and Reliability

Module Testing and Technology Validation

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	**Organization Type**: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Carl R. Osterwald **Phone:** 303-384-6764 **Fax:** 303-384-6790 **E-mail**: carl_osterwald@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E-mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $1,067,500 2000: $1,006,055	**Cost Share Funding:**

Project Objective: The objective of this task is to provide module performance measurements over a range of outdoor conditions, to thoroughly investigate module reliability issues using a variety of accelerated aging tests, and to develop or improve industry-standard module qualification tests. DOE-sponsored projects such as PVMaT, PV:BONUS, the Thin Film Partnership, and the Concentrator Alliance are strongly supported, in order to help guide their technology developments, and established module manufacturers, companies with emerging module technologies, codes & standards organizations, and system users all benefit from efforts conducted in this task.

Approach/Background: Well established laboratory capabilities and expertise at NREL are used for module stability testing of thin-film and advanced PV technologies by conducting long-term exposure tests and controlled light-soaking experiments. Accelerated stress testing and analytical investigation of the resulting failure mechanisms is emphasized by this task, including efforts to correlate failure mechanisms and degradation rates observed in accelerated tests with those observed in fielded systems, particularly for newer thin-film technologies. This correlation, when achieved, will help validate the computer models being used by NREL for module service lifetime predictions. As part of this effort to correlate the effects of accelerated tests with real-time exposure, long-term ultraviolet (UV) exposure testing of commercial modules was continued. Research efforts in this task also addressed the development of a standardized “module energy rating (MER).” For individual modules, the MER will provide relative energy production at five different operating conditions, chosen to represent a range of geographic sites. The MER development has the support of industry and is envisioned to be an expansion of the “nameplate” performance information currently provided on commercial modules. The task continued its role in the development of national and international standards by participating on IEEE and ASTM committees.

Status/Accomplishments:

- During this period, the long-term comparison of UV exposure and weathering methods continued toward the goal of 2000 MJ/m^2 total UV exposure.
- The 1999 Photovoltaic Performance and Reliability Workshop (NREL/CP-520-27723) was held at the Vail Cascade Hotel in Vail Colorado on October 18 - 21, 1999. This was the 12th such workshop since its inception and was sponsored through the National Center for Photovoltaics, and hosted by the National Renewable Energy Laboratory. The workshop focus was on testing, test methods, evaluation, and standards in the four following topical areas: Module Performance Rating, Module Qualification Testing, Power Processing, and Systems Evaluation.
- The module wind/thermal performance test bed at the SRRL on top of South Table Mountain was completed and data collection initiated. An analysis of the thermocouple locations on the backs of the modules was done in February 2000 using the IR imaging camera.
- Indoor accelerated module environmental stress testing on samples from BP Solar, TerraSun, Global Solar, and Sovlux was completed and the results were transmitted to the respective manufacturers.

Contract #: DE-AC36-98-GO10337

Status/Accomplishments continued:

- We completed the installation of an attachment to the small BMA environmental chamber that allows four modules to be biased up to 600 V between the shorted leads and the grounding point. Voltage biasing is normally done in conjunction with damp heat testing (85°C, 85% RH) to accelerate effects that may occur in large high-voltage arrays. Working with the manufacturer, we initiated a testing program to investigate such effects in a-Si modules as a function of temperature. By testing at 85% RH and three different temperatures (85°C, 72°C, and 60°C), we have measured an activation energy of 0.83 eV for the damage observed in these modules.
- The Reference Meteorological and Irradiance System (RMIS) was upgraded to provide global normal irradiance data, and a new mounting platform for the fixed-tilt instrumentation was installed that minimizes shadowing problems from people walking through the array field at the Outdoor Test Facility.
- New modules installed in the Performance and Energy Ratings Testbed (PERT) include six polycrystalline silicon modules from three manufacturers for a long-term energy-production comparison experiment, two BP Solar best efficiency (10%) CdTe for outdoor performance, and a Sanyo HIT module for outdoor performance.
- Several test reports covering results from the PERT were transmitted to the respective manufacturers, including: a six-month summary of outdoor performance of two EPV tandem junction a-Si modules, 1000 hours of indoor light soaking of 13 Sovlux triple-junction a-Si/a-Si/a-SiGe minimodules, and 1000 hours of indoor light-soaking of two USSC triple-junction a-Si modules.

Planned FY 2001 Activities:

- Continue module stability testing for thin-film and advanced PV technologies by conducting long-term exposure tests and controlled light-soaking experiments.
- Continue the long-term comparison of UV exposure methods on commercial modules using real-time fixed tilt, two-axis tracking, two-axis tracking with mirror enhancement, two-sun Xe, and UVA fluorescent tube exposure.
- Real-time monitoring of module performance will be continued in the PERT.
- Perform indoor accelerated stress testing as needed in support of deliverable testing from DOE-sponsored programs and CRADAs.
- Continue the support of module energy ratings development with the PERT facility and the wind/thermal performance testbed.
- Initiate work to determine the feasibility of developing a way to estimate annual energy production at any U.S. location from the standard energy ratings.
- Continue to support the development of national and international standards through participation on ASTM and IEEE PV standards development committees.

Major Reports Published in FY 2000:

W. Marion, (2000), "*A Photovoltaic Module Energy Rating Procedure*," Proceedings of the PV Performance, Reliability and Standards Workshop, Vail CO, October 1999, NREL/CP-520-27723.

B. von Roedern and J.A. del Cueto, "*Model for Stabler-Wronski Degradation Deduced from Long-Term, Controlled Light-Soaking Experiments*," Proceedings of the Materials Research Society Meeting, April 2000, Boston, MA.

J.A. del Cueto, "Thermal Characteristics of Flat-Plate Photovoltaic Modules Deployed at Fixed Tilt.," Presented at the NCPV Program Review Meeting, April 2000.

C.R. Osterwald, J. Pruett, S. Rummel, A. Anderberg, and L. Ottoson, "Forward-Biased Thermal Cycling: A New Module Qualification Test," Presented at the NCPV Program Review Meeting, April 2000.

T. Basso, "The NREL Outdoor Accelerated-Weathering Tracking System Photovoltaic Module Exposure Results.," Presented at the NCPV Program Review Meeting, April 2000.

Major Articles Published in FY 2000:

J.A. del Cueto, "Method for Analyzing Series Resistance and Diode Quality Factors from Field Data Part II: Applications to Crystalline Silicon", *Sol. Eng. Mat. and Solar Cells* **59**, pp. 393-405 (1999).

C.R. Osterwald, et al., "The World Photovoltaic Scale: An International Reference Cell Calibration Program," *Prog. Photovolt: Res. Appl.* **7**, 287-297 (1999)

C.R. Osterwald and K.A. Emery, "Spectroradiometeric Sun Photometry," *J. Atm. Oc. Tech.* **17**, pp. 1171-1188 (2000).

Industry-Guided Module Durability Research

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic System Components Department	
	Organization Type: FF	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Michael A. Quintana **Phone:** 505-844-0474 **Fax:** 505-844-1504 **E-mail:** maquint@sandia.gov	
Technical Monitor: Joe R. Tillerson **Phone:** 505-844-1806 **Fax:** 505-844-6541 **E-mail:** jrtille@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $528,000 2000: $507,000	**Cost Share Funding:**

Project Objective: The objective of the Module Durability Research Cooperative (MDRC) is to improve durability of commercial photovoltaic modules. This work is highly collaborative with manufacturers often participating in the research and often cost sharing the expense. MDRC work has been performed in collaboration with BP Solar, Spire, STR, ASE Americas, AstroPower, USSC, Siemens, Photocomm, First Solar, and Evergreen.

Approach/Background: The technical approach for conducting MDRC studies has been to 1) collaboratively identify module durability issues, 2) examine the underlying physical mechanisms associated with these durability issues, and 3) feed back the resultant information to positively influence the reliability of future photovoltaic products. This is accomplished by utilizing expertise and resources available at Sandia National Laboratories, NREL, Southwest Technology Development Institute (SWTDI), and the Florida Solar Energy Center (FSEC).

FY99 MDRC activities examined issues related to:
1. Adhesion of EVA and PVB encapsulants to the glass, fluorocarbon, and cell surfaces
2. Adhesion of UV accelerated EVA
3. Integrity of as-manufactured and field-aged solder-joints
4. Status of lead-free solder as a manufacturing material
5. Infrared thermometry techniques for characterizing cell, module and array performance
6. Dark IV measurements as a method of identifying solder-joint degradation in cells and modules
7. Ultrasonic techniques for determining the integrity of as-manufactured solder-joints on cells and modules
8. Module performance changes due to solder-joint degradation
9. Geometrical variations in solder-joints and potential effects
10. Electrical performance of thin-film and crystalline cells and modules
11. Parameters that define module lifetimes.

Status/Accomplishments: A strong synergy exists between durability research and manufacturing verification. Test techniques used for durability studies have developed a set of metrics that not only apply to the description of physical changes in field-aged modules but also can assist manufacturers to determine the effectiveness of their manufacturing processes. Some of the highlights are:

Ultrasonic Characterization of Solder-Joints
Sandia invested significant time and resources to develop a non-destructive test technique to characterize solder-joints on the manufacturing line. This effort was in response to a request by manufacturers who expressed a need for a quality control technique that would accurately characterize quality of solder-joints on manufactured cell strings prior to the lamination process. Additionally, manufacturers required a technique that would not adversely affect yield. Despite not being fully developed, the ultrasound technique has already begun to provide valuable information to manufacturers wishing to improve their soldering process. In

addition, the technique has provided some durability information on field-aged modules. Sandia's role in providing testing and analysis of solder-joints will provide additional value as the industry continues to address cost and reliability issues.

Status/Accomplishments (continued):

Analysis of Twenty Year-Old Module Technology

The MDRC performed a detailed analysis of the technology employed by Spectrolab Inc. to manufacture modules fielded at Natural Bridges National Monument in southern Utah twenty years ago. A field survey, system performance tests, and a series of module and materials tests have confirmed the durability of the modules in the array. The combination of manufacturing processes, materials, and quality controls used by Spectrolab resulted in modules that have maintained a performance level close to the original specifications for twenty years. Specific contributors to the durability of the modules included polyinyl-butyral (PVB) encapsulant, expanded metal interconnects, silicon oxide anti-reflective coating, and excellent solder/substrate solderability. One of the main objectives of this study was to understand what characteristics will provide long term service in order to make an accurate comparison to products made with the modern automated processes and materials.

Module Long Term Exposure

During FY98 the Module Long Term Exposure (MLTE) task was initiated. The objective of this task was to examine subtle module degradation mechanisms as they occur by conducting a structured and controlled outdoor exposure (minimum of five years) of commercially available modules. Manufacturers participate by submitting modules for outdoor exposure. Modules are concurrently exposed to a hot and humid climate at the Florida Solar Energy Center and to a hot and dry climate at the Southwest Technology Development Institute. During FY00 modules from ASE Americas, BP Solar, Siemens (c-Si and CIGS), and USSC were tested and inspected monthly looking for the earliest signs of the field-induced degradation.

Planned FY 2001 Activities: Emphasize R&D on fundamental failure mechanisms and the link to improved manufacturing processes. This R&D should specifically address applicable goals identified in the Roadmap Workshop and DOE's Five Year Plan. The work is highly collaborative and depends heavily on module manufacturers participation. The two durability issues that will continue to receive the most emphasis are loss of encapsulant adhesion (delamination) and solder-joint failures (power loss) due to thermal cycling in the field. Moisture intrusion into modules has been linked to encapsulant browning, module delamination, electrical safety issues, and corrosion of metal contacts; a better fundamental understanding is needed. As a result, specific emphasis will be given to the topic of moisture intrusion in FY01.

Major Reports Published in FY 2000:

D. L. King, et al., "Photovoltaic Module Performance and Durability Following Long-Term Field Exposure," 16 pp., Progress in Photovoltaics: Research and Applications, 2000; **8**: 241-256.

B. Kroposki, W. Marion, D. King, W. Boyson, and J. Kratochvil, "Comparison of Module Performance Characterization Methods," 55 pp., NREL/TP, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000:

D. King, J. Kratochvil, and W. Boyson, "Stabilization and Performance Characteristics of Commercial Amorphous-Silicon PV Modules," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

D. King, B. Hansen, J. Moore, and D. Aiken, "New Methods for Measuring Performance of Monolithic Multi-Junction Solar Cells," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

D. King, J. Kratochvil, M. Quintana, and T. McMahon, "Applications for Infrared Imaging Equipment in Photovoltaic Cell, Module, and System Testing," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

B. Kroposki, W. Marion, D. King, W. Boyson, and J. Kratochvil, "Comparison of Module Performance Characterization Methods," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

M. Quintana, D. King, F. Hosking, J. Kratochvil, R. Johnson, and B. Hansen, "Diagnostic Analysis of Silicon Photovoltaic Modules after 20-yr Field Exposure," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

T. McMahon, G. Jorgensen, R. Hulstrom, D. King, and M. Quintana, "Module 30 Year Life: What Does it Mean and is it Predictable/Achievable," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, (2000).

Module and Array Performance and Reliability

Module/Array Performance Testing and Modeling

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
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E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Sandia National Laboratories
Photovoltaic System Components Department</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
David L. King
Phone: 505-844-8220 Fax: 505-284-3239 E-mail: dlking@sandia.gov</td></tr>
<tr><td rowspan="2">Technical Monitor:
Joe R. Tillerson
Phone: 505-844-1806
Fax: 505-844-6541
E-mail: jrtille@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $371,000
2000: $697,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this task is to apply measurement and modeling capabilities available at Sandia to characterize the electrical, thermal, and optical behavior of photovoltaic modules and arrays. These efforts are tailored to, and conducted in close cooperation with, module manufacturers, system designers/integrators, system owners, and organizations that establish or perform module qualification testing procedures.

Approach/Background: The technical activities associated with this task can be described in three categories: (1) development and application of improved outdoor test methods for module and array performance, (2) development and validation of improved field testing procedures for photovoltaic array performance characterization (rating), and (3) the incorporation of improved testing and modeling procedures in both consensus standards and the software used for photovoltaic system design and sizing.

At industry's request, comprehensive outdoor tests are conducted that provide a combination of specific module performance characteristics not available elsewhere. Improved outdoor test methods are continually being developed at Sandia. The information gained from the testing provides not only traditional performance "calibrations" at ASTM Standard Reporting Conditions but also module parameters required for system engineering (design, sizing, rating). Specific tests provide: module temperature coefficients, direct measurements of the influences of solar spectral variation and solar angle-of-incidence, module thermal time constants, operating temperature versus wind speed, thermal "hot-spot" behavior in reverse-bias, etc. Complementary dark current-voltage measurements provide physical parameters (series resistance, shunt resistance, saturation currents, diode factor) required for electrical modeling of cell circuits. In many cases, individual cell measurements in Sandia's Photovoltaic Device Measurement Laboratory are also used to confirm characteristics observed in outdoor module testing.

The development and improvement of field testing procedures for arrays has been accomplished by adapting our outdoor module measurement procedures to large photovoltaic arrays. Validation of the field test procedures has been accomplished by applying the method to about ten different arrays in different system applications, totaling over a megawatt of installed PV modules. By doing so, a significant improvement in the accuracy and utility of performance characterizations (ratings) of large arrays has been obtained, and now integrated in field testing standards such as IEEE 1373.

Status/Accomplishments: During the last two years, improved array testing procedures have been successfully demonstrated for virtually all commercial photovoltaic technologies; flat-plate and concentrator. Sandia's testing procedures, data analysis, and performance modeling method are being considered for inclusion in a variety of domestic and international standards (IEEE 1479, IEEE 1513, ASTM E1036, IEEE 1262, IEC 1215, IEC 1646). This year, Sandia's module performance model was incorporated by a software vendor in commercial PV system design software (PV-DesignPro by Maui Solar Energy Software Corporation.) Sandia's unique outdoor module testing capabilities were applied, at manufacturer's request, to provide comprehensive performance characterization of modules from ASE Americas, AstroPower, BP Solar, EPV, Kyocera, Matrix Solar, PVI, Siemens Solar, and USSC. Associated cell performance tests were performed for AstroPower, BP Solar, PVI, SunPower Corp., and Matrix Solar. Reference cell, reference module, and pyranometer calibrations were performed for ASE Americas, AstroPower, BP Solar, ASU/PTL, FSEC, SWTDI, and NREL.

Contract #: DE-AC04-94AL85000

Status/Accomplishments (continued): A comprehensive effort was also conducted in collaboration with NREL to compare and validate alternative module performance models proposed for use in determining module energy ratings associated with the IEEE 1479 standard. This effort involved model verification using year-long performance measurements recorded by NREL on five different module technologies; resulted in detailed NREL technical report and IEEE PVSC paper.

Planned FY 2001 Activities: Emphasize performance testing and modeling directly related to system annual energy production and module energy ratings, directly addressing needs identified in DOE's Five Year Plan. The work is highly collaborative with module manufacturers, system designers/integrators, and users. The continued development of improved testing procedures and performance models will be validated and incorporated by others in commercially available system design software. Thorough documentation of test procedures and models is an integral part of this activity. In addition to published reports and articles, ten or more performance test reports will be provided in support of industry or DOE program requests.

Major Reports Published in FY 2000:

D. L. King, et al., "Photovoltaic Module Performance and Durability Following Long-Term Field Exposure," 16 pp., Progress in Photovoltaics: Research and Applications, 2000; **8**: 241-256.

B. Kroposki, W. Marion, D. King, W. Boyson, and J. Kratochvil, "Comparison of Module Performance Characterization Methods," 55 pp., NREL/TP, Golden, CO: National Renewable Energy Laboratory.

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D. King, J. Kratochvil, and W. Boyson, "Stabilization and Performance Characteristics of Commercial Amorphous-Silicon PV Modules," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

D. King, B. Hansen, J. Moore, and D. Aiken, "New Methods for Measuring Performance of Monolithic Multi-Junction Solar Cells," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

D. King, J. Kratochvil, M. Quintana, and T. McMahon, "Applications for Infrared Imaging Equipment in Photovoltaic Cell, Module, and System Testing," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

P. Thacher, W. Boyson, and D. King, "Investigation of Factors Influencing the Accuracy of Pyrheliometer Calibrations," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

B. Kroposki, W. Marion, D. King, W. Boyson, and J. Kratochvil, "Comparison of Module Performance Characterization Methods," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

M. Quintana, D. King, F. Hosking, J. Kratochvil, R. Johnson, and B. Hansen, "Diagnostic Analysis of Silicon Photovoltaic Modules after 20-yr Field Exposure," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

T. McMahon, G. Jorgensen, R. Hulstrom, D. King, and M. Quintana, "Module 30 Year Life: What Does it Mean and is it Predictable/Achievable," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, (2000).

Module and Array Performance and Reliability

Collector & Systems Testing Support

Contract #: AK-0748B	**Contract Period:** 10/1/99–8/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Spectra Research Albuquerque, NM 87119	
	Organization Type: IN	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** None	
Technical Monitor: Michael A. Quintana **Phone**: 505-844-0474 **Fax**: 505-844-6541 **E-mail:** maquint@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1996: $325,000 2000: $0 1997: $0 1998: $99,000 1999: $110,000	**Cost Share Funding:**

Project Objective: Provide on-site technical support for module performance testing.

Approach/Background: Provide computer programming, solar resource measurements, and performance testing, and analysis support.

Status/Accomplishments: Spectra Research Institute provides manpower resources to the Module and Array Performance and Reliability Project. Status/Accomplishments are covered in the contract summary for the Project.

Planned FY 2001 Activities: See Module and Array Performance and Reliability Project

Major Reports Published in FY 2000:
See Module and Array Performance and Reliability Project

Major Articles Published in FY 2000:
See Module and Array Performance and Reliability Project

Balance-of-Systems Components Development

PV Balance-of-System Reliability Analysis

Agreement #: DE-FC36-99GO10443	**Project Period:** 6/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Alec Bulawka
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E-mail: Alec.Bulawka@ee.doe.gov</td><td colspan="2">Control Systems Associates (CSA)
1777 Adams Way
Monterey Park, CA 91755</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 31</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
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Phone: 626-571-1203 Fax: 626-571-1203 E-mail: krauthamer@earthlink.net</td></tr>
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E-mail: lizana_pierce@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information: None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $15,000
2000: $60,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Under this award, Control Systems Associates (CSA) intends to analyze the U.S. Navy's Power Electronic Building Block (PEBB) technology to determine if it is a viable option for PV application and, if so, establish a set of recommendations on how to transfer this technology to the PV industry.

This effort will assess the issues of reliability in PV BOS and to see if the incorporation of PEBB devices will change the focus of the PV-BOS community and possibly resulting in improved reliability. The power Electronics Building Block (PEBB) Program initiated by the office of Naval Research is a new high reliability approach that simultaneously develops Science, Technology, and Engineering with a Commercialization Program for rapid insertion of products and technology into commercial and naval systems. The basic objective of this project is to report to the PV power conditioner industry the availability and characteristics of PEBB modules that will be available as a result of the PEBB program and to establish a set of recommendations on how to transfer this technology to the PV Industry. Application of PEBB devices will be reviewed and assessed. Modules developed should be available to the PV industry and will assist the industry to improve reliability, reduce costs and open a new window of opportunity for large scale manufacturer of photovoltaic systems. PEBB Program reliability efforts at PEBB will be analyzed for their applicability to improve PV Balance of System (BOS).

This task will be collaborative effort with the PEBB program and the PV industry and will result in a report that will outline the results of the PEBB Module program and associated reliability improvement. The report will identify the applicable PEBB Devices that can be used by PV-Power conditioner manufacturers in their products, and to establish a set of recommendations on how to transfer this technology to the PV industry. Furthermore, the report will identify sources and suppliers of the PEBB modules, including application recommendations. The basic objective is to improve reliability, performance and to help open new large scale markets for PV by reducing cost.

Approach/Background: This is a solicited severable award with a duration of thirteen (13) months for the analysis and assessment of the U.S. Navy's Power Electronic Building Block (PEBB) technologies and its applicability to increasing the reliability of PV Balance-of-Systems (BOS). CSA was selected under the Broad-Based Solicitation, Supplemental Announcement 05.

Status/Accomplishments: During the period Control Systems Associates (CSA) continued data base review and collection activities, coordination and meetings with DOE, PEBB module manufacturers, PV power conditioner manufacturers, Office of Naval Research, California Energy Commission (CEC), PEBB representatives were conducted, participated in various meetings including the PEBB program meetings, Intercontinental Electronic Device Meeting, International Conference on Power & Energy Systems, International Multi-Chip Advanced Power Systems, and the Power System World Conference '99

Agreement #: DE-FC36-99GO10443

Planned FY 2001 Activities: All activities under the agreement were completed. During FY 2001, CSA will finalize and submit the final report and publish the results via a DOE publication. The Final Report and publication will include details of: 1) viability of PEBB modules for PV applications; 2) PEBB module characteristics; 3) PEBB module applications information; 4) PEBB module reliability issues; 5) summary of PV-PCU manufacturers requirements; 6) assessment of PEBB modules; 7) reliability issues in PV-BOS and resultant impact of PEBB; and 8) PV-PCU specifications

Major Reports Published in FY 2000:
S. Krauthamer, and V. Boyadzhya, (2000), Quarterly Project Reports

Major Articles Published in FY 2000:
V. Boyadzhyan, S. Krauthamer, and J. Choma Jr., "Silicon Germanium Technologies for System on a Chip' Solutions (Integrated 'On Chip' RF/microwave & Sensor Technologies)," PATMOS '99, KOS Island, Greece.

Balance-of-Systems Components Development

PV Battery and Charge Controller Testing and Development

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
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E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Sandia National Laboratories
Photovoltaic System Applications Department</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
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<tr><td rowspan="2">Technical Monitor:
Joe R. Tillerson
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E-mail: jrtille@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $303,000
2000: $220,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: PV system field test evaluations have identified the battery as one of the highest life-cycle cost components. Many times battery life-cycle cost is well over 1/3 of the initial capital costs of the system. In some cases the frequent battery replacements and added costs make the PV system unsustainable. Field test data has shown that inappropriate battery design/installation, improper battery charging, and a lack of maintenance were the predominate contributors to capacity loss and early failure. In an effort to reduce PV system life-cycle costs, the Balance-of-Systems Components Development project at Sandia is working to educate PV system designers on PV battery requirements, identify PV battery charging requirements with laboratory and field testing, and promote improved battery designs and charge controllers in fielded PV systems.

Approach/Background: Work is progressing in education, laboratory and field battery testing, and charge controller development. Maintaining a good line of communication with battery manufacturers, charge controller manufacturers, and system integrators is key to the success of this effort. Many times battery manufacturers do not understand the unique requirements of a PV system and need a technical interface between them and the PV industry. In turn, most charge controller manufacturers and system integrators do not have effective communications with the battery manufacturers. Sandia has and continues to facilitate improved communications among different segments of the industry. To quantify battery performance, laboratory test procedures have been developed to test batteries in small stand-alone PV systems and in PV hybrid systems. These test procedures make it possible to understand why PV batteries are not performing as expected by quantifying the degradation caused by common PV use environments. The laboratory testing also identifies improved management strategies usually with minimal or no additional costs to the system. Field testing is used for verification of new battery technology and/or improved charge control. It's always a key element in any laboratory testing program. Many times the work in the lab has shown that commercially available charge controllers do not use the regulation voltage that is appropriate or that the engine generator battery charge control in PV hybrid systems is inadequate. In these cases Sandia works with the charge controller manufacturers to upgrade and/or test their product. Examples of this support where significant improvements were made are Morningstar, Pulse Energy, and Digital Solar charge controller manufacturers.

Status/Accomplishments: The PV Battery and Charge Controller Testing and Development project has completed a number of projects such as:

1. development, testing, and fielding of the new microprocessor based PV hybrid system controller called the MPR-9400 manufactured by Digital Solar Technologies,
2. development and testing of a new PV hybrid battery test procedure,
3. completed testing on many of the most popular PV batteries used by the PV industry in support of battery manufacturers and the PV industry,
4. provided data acquisition and technical support to Sandia National Labs, Air Force, and Park Service for the Mt. Washington, Grasmere, Mojave, and Joshua Tree PV hybrid systems, and
5. published reports on the PV Battery Hybrid Battery Test Procedure and the Mt. Washington PV hybrid system at the 2000 NREL program review meeting and at the 2000 IEEE PVSC conference in Anchorage.

Contract #: DE-AC04-94AL85000

Status/Accomplishments (continued):
Without this project the above activities would not have occurred. The funding, development, and testing of the MPR-9400 system controller is an example of integrating the battery, system, and user needs into a complete system controller. The controller is now being used in many remote high value telecommunications sites because it provides reliable charge control and system command and control and data acquisition (SCADA). This in conjunction with battery testing provides the sound technical basis with appropriate hardware for reliable the PV system design and control.

Planned FY 2001 Activities: Work will continue in the area of battery testing, IEEE standards, PV industry support, and system monitoring.

Major Reports Published in FY 200: none

Major Articles Published in FY 2000:
T. D. Hund, "PV Hybrid Battery Testing," NREL NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO.

T. D. Hund and John Stevens, "PV Hybrid VRLA Battery Test Results From A Telecommunication Site," *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Balance-of-Systems Components Development

PV Power Processing (BOS) Program

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic Systems Applications Department **Organization Type:** FF	**Congressional District:** 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Russell Bonn **Phone:** 505-844-6710 **Fax:** 505-844-2890 **E-mail:** rhbonn@sandia.gov	
Technical Monitor: Joe R. Tillerson **Phone:** 505-844-1806 **Fax:** 505-844-6541 **E-mail:** jrtille@sandia.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1999: $1,080,000 2000: $1,136,000	**Cost Share Information:** **Cost Share Funding:**

Project Objective: The Sandia balance-of-system (BOS) program goals are to:

- Promote the development of improved and innovative BOS components
- Advance the reliability of PV electronic components to the levels achieved by more mature products
- Reduce life-cycle cost
- Remove implementation barriers to PV
- Assist component manufacturers with the development of more reliable, cost effective systems

Approach/Background: The SNL Balance of Systems Project is a partnership with industry that provides special waveform testing, laboratory evaluations, technical support, accelerated lifetime testing, and promotes contractor in-house quality programs. Another important element of the program is R&D contracts with industry to provide research and development funding for state-of-the-art advances in BOS components. Finally it disseminates information concerning BOS advances and SNL benchmarking activities.
Emerging technologies and changing customer requirements drive research advances in BOS electronic components.
Targeted areas include improved inverters and inverter components, improved islanding techniques, new storage methods, and improved understanding of issues that degrade components (such as battery over temperature).
Reliability issues are addressed in partnership with manufacturers. A major issue that has been identified by manufacturers and users is that line surges due to nearby lightning have resulted in numerous field failures. Recently implemented surge testing at SNL has identified vulnerabilities to induced pulses in existing inverter designs. Pulsed evaluation of inverters will be expanded to include more inverters and charge controllers.
Reliability will also be improved as a result of Highly Accelerated Lifetime Testing (HALT) evaluations on new hardware.
Quality evaluations at larger BOS manufacture's plants will be offered as a service to PV BOS manufacturers.
The in-house laboratory will continue to provide a test bed that supplements the limited capability of PV manufacturers

Status/Accomplishments:

- Because lightning is believed to be a major source of field failures, a surge test bed was developed to evaluate the effects of nearby lightning. As a result of this work a paper was published on test methodology, testing resulted in New Hampshire acceptance of the Trace Engineering inverter, inverter manufacturers were convinced they need mitigation devices, and one popular mitigation device was found inadequate for inverter protection.
- PV inverter anti-islanding technology was developed and a SNL developed test methodology was implemented in IEEE – 929. Several utilities have adopted the new 929 as a requirement and have consequently removed other paper barriers for PV implementation. Sandia has released SAND2000-1939, "Development and Testing of an Approach to Anti-Islanding in Utility-Interconnected Photovoltaic Systems" which further describes the anti-islanding approach. This document is very valuable for inverter manufacturers. UL1741 has adopted the Sandia test procedure to verify compliance with IEEE 929.

Contract #: DE-AC04-94AL85000

Status/Accomplishments (continued):

- In laboratory evaluations of inverters 7 grid-tied and 9 off-grid inverters were evaluated for industry. These evaluations assisted manufacturers with development of new products and resulted in improved reliability and lowered life-cycle cost of inverters. Problems were identified with two new inverters.
- The evaluation of an off-grid integrated system quantified incorrect operation of the charge controller and design problems in: code, grounding, maintenance, and mismatching of components. Feedback from SNL test program has improved future design and Sandia has provided training for electricians in the program

Planned FY2001 Activities:
This project will enlist the aid of recognized experts on power electronics to assist in the preparation of a report entitled "Balance-of-systems Component Needs for the 21st Century". The report will include the first component of the 'systems engineering' of a new universal inverter.

PV inverter mean time to first failure (MTFF) is currently less than five years. Sandia will initiate the multi-year development of a new universal inverter that has a MTFF greater than ten years with a cost of less than 65 cents/watt.
Reliability will also be improved as a result of Highly Accelerated Lifetime Testing (HALT) evaluations on new hardware.
Sandia, having solved the problem of islanding of PV inverters, is expanding its test capability (with Sandia funding) to include a distributed resources test bed. This test bed will be utilized to examine undesirable interactions between PV sources and other types of distributed generation.

The in-house laboratory will continue to provide a test capability that supplements the limited capability of PV manufacturers and provides benchmarking of PV inverters.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

System Engineering and Applications

Photovoltaic System Performance and Engineering

PV Interconnection Issues

Contract #: AS-3621	**Contract Period:** 2/25/96–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Ascension Technology Lincoln Center, MA 01773 **Organization Type**: IN	 **Congressional District:** 7
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Ed Kern **Phone:** 781-684-6101 **Fax**: 781-684-2050 **E-mail:** ekern@ascensiontech.com	
Technical Monitor: John W. Stevens **Phone:** 505-844-7717 **Fax:** 505-844-6541 **E-mail:** jwsteve@sandia.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1996: $16,000 2000: $4,000 1997: $0 1998: $4,000 1999: $5,400	**Cost Share Information**: None **Cost Share Funding:**

Project Objective: Install grid-tied 30KW inverter for existing PV system. Establish monitoring technique to provide data for reliability project.

Approach/Background: Communicate with reliability project leader to determine exact data requirements for reliability project. Configure data monitoring system to provide that information.

Status/Accomplishments: Continued monitoring system events.

Planned FY 2001 Activities: Complete all monitoring activities and provide final report.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Photovoltaic System Performance and Engineering

Field Module Durability and System Rating

Contract #: AP-7660	**Contract Period:** 9/3/95–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Florida Solar Energy Center
Cocoa, FL 32816-0150</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 8</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
N Dhere
Phone: 321-638-1000 Fax: 407-638-1010 E-mail: dhere@fsec.ucf.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Michael A. Quintana
Phone: 505-844-0474
Fax: 505-844-6541
E-mail: maquint@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1996: $180,000
1997: $350,000
1998: $150,000
1999: $188,000
2000: $65,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Assist Sandia and the U.S. PV industry to identify and study PV module durability issues.

Approach/Background: FSEC continues to provide critical support to Sandia and the U.S. PV industry by providing expertise and resources necessary to address module durability. Leveraging this work by taking advantage of Florida University system test facilities and links to think-film as well as crystalline technologies provides exceptional value to the US DOE Photovoltaics Program.

Status/Accomplishments The contract with FSEC was allowed to expire during FY00. During the short period that the contract was in place FSEC performed studies related to module durability. Work was primarily focused on module encapsulant adhesion and glass optical transmission studies. Adhesion required analysis of different cell and encapsulant interface surfaces as well as measuring the adhesion in new and field-aged modules. Additionally, FSEC began a study of the physics of failure of microelectronic devices and applied the information to the durability photovoltaic modules during this time period.

Planned FY 2001 Activities: none. Contract expired.

Major Reports Published in FY 2000:
N. G. Dhere, "PV Module Durability In Hot And Dry Climate", Proc. 16th European Photovoltaic Solar Energy Conference, Glasgow, UK, May 1-5, 2000, (to be published).

Major Articles Published in FY 2000:
"Adhesional Strength and Encapsulant Surface Analysis of a PV Module Deployed for Twenty Years at Natural Bridges-A Success Story"; Module Durability Research Cooperative Tech Brief.

"Comparison of Optical Transmittance Spectra of New Tempered Glass with that of Superstrate Glass Extracted from a Field-Aged PV Module"; Module Durability Research Cooperative Tech Brief.

SERES Field Evaluation

Contract #: AV-5590	**Contract Period:** 5/1/95–10/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Florida Solar Energy Center Cocoa, FL 32816-0150	
	Organization Type: CU	**Congressional District:** 8
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** J. Ventre **Phone:** 407-638-1470 **Fax:** 407-638-1010	
Technical Monitor: Michael G. Thomas **Phone:** 505-844-1548 **Fax:** 505-844-6541 **E-mail:** mgthoma@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1996: $380,000 1999: $440,000 1997: $650,000 2000: $0 1998: $600,000	**Cost Share Funding:**

Project Objective: Support US PV Industry and DOE PV Program personnel.

Approach/Background: Regional assistance with agencies and utilities, integration of buildings program at FSEC with PO, education and training for regional customers, and development of statewide programs in Florida.

Status/Accomplishments: Contract ended shortly after fiscal year began

Planned FY 2001 Activities: none. Contract ended.

Major Reports Published in FY 2000: none.

Major Articles Published in FY 2000: none.

Photovoltaic System Performance and Engineering

Photovoltaic Solar Radiometric Measurements

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd Golden CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** D.R. Myers **Phone:** 303-384-6768 **Fax:** 303-384-6391 **E-mail**: daryl_myers@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E-mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $485,100 2000: $566,365	**Cost Share Funding:**

Project Objective: The Photovoltaic (PV) Solar Radiometric Measurements task supports the radiometric needs of the NREL PV research program tasks, measurement and characterization activities, and the PV industry. The project performs optical radiation broadband and spectral calibrations (metrology) and measurements, and provides technical expertise in the subject areas as requested. The project strives to meet the requirements for appropriate levels of uncertainty in areas of solar and optical radiometry directly applicable to PV research and development (R&D) , production, and deployment.

Approach/Background: Accurate solar irradiance and optical radiation measurements are essential to the national labs' role in supporting internal PV R&D activities and the evolving PV industry. This accuracy is required in the R&D laboratory during calibration and performance testing of cells and modules, in the production environment for quality control and production monitoring, and in the field during performance characterization and monitoring of photovoltaic arrays. The project maintains measurement instrumentation, expertise, and traceability to organizations such as the National Institute for Standards and Technology (NIST), the World Meteorological Organization (WMO/WCRP), and the recently proposed World Photovoltaic Scale (WPVS). This internationally established traceability is continually transferred to industry by NREL and Sandia via several activities.

These activities include: calibration of broadband and spectral solar irradiance sensors; optical metrology for cell and module calibrations for manufacturers and universities; technical support in the field of optical radiometry and solar radiometry for standards activities within the American Society for Testing and Materials (ASTM), Institute of Electrical and Electronic Engineers (IEEE), International Electrotechnical Commission (IEC), etc.; and radiometric calibrations for accreditation of commercial test laboratories (PowerMark, Arizona Statue University Photovoltaic Testing Laboratory (ASU/PTL). Specific technical activities include the maintenance and operation of the NREL Optical Metrology Laboratory for spectral radiometry and optical radiation research; operating the NREL Solar Radiation Research Laboratory (SRRL) for monitoring the solar and meteorological environment in support of PV testing under prevailing conditions and radiometric sensor calibration and characterization; the calibration and measurement of solar simulators for PV performance testing; measurement of natural and artificial sunlight in outdoor and indoor accelerated (high flux) testing ; measurements for the validation of radiometric aspects of consensus national and international standards and codes developed to support the PV industry; and research into improved measurement and modeling of spectral and broadband terrestrial solar radiation resources available to PV systems as a function of meteorology, climate, and atmospheric radiative transfer.

Status/Accomplishments:
Spectral Calibrations and Measurements:_ Six NREL spectroradiometer systems were calibrated with respect to NIST standards, and used to characterize or evaluate nine NREL PV test and measurement systems at the Outdoor Test Facility (OTF) or the PV Measurement and Characterization Laboratory in the Solar Energy Research Facility (SERF). An Analytical Spectral Devices (ASD) unit was acquired as a capital equipment upgrade to complement our older technology systems. Example PV testing systems evaluated or tested included the Spectrolab X-25 Solar Simulator, NREL Spire 240 Pulse Simulator, Large Area Continuous Pulse Solar Simulator (LACSS), Large Area Pulse Solar Simulator (LAPSS), High Intensity Pulse Solar Simulator (HIPSS), Atlas XR 260, SC 1600, and Vortek lamp sources. The task also re-calibrated three other Li-Cor Li-1800 spectrometers used by the PV M&C team in the outdoor calibration of primary reference PV cells. A program of regular monthly spectral measurements of the Spires 240 simulator provided information on long term spectral shifts (on the order of 5%). Reference spectroradiometers were used to calibrate Ultraviolet (UV) radiometers [8 for NREL and two for the ASU/PTL]. NREL and ASU/PTL PV UV-exposure tests are run at elevated temperatures (65°C). We characterized the temperature response of the UV monitor in the OTF chamber to be 5%/°C (25°C to 45 °C).

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Status/Accomplishments (continued):
Broadband Radiometric Calibrations: In October, 1999, we conducted an intercomparison of absolute cavity pyrheliometers at the SRRL to maintain the WRR factors of the NREL and other participating cavity radiometers. The WRR factors and uncertainty with respect to *System Internationale* (SI) units for NREL cavity radiometers used as the standard for PV reference cell calibrations and at the outdoor test Facility Reference Meteorological and Irradiance System (RMIS) were less than 0.39% for un-windowed and 0.50% for windowed cavity radiometers. Improvements in outdoor calibration techniques and instrumentation reduced bias errors in radiometers by about 1/2 (2%). We verified the removal of thermal offsets in diffuse reference irradiance components, improved incidence angle calculation accuracy by employing Global Positioning System (GPS) based time information. Eighteen NREL and 6 ASU/PTL broadband pyranometers and pyrheliometers are calibrated against NREL reference absolute cavity pyrheliometers traceable to the WMO WRR.

Solar Radiation and PV Performance: The NREL Optical Metrology Laboratory was relocated to the new SRRL building in Dec, 1999. The SRRL Baseline Measurement System was removed from service in July, 1999, for relocated to the new instrument platform., New sensors will be added to provide 38 radiometric and meteorological parameters, accessible over the internet. Frequency of occurrence of DNI values by hour were investigated to determine what DNI values may represent "typical" conditions for various candidate concentrator system site resource availability. We developed a simple algorithm to convert averaged data into data with higher resolution. For example, to estimate 365 daily values from 12 monthly averages; or minute (or any other higher time resolution desired) data from hourly averaged data. The algorithm was submitted to Solar Energy for publication in May 1999.

PV Standards and Codes Support: We published a technical basis for identifying “peak power rating” (PPR) and spectral conditions for concentrator systems when global normal irradiance is near the standard reporting condition (SRC) of 1000 W/m^2 . Statistical analysis of prevailing conditions near SRC suggests 850 W/m^2 is a reasonable DNI value for rating concentrator collectors. We evaluated the ASTM E892 reference spectrum with respect to measured spectra extracted from the SERI Solar Spectral Data Base for GNI and DNI within 10 W/m^2 of 1000 W/m^2 and 850 W/m^2. Atmospheric turbidity of approximately 0.10 and wind speed of 4 m/s prevail when irradiance conditions are near SRC in the southwest United States. Measured DNI spectra near SRC conditions show the reference direct spectrum is blue deficient (due to the high turbidity - 0.27 - used in generating the spectrum). The reference global tilt spectrum is closer to the available measured *direct* spectra, especially for areas appropriate for concentrator technology deployment. Thus the existing *global tilt* reference spectrum (ASTM E-892) can be interpreted as a *direct normal spectrum* under specific conditions. Rather than develop a new reference spectrum for evaluating concentrator module performance, new procedures using the existing, or a slightly modified, global tilted reference spectrum will be investigated.

Planned FY 2001 Activities: NREL reference absolute cavity radiometers will participate in the 9th International Pyrheliometer Comparisons (IPC IX) to be conducted by the World Meteorological Organization at Davos, Switzerland in October, 2000. Stability of NREL World Radiation Reference (WRR) correction factors will be evaluated. We will continue to provide spectral and broadband radiometer calibrations for the NREL and PV industry community with NIST and World Radiometric Reference traceability. Routine and as-requested broadband radiometer calibrations will be improved by upgrading the current software used for Radiometer Calibration and Characterization (RCC) to reduce uncertainties, provide better radiometer responsivity maps, and have greater operational and user friendliness. We will continue to perform regular monthly and as-needed spectral distribution measurements of critical PV test sources (X-25, Spire 240, LACSS, LAPSS, HIPSS). The SRRL baseline measurement system instrumentation and internet accessible data will be upgraded as the new instrument platform is populated. Issues with the ASTM reference spectra will be investigated and discussed with an eye to possible improvements and revisions to the ASTM standards, through the ASTM standards committees E-44.09 and G-3.09. Spectral and broadband solar modeling and model validation will continue, to provide data supporting R&D and deployment questions such as available resources and their variability, and PV module energy rating standards.

Major Reports Published in FY 2000:
Myers, D.R., T.L. Stoffel, A. Andreas, S. Wilcox, I Reda, "Improved Radiometric Calibrations and Measurements for Evaluating Photovoltaic Devices". NREL Technical Report, TP-520-28941 Oct 2000. Golden, CO, National Renewable Energy Laboratory.

Major Articles Published in FY 2000:
Myers, D.R., A. Andreas, M. Rymes, T.L. Stoffel, S. Wilcox,, I Reda, J. Treadwell, "Radiometric Measurements and Data for Evaluating Photovoltaics"; 16th NREL/SNL PV Program Review Meeting, Denver, CO, 16-19 Apr 2000.

Myers D. R., S. Kurtz, C. Whitaker, T. Townsend, A. Maish, "Preliminary Investigations of Outdoor Meteorological Broadband and Spectral Conditions for Evaluating PV Modules and Systems" 16 NREL/SNL PV Program Review Meeting, Denver, CO, 16-19Apr 2000.

Rymes, M.D., and D.R. Myers, "Mean Preserving Algorithm for Interpolating Average Data to Higher Resolution". Submitted to *Solar Energy* May 2000.

Myers, D.R, S. Kurtz, K. Emery, C. Whitaker, T. Townsend, "Outdoor Meteorological Broadband and Spectral Conditions for Evaluating Photovoltaic Modules" *28th IEEE PV Specialists Conference*, Anchorage AK, 17-22 Sep 2000.

Photovoltaic System Performance and Engineering

Photovoltaic Systems Performance and Standards

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **Email:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Richard DeBlasio **Phone:** 303-384-6452 **Fax:** 303-384-6491 **E-mail:** deblasid@tcplink.nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **Email**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1997: $830,000 1999: $905,000 1998: $843,000 2000: $823,070	**Cost Share Funding:**

Project Objective: The overall objective of the Photovoltaic System Performance and Standards Task is to address PV system, subsystem, and component technical and infrastructure issues and provide solutions that support the DOE PV Program five year plan (1996-2000) goals, and to accelerate PV technology readiness and commercialization. Specific objectives are to provide engineering solutions and approaches that will reduce technical barriers to commercialization and advance photovoltaic system, subsystem, and component performance, safety, and quality.

Approach/Background: The technical approach to achieving task objectives include: (1) conducting system, subsystem, and component interface performance characterization outdoor testing and establishing standardized measurement and test procedures; (2) verifying PV system, subsystem and component development and advances through baseline outdoor performance testing, evaluation, and comparative analysis; (3) developing and documenting engineering best practices and technical guidelines for standardized system, subsystem, and component design and interface criteria and test procedures; (4) leading and supporting the development of national and international PV consensus standards and codes; (5) participating and supporting the development, implementation, and operation of domestic and international system and component certification and test facility accreditation programs; (6) facilitating information exchange and technology transfer through topical meetings, forums, and workshops; and (7) providing technical assistance and support to the domestic and international PV community for PV technology development and systems engineering and applications.

Status/Accomplishments:

1. Conduct validation of system testing procedure in coordination with international round-robin.
Completed the final report on the validation testing of six PV lighting systems at NREL, SWTDI, FSEC, and GENEC (France). The technical report entitled "*Validation Testing of Procedures for Determining the Performance of Stand-Alone Photovoltaic Systems*" NREL/TP-520-29185 presents an overview of the procedures and results from three validation tests conducted between January 1999 and September 2000. The performance procedures were found to be valuable in detecting some deficiencies of stand-alone PV systems. A summary paper on this work was presented at the IEEE PVSC in Anchorage, Alaska.

2. Host IEC TC82 PV International Standards meeting in the U.S. at ASU.
Over 40 representatives, including chief delegates and working group members participated in 5 days of coordination and working meetings to develop PV international standards at Arizona State University. Progress on standards projects were reviewed by delegates on modules, systems, BOS, certification, and storage with working groups (WG 1-7) meeting before and after the general IEC TC82 meeting (May 15-17), chaired by Dick DeBlasio.

3. Initiate Development of small systems qualification testing procedure
Initial development of a small-systems qualification test procedure was conducted. A summary of this information was included as part of NREL/TP-520-29185. A conceptual outline to identify failure mechanisms in fielded systems, determine accelerated conditions to duplicate the failures, and establish qualification procedures was developed.

4. Conduct system characterization of installed PV systems at OTF.
Ongoing testing and reporting continued on the 20 current PV systems installed at the Outdoor Test Facility. These include six grid-connected and 14 stand-alone PV systems. Completed four test reports on PV systems installed at the OTF.

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5. Lead IEEE Development of Energy Ratings P1479 and Small System Testing P1526 Standards.
Chaired working groups on P1479 "Recommended Practice for the Evaluation of Module Energy Production" and P1526 "Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems". Completed new drafts of Energy Ratings and Small System Test standards.

Planned FY 2001 Activities:
- Complete test procedure to determine performance of stand-alone PV systems and facilitate development of consensus standard IEEE 1526.
- Establish details on PV system failure mechanisms and preliminary test procedures for system qualification test.
- Lead and support IEEE SCC21 and IEC TC82 work in the development of national and international standards and certification programs (PMC and PVGAP), national electric code (NEC 690), and accreditation and certification testing laboratories.
- Conduct system characterization of installed PV systems at OTF.

Major Reports Published in FY 2000:
STR00SRX.001 - covered the performance of the 1kW array and 1.2 kW array from BP Solar.

STR00SCI.001 - covered the performance of the SCI 1kW CdTe system.

STR00SSI.001 - covered the performance of the Siemens Solar CIS 1kW array.

STR00ATI.001 - covered the performance of the SunSine 300 and the old beta unit SunSine 325.

Major Articles Published in FY 2000:
"Technology for the New Millennium: Photovoltaics as a Distributed Resource", B. Kroposki and R. DeBlasio, IEEE PES Summer Meeting, Seattle, WA 7/00.

"Comparison of Module Performance Characterization Methods", B. Kroposki, W. Marion, D. King, W. Boyson, and J. Kratochvil, 28th IEEE PVSC, Anchorage, AK, 9/00.

"Procedures for Determining the Performance of Stand-Alone Photovoltaic Systems", P. McNutt, B. Kroposki, R. Hansen, D. DeBlasio, K. Lynn, W. Wilson, and P. Boulanger, 28th IEEE PVSC in Anchorage, AK, 9/00.

Photovoltaic System Performance and Engineering

Solar Resource Characterization

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/98–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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Golden, CO 80401</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
1000 Independence Ave., SW
Washington, DC 20585</td><td colspan="2">Principal Investigator (s)
David S. Renné
Phone: 303-275-4648 Fax: 303-275-4675 E-mail: david_renne@nrel.gov</td></tr>
<tr><td rowspan="2">Technical Monitor:
R. Hulstrom
Phone: 303-384-6420
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E-mail: roland_hulstrom@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1998: $500,000 2000: $520,000
1999: $500,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The FY 2001 objective of this project is to develop and disseminate key information on solar energy resources to the U.S. industry and to energy planners in order to facilitate and accelerate the deployment of their technologies domestically and world-wide, and to attract investments for these deployments.

Approach/Background: To achieve this objective, the following approach will be undertaken in FY 2001:

- Refine the contents of an electronic "solar atlas", which covers a large portion of North America. These refinements include the incorporation of our previously-developed "PV Watts" algorithm into the 40-km resolution data grids, and the results of studies to relate short-term satellite time-series data to longer-term ground-based solar measurement data.
- Improve the capabilities to develop and deliver international solar resource data, including testing of and refinements to NREL's Climatological Solar Radiation (CSR) model, collaboration with the NASA/Langley Research Center (LaRC) in their global atlas development, and continued support to the World Radiation Data Center archive.
- Develop Geographic Information System tools to support more effective use of our data products for facilitating both domestic and international solar deployments;
- Maintain and expand upon the RReDC, which provides access to on-line solar resource data and information through the World Wide Web.

Status/Accomplishments: Key accomplishments in FY00 are as follows:

- An "electronic" solar atlas of North America. consisting of a series of map products available electronically through the Renewable Resource Data Center (RReDC), was developed using GIS-based software. This allows the user to customize his/her own maps, and specify the type of information to be included in the maps.
- Using DDRD funding we have created an archive on DVD media of the 20,000 DATSAV2 surface meteorological data set that has been acquired by the National Climatological Data Center. We have been unsuccessful, however, in negotiating a satisfactory follow-up activity with the World Radiation Data Center to continue with the archival of the world radiation dataset. Domestically, we continue to process and archive solar data acquired through the CONFRRM/HBCU networks.
- We have continued to add data sets and related information to the Renewable Resource Data Center, and have performed hardware upgrades to this system.

Planned FY 2001 Activities: This project consists of five tasks:
North American Solar Atlas Refinements. In FY01 the North American Solar Atlas will be expanded to allow for the calculation of total energy production for a user-specified grid-connected PV system in any data grid using the PV Watts algorithm. The existing U.S. surface monitoring network information will also be superimposed on the atlas. Further refinements, using geospatial software technology are contemplated. An additional component of this task is to review the need for an updated NSRDB by examining the trends in changes in solar radiation over the past one to two decades.

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Worldwide Solar Energy Database Developments: This task includes two subtasks:

- A study comparing surface measured, surface modeled, and satellite-derived solar radiation for multiple climate zones will be conducted. The study will address whether satellite-modeled time series are adequate for time dependent PV system analysis (such as Typical Meteorological Years, days of autonomy, etc.)

- A study to explore improvements to the CSR model by using cloud cover data available from the International Satellite Cloud Climatology Project of the World Climate Research Programme. A sample data set will be provided by ISCCP to be tested in the CSR model. The results will be verified using model outputs from NASA and other organizations at midlatitude and equatorial locations.

Enhancements of the World Radiation Data Centre web server at NREL. We will improve the user interface for the data distribution system to include improved site selection capabilities and clickable maps for data downloads. This effort will also make available software tools to aid users in extracting data from the WRDC format.

Enhancement of Web-based Map-Server Applications and other GIS Tools: We will continue development of a user-interactive GIS-based map server. We anticipate greatly enhanced capability based on new GIS software products, which will allow us to provide tools that improve access to geospatial solar resource data for analysis and interpretation. An archive of map images developed over the past several years for various clients will be established for use by NREL researchers.

Maintenance and Enhancements of the RReDC: We will continue to incorporate resource databases into the RReDC, and to develop links to other resource sites around the world. We will also continue to respond to the numerous public enquiries regarding the contents of the RReDC. Appropriate linkages between the RReDC and the on-line GIS web pages will be designed.

Major Articles Published in FY 2000:

B. Marion, M. Anderberg: PVWATTS: An Online Performance Calculator for Grid-Connected PV Systems. *Solar 2000, Madison, Wisconsin, 18-21 June, 2000.*

D. Renné, T. Stoffel, M. Anderberg, P. Gray-Hann, J. Augustyn: Current Status of Solar measurement Programs in the U.S., *Solar 2000, Madison, Wisconsin, 18-21 June, 2000.*

D. Renné, R. George, L. Brady, B. Marion, and V. Estrada-Cajigall: Estimating Solar Resources in Mexico Using Cloud Cover Data. *ISES Millennium Conference, Mexico City, 18-22 September, 2000.*

PV Certification and Accreditation Management Support

Contract#: AAX-7-16821-01	**Contract Period:** 11/18/99–11/17/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	PowerMark Corporation 4044 East Whitton Ave. Phoenix, AZ 85018-5940	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** S. Chalmers **Phone:** 602-955-7214 F**ax:** 602-955-7295 **E-mail:** chalmers@powermark.org	
Technical Monitor: Richard DeBlasio **Phone:** 303-384-6452 **Fax:** 303-384-6490 **E-mail**: dick_deblasio@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None
	DOE Funding Allocation: 1996: $49.970 1998: $60,000 1997: $35,000 1999: $60,000 2000: $60,000	**Cost Share Funding:**

Project Objective: To support an appropriate organization, PowerMark Corporation(PMC) to manage and administer the operation of a component and system certification and laboratory accreditation program. Administer corporate board and committee activities, and liaison activities with domestic and international organizations associated with certification, accreditation, standards, codes, and test method development and validation.

Approach/Background: The development of a domestic PV system and component certification and test facility accreditation program that is recognized, has reciprocity between other organizations and has testing conducted by accredited test facilities and products manufactured in a quality environment is a key to a PV component and system quality system. PowerMark Corporation was created to implement and manage a PV module certification program based on the ASU/ NREL/DOE study and has expanded it's role to include systems /components. PowerMark Corporation has been appointed the USA administrator for the Global Approval Program PV-GAP and in this roll is in a positioned to influence the harmonization of international and national efforts toward development of PV product certification and the supporting standards. A international ISO Guide 25 approved testing laboratory at Arizona State University Photovoltaic Testing Laboratory (ASU/PTL) has previously been approved. It provides a USA PV module test facility. There are only three facilities in the world so qualified and the other two are in Europe.
Florida Solar Energy Center (FSEC) with PMC encouragement and direction is in the process of being accredited for balance of systems components. With their approval in 2001 there will be in the USA facilities to do all PV testing.

Status/Accomplishments:
- Held regular Board meetings and submitted to NREL monthly progress reports as required in the contract.
- Represented the PV industry and PMC at the IECQ Electronic Component Certification Board (ECCB) meetings. The ECCB is the USA management committee for the Supervisory Inspectorate (SI) Underwriters Laboratory. Advocated and received support for system changes in IECQ to meet the requirements of PV. Obtained budgetary approval of funds to support incentives for manufactures for joining the PV-GAP certification process.
- Reviewed at the laboratory site the ASU/PTL audit documents that resulted in the renewal of approval of the laboratory by A2LA. The findings resulted in continued PMC recognition of the laboratory for module testing.
- Advised FSEC on the PMC requirements to become ISO Guide 25 approved for components.
- Provided a technical reviews for the World Bank and United Nations Development Program of Chinese and Uganda Standards and prepared reports regarding the harmonization of the standards with international IEC standards. Arranged to have a PMC Technical representative go to China and Uganda to meet with them and discuss harmonization and IECQ approval procedures,
- Up dated the PMC Trademark application (PV Mark of Quality and Design) to minimize conflict with other existing marks.
- Published a PMC brochure showing new officers and committee persons. Revised the web site to show the new information.
- Presentations were given at the National Center for PV in Denver, ECCB meetings in Virginia and Phoenix.
- The Technical Committee drafted and the Board approved the retesting requirement when changes are made in an approved module. These changes are proposed for adoption by IEC-TC-82.
- Initiated discussions regarding the possibility of developing a PMC module power rating that is less than a full qualification test.

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Status/Accomplishments (continued):

- Module proficiency test were performed and witnessed at ASU/PTL .The test conducted were will within the 5% PMC requirement
- Developed a mission statement
- Presented a summary of requirements for the utilization of standards and certification of PV products to the Arizona Corporation Commission Staff and the Solar Energy Advisory committee
- Participated in the preparation of a Committee Draft IEC 62078 *Certification and Accreditation Program for Photovoltaic (PV) Components and Systems* that was circulated for comments to the participating countries. The Certification Activities Board (CAB) of IEC has established a committee to take over the work and to develop a program for PV. The CD and comments provide a good starting place the CAB committee.

Planned FY 2001 Activities: Hold monthly meetings (Tele-conference) of the PMC Board. Increase industry representation on the board and committees for component and systems sectors. Exert best efforts to encourage reciprocity protocols from associated certification programs. Maintain PMC web site. Provide presentations of PMC and PVGAP at technical and industry meetings. Facilitate the IECQ approval of U.S. laboratories and manufacturers.

Major Reports Published in FY 2000:
FY 1999 Photovoltaic Energy Program Contract Summary, DOE/GO-102000-0976 (2000). Subcontract monthly reports, travel reports, meeting minutes, and annual report.

Major Articles Published in FY 2000:
Promotional material describing the PMC organization and benefits of PMC certification were provided during presentations at the IEEE SCC21 meetings.

Photovoltaic System Performance and Engineering

Systems Engineering

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic Systems Applications Department	
	Organization Type: FF	**Congressional District:** 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Mike Thomas **Phone:** 505-844-1548 **Fax:** 505-844-6541 **E-mail:** mgthoma@sandia.gov	
Technical Monitor: Joe R. Tillerson **Phone:** 505-844-1806 **Fax:** 505-844-6541 **E-mail:** jrtille@sandia.gov	**B&R Code:** EB22	**Cost Share Information:**
	DOE Funding Allocation: 1999: $1,880,000 2000: $ 1,718,000	**Cost Share Funding:**

Project Objective: The program provides system, subsystem, and component-level information and technical assistance to the photovoltaic community, primarily through the Photovoltaic Systems Assistance Center (PVSAC), and work on standards and codes, especially as they relate to IEEE and the National Electrical Code. The goal is to provide value-added engineering on both fielded and prototypical systems and components. Sandia has primary responsibility within DOE's PV program for developing and disseminating technical information on PV systems engineering. Goals and objectives are:

- reducing the life-cycle cost of PV systems
- reducing barriers to systems acceptance
- providing systems engineering best practices and guidelines
- leading the national effort in performance and reliability testing, with the overall goal of ensuring that PV systems meet customers' needs by working as expected.

Approach/Background: The systems engineering program seeks to improve PV system design, deployment, and operation, thereby achieving the goal of lower cost, more reliable systems

Status/Accomplishments:

- Developed rural development program with Navajo Tribal Utility Authority, including electrician training, system maintenance, and established data collection for off-grid houses.
- Delivered technical training through installation workshops and 13 workshops for electrical inspectors in 10 states.
- Maintained a comprehensive website at Sandia (average 100,000 hits/month) and two satellite websites at FSEC and SWTDI.
- Developed a detailed system performance database, with industry.
- Provided technical assistance to the National park Service and Bureau of Land Management at Joshua Tree, Dry Tortugas, Mojave, and Ft. Craig.
- Hosted IEC TC82 systems meeting in Tempe, Arizona and continued participation in IEA's Task V.
- Expanded Florida's State Buildings Program to include all the investor-owned utilities in Florida and 10 of the municipal utilities.
- Delivered six workshops to Million Solar Roofs partners to jumpstart deployments.

Planned FY 2001 Activities:

- Identify new applications for PV
- Lead national lab effort to facilitate/publish industry roadmap
- Gain accreditation for certification of PV systems
- Define life-cycle costs of residential off-grid and grid-tied systems.
- Establish benchmark requirements for 25-year system lifetimes
- Coordinate codes and standards development program within the US and IEC
- Publish report on American Indian uses of PV
- Report to industry on method for accurate energy prediction to OV industry.

Contract #: DE-AC04-94AL85000

Major Reports Published in FY 2000:

Stevens, John, et al. *Development and Testing of an Approach to Anti-Islanding in Utility-Interconnected Photovoltaic Systems*, SAND 2000-1939, Sandia National Laboratories, August 2000.

Brooks, Connie. *Power Where You Need It: The Promise of Photovoltaics*, SAND 2000-1124, Sandia National Laboratories, May 2000.

Major Articles Published in FY 2000:

Bower, Ward. "Inverters – Critical Photovoltaic Balance-of-system Components: Status, Issues, and New-Millennium Opportunities," Progress in Photovoltaics: Research and Applications, 8, 113-126, 2000.

Bower, Ward and John Wiles. "Investigation of Ground-Fault Protection Devices for Photovoltaic Power Systems Applications, 28th IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

Post, Harold N., et al. "Certification of Solar Products: The Florida Experience," Proceedings: American Solar Energy Society, Portland, Maine, June 2000.

Rosenthal, Andrew, et al. , "Technical Support for the Navajo Photovoltaic Program," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064.

Stevens, John , "IEEE Std 929-2000 – Background, Implications and Requirements," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064.

Thomas, Mike and Chris Cameron , "A Discussion on Life-Cycle Costs of Residential Photovoltaic Systems," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064.

Moore, Larry M. , "A Database Prototype has been Developed to help Understand Costs in Photovoltaic Systems," Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: 12857	**Contract Period:** 9/11/00-9/21/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Soluz, Inc. North Chelmsford, MA 01863-1561 **Organization Type**: IN	**Congressional District**: 7
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS-0753 Albuquerque, NM 87185-0753	**Principal Investigator (s)** John Rogers **Phone:** 978-251-5290 **Fax:** 978-251-5291 **Email:** jhrogers@igc.apc.org	
Technical Monitor: Larry M. Moore **Phone**: 505-845-9191 **Fax**: 505-844-6541	**B&R Code**: EB22 **DOE Funding Allocation:** 2000: $25,000	**Cost Share Information**: **Cost Share Funding:**

Project Objective: This contract represented a survey to determine available and appropriate data for compatibility with existing data on fielded systems that are representative of actual and likely future markets.

Approach/Background: To draw preliminary and specialized inferences about causes of reliability and performance problems of fielded PV systems.

Status/Accomplishments: Data received; activity completed.

Planned FY 2001 Activities: None. Contract expires.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Photovoltaic System Performance and Engineering

SWRES Field Evaluation

Contract #: AV-5589	**Contract Period:** 3/19/97–10/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Southwest Technology Development Institute Box 30001, Dept. 3SOL Las Cruces, NM 88003-0001	
	Organization Type: CU	**Congressional District:** 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** A. Rosenthal **Phone**: 505-646-1323 **Fax**: 505-646-3841	
Technical Monitor: Michael G. Thomas **Phone:** 505-844-1548 **Fax:** 505-844-6541 **E-mail:** mgthoma@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1994: $263,000 1998: $600,000 1995: $404,000 1999: $467,000 1996: $400,000 2000: $0 1997: $780,000	**Cost Share Funding:**

Project Objective: Utilize field experience to monitor performance of systems.

Approach/Background: Systems installed are monitored for initial performance, performance changes, and safety issues.

Status/Accomplishments: Contract ended shortly after fiscal year began

Planned FY 2001 Activities: none. Contract ended.

Major Reports Published in FY 2000: none.

Major Articles Published in FY 2000: none.

Photovoltaic System Performance and Engineering

Management and Administration of the IEC TC82

Contract #: ACQ-0-30907-01	**Contract Period:** 1/1/00 to 12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Sunset Technology, Inc. 441 Wildlife Club Lane Taylorsville, NC 28681 Phone: 828-495-1274 FAX: 828-495-3441	
	Organization Type: IN	**Congressional District:** 10
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J. Anderson **Phone:** 828-495-1274 **Fax:** 828-495-3441	
Technical Monitor: Richard DeBlasio **Phone:** 303-384-6452 **Fax:** 303-384-6490 **E-mail**: dick_deblasio@nrel.gov	**B&R Code:** EB22	**Cost Share Information:**
	DOE Funding Allocation: 1997: $ 65,000 2000: $65,000 1998: $ 65,000 1999: $ 65,000	**Cost Share Funding:**

Project Objective: To support an appropriate organization (Sunset Technology, Inc.) designated by the ANSI USNC (American National Standards Institute, United States National Committee) to manage and administer Secretariat responsibilities for the International Electrotechnical Commission (IEC) PV/Technical Committee (TC) 82 for PV Solar energy systems standards, and coordinate and support U.S. technical participation in the IEC PV/TC82 and its working groups.

Approach/Background: The IEC TC-82 is an international standards making committee on solar PV energy systems. The committee prepares consensus international standards and publishes them for the PV industry and community. The committee consists of 9 working groups on glossary, modules, systems, certification, BOS components, concentrators, batteries (jointly with TC21), Conformity Assessment (jointly with the IEC Conformity Assessment Board) and distributed energy systems (jointly with TC 21 – batteries and TC 88 – wind energy)..

Status /Accomplishments: There are 21 participating (voting status) and 11 observing (commentary status) countries involved in TC 82 work. A complete listing of the member countries is given in Table 1. The number of working groups and the number of international experts participating in this work has nearly tripled in size during the past 6 years. Currently, the working groups and the participants are as follows:

Working Group 1 (Glossary) – 9 experts;
Working Group 2 (Modules) – 16 experts;
Working Group 3 (Systems) – 26 experts;
Working Group 5 (Certification) – 12 experts;
Working Group 6 (BOS Components) – 21 experts;
Working Group 7 (Concentrators) – 8 experts;
Joint Working Group - Batteries - TC 21/TC 82 – 4 TC 82 experts.
Joint Working Group - Conformity Assessment Schemes - CAB/TC 82 – 2 TC 82 experts.
Joint Coordinating Group - Distributed Renewable Energy Systems TC82/TC21/TC88 – 22 experts.

Currently, 27 standards have been published. These are listed in Table 2. Significant progress has also been made in FY 2000 on two new PV module safety standards, a comprehensive Part 2 to the Glossary Technical Report, a system standard for small stand-alone systems, two inverter safety standards, an environmental test standard for the type approval of BOS components and a total quality program standard for product certification and laboratory accreditation. This latter document has lead to a high level review of product certification within the IEC and to the creation of a blue ribbon committee comprised of members of the IEC Committee of Action, the IEC Conformity Assessment Board and TC 82. The outcome of this could be a new approach for certification involving a cooperative effort between ISO and IEC.

Contract #: ACQ-0-30907-01

TABLE 1
Committee Membership for IEC/TC 82

AUSTRALIA	Participating	JAPAN	Participating
AUSTRIA	Participating	NETHERLANDS	Participating
BELGIUM	Observer	NEW ZEALAND	Observer
BRAZIL	Observer	NORWAY	Observer
BULGARIA	Observer	POLAND	Observer
CANADA	Participating	PORTUGAL	Participating
CHINA	Participating	ROMANIA	Participating
CZECH REPUBLIC	Participating	RUSSIAN FEDERATION	Participating
DENMARK	Participating	SOUTH AFRICA	Participating
FINLAND	Observer	SPAIN	Participating
FRANCE	Participating	SWEDEN	Observer
GERMANY	Participating	SWITZERLAND	Participating
HUNGARY	Observer	UKRAINE	Observer
INDIA	Participating	UNITED KINGDOM	Participating
INDONESIA	Participating	UNITED STATES OF AMERICA	Participating
ITALY	Participating	YUGOSLAVIA	Observer

Planned FY 2001 Activities: To conduct a TC 82 general meeting and a series of working group meetings. To develop a new PV product certification and laboratory accreditation scheme under the auspices of the IEC Conformity Assessment Board. To complete Committee Drafts for the two new PV module safety standards, the new Glossary Technical Report, the system standard for small stand-alone systems, the two inverter safety standards and the environmental test standard for the type approval of BOS components

Major Reports Published in FY 200:
IEC 82/250/RM, TC 82 General Meeting Report.
TC 82 Working Group meeting reports, and subcontract monthly, quarterly and annual reports.

Table 2. Published IEC TC 82 Standards

1. IEC 61836: 1997, *Solar photovoltaic energy systems – terms and symbols*
2. IEC 60891: 1987, *Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic (PV) devices. Amendment No 1 (1992)*
3. IEC 60904-1: 1987, *PV - Part 1: Measurements of PV current-voltage characteristics*
4. IEC 60904-2: 1989, *Photovoltaic devices - Part 2: Requirements for reference solar cells.*
5. IEC 60904-3: 1989, *Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*
6. IEC 60904-5: 1993, *Photovoltaic devices - Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method*.
7. IEC 60904-6: 1994, *Photovoltaic devices - Part 6: Requirements for reference solar modules*.
8. IEC 60904-7: 1995, *Photovoltaic devices - Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device*.
9. IEC 60904-8: 1995, *Photovoltaic devices - Part 8: Guidance for spectral measurement of spectral response of a photovoltaic (PV) device. Second edition (1998)*
10. IEC 60904-9: 1995, *Photovoltaic devices - Part 9: Solar simulator performance requirements*
11. IEC 60904-10: 1998, *Photovoltaic devices – Part 10: Linearity measurement methods*
12. IEC 61215: 1993, *Crystalline silicon terrestrial PV modules - Design qualification and type approval*
13. IEC 61345: 1998, *UV test for photovoltaic (PV) modules*
14. IEC 61646: 1996, *Thin film silicon terrestrial PV modules - Design qualification and type approval*
15. IEC 61701: 1995, *Salt mist corrosion testing of photovoltaic (PV) modules*
16. IEC 61721: 1995, *Susceptibility of a module to accidental impact damage (resistance to impact)*
17. IEC 61173: 1992, *Overvoltage protection for photovoltaic (PV) power generating systems*
18. IEC 61194: 1993, *Characteristic parameters of stand-alone photovoltaic (PV) systems*
19. IEC 61277: 1995, *Guide: General description of photovoltaic (PV) power generating systems*
20. IEC 61702: 1995, *Rating of direct coupled photovoltaic pumping systems*
21. IEC 61724: 1998, *Photovoltaic system performance monitoring - guidelines for measurement, data exchange and analysis*
22. IEC 61725: 1997, *Analytical expression for daily solar profiles*
23. IEC 61727: 1995, *Photovoltaic (PV) systems - Characteristics of the utility interface*
24. IEC 61829: 1995, *Crystalline silicon PV array - On-site measurement of I-V characteristics*
25. IEC 61683: 1999, *PV systems - Power conditioners - Procedure for measuring efficiency*
26. IEC PAS 62111: 1998, *General Directives for the use of REN in Decentralised Rural Electrification.*
27. IEC 61427: 1998, *Secondary cells and batteries for solar photovoltaic energy systems – General requirements and methods of test was published this quarter*.

Combining Satellite and Ground Measurements for the Production of Site/Time Specific Solar Irradiance

Contract #: XAH-5-15222-01	**Contract Period:** 6/16/95–9/20/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	The Research Foundation of the State University of New York, Albany Atmospheric Sciences Research Center 251 Fuller Road Albany, NY 12203	
	Organization Type: CU	**Congressional District:** 21
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Richard Perez **Phone:** 518-437-8751 **Fax:** 518-437-8711 E-mail: perez@asrc.cestm.albany.edu	
Technical Monitor: David. S. Renné **Phone**: 303-275-4648 **Fax**: 303-275-4675 **E-mail**: david_renne@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1998 $30,000 1999: $30,00 2000: $20,000	**Cost Share Funding:** 2000: $6,000

Project Objectives: Building upon accomplished satellite model development and validation tasks, the FY 00 objectives of this project are:

1. To continue receiving and archiving GOES-8 and GOES-9 visible channel northern hemisphere frames on a regularly scheduled basis; processing these frames into a 10-km grid with normalized values acceptable to our satellite-to-irradiance model; and forwarding processed data to NREL.
2. To determine the Effective Accuracy of Satellite-Derived Hourly Irradiances by acquiring a complete year of hourly global horizontal solar irradiance data from the approx. 20 stations comprising the ARM/CART site in north-central Oklahoma. The hourly solar irradiance over the same period using a method based on geostationary satellite data developed in earlier tasks will be calculated. The Root Mean Square error of the satellite estimates relative to the ground estimates is to be calculated and the various components of this RMSE are to be enumerated. The "effective RMSE" is also to be calculated. The results of this study are to be compared to earlier results developed in the northeastern United States.

Approach/Background: *Archiving of GOES Data:* Visible channel GOES-8/10 data broadcasted by UCAR to its member universities are acquired and processed into $.1^{o}$ x $.1^{o}$ grid archives (i.e. ~ 10 km). Every frame archived is visually inspected. Each image including visual defects (e.g., tainted with black, white streaks or distortion patterns) is flagged as questionable.

Effective Accuracy: In a previous study Zelenka and Perez [1] have shown that the effective accuracy of time/site specific hourly satellite-derived irradiances was considerably better than the apparent accuracy obtained by direct comparison with a ground measurement station. This study was based on measured irradiance data from two networks in the northeastern US and in Switzerland, and was limited to global irradiance. A practical consequence of this observation is the notion of breakeven-distance from a measurement station, beyond which a satellite estimate becomes preferable to the ground measurement. For site-time specific hourly global irradiance, this distance was estimated at 25-30 km. In this investigation, we expand this initial analysis and address many of its perceived weaknesses (A) Climate: the original study was limited to humid temperate climates with marked localized orographic influences. We now cover the US southern Great Plains with a much drier climate and considerably less localized microclimatic influences.(B) Data quality: the instrument networks used in the original study were not designed for research, and uncertainties linked to data quality were noted (e.g., [2]). The present network was designed for climatic research purposes [3] and features well calibrated and well maintained and controlled first-class instruments. (C) Irradiance components: this addresses direct and diffuse irradiance in addition to global. (D) Time step: the initial study took a qualitative look at other time steps, besides hourly. We take a systematic look at effective accuracy for different time steps, ranging from one minute to one day, for each considered irradiance component.

Status/Accomplishments: A detailed publication, "Determination of the Effective Accuracy of Satellite-Derived Global, Direct and Diffuse Irradiance in the Central United States", is under final stages of completion. This is scheduled for presentation at the ASES 2000 Forum in Washington, DC. A version of this article will be submitted to the reviewed literature.

Planned FY 2001 Activities: Not applicable: contract has been completed.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Photovoltaic System Performance and Engineering

Site/Time Specific Solar Irradiance Using Satellite Imagery

Contract #: AXE-0-30070-01	**Contract Period:** 6/28/00–6/28/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	The Research Foundation of the State University of New York, Albany Atmospheric Sciences Research Center 251 Fuller Road Albany, NY 12203	
	Organization Type: CU	**Congressional District**: 21
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Richard Perez **Phone:** 518-437-8751 **Fax:** 518- 437-8711 **E-mail:** perez@asrc.cestm.albany.edu	
Technical Monitor: Raymond L. George **Phone**: 303-275-4669 **Fax**: 303-275-4675 **E-mail**: ray_george@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 2000: $34,886	**Cost Share Funding:**

Project Objectives:
Building upon accomplished satellite model development and validation tasks, the FY 00-01 objectives of this project are to investigate the use of GOES satellite-derived solar resource data developed at the Atmospheric Sciences Research Center, State University of New York at Albany (SUNY/Albany) to generate site-specific TMY information, both by the creation of satellite time series of solar radiation at specific locations, and by using high-resolution satellite-derived radiation field structures to enhance basic interpolation between surface TMY sites. The end product of this procurement will include 1) high-resolution maps fully compatible with existing TMY2 data sets, 2) satellite time series coincident with surface radiation measurements for 6 different locations in the United States, and 3) progress toward a capability of generating TMY data sets at any point on the map's mesh.

In addition, the project will continue receiving and archiving GOES-8 and GOES-9 visible channel northern hemisphere frames on a regularly scheduled basis; processing these frames into a 10-km grid with normalized values acceptable to our satellite-to-irradiance model; and forwarding processed data to NREL.

Approach/Background:
Archiving of GOES Data: Visible channel GOES-8/10 data broadcast by UCAR to its member universities are acquired and processed into $.1^o$ x $.1^o$ grid archives (i.e. ~ 10 km). Every frame archived is visually inspected. Each image containing visual defects (e.g., tainted with black, white streaks or distortion patterns), is flagged as questionable.

Site-specific TMY information: The use of high-resolution satellite imagery to infer ground-level solar insolation holds significant promise for greatly improving the spatial and temporal assessment of solar resources. When combined with high-quality ground level data, the uncertainties associated with use of satellite data are even further reduced, providing a powerful and potentially cost-effective resource assessment tool for site/time specific analyses. Significant progress is being made with use of the visible channels of the GOES-8 and GOES-10 geostationary meteorological satellites for developing large area site/time specific solar resource assessments. However, in the U.S. these methods have been developed, tested and evaluated for only a limited set of regions, and have not yet taken full advantage of existing ground data for improving their performance. Furthermore, since solar energy planners and developers require reliable long-term time series data for their work, techniques are needed to extrapolate the relatively short-period satellite observations to longer-term climatological data sets.

In collaboration with NREL, the contractor will upgrade the auxiliary inputs to the SUNY/Albany satellite model. This includes regional climatological turbidity, terrain elevation and cloud cover data (which will be developed by NREL). The model shall be run with these revised inputs on the Northeast region, plus other selected small regions where high quality concurrent surface measurements are available. In a second step, contractor will compile hourly satellite and surface estimates of global radiation. This shall be done for as many hours as concurrent data are available, for 6 different locations to be chosen jointly by NREL and the subcontractor. Data shall be analyzed by month and year for diurnal patterns, mean bias, RMS error, and frequency distribution.

Contract #: AXE-0-30070-01

A third step will be to develop/apply the long-term (monthly) satellite-aided interpolation technique. In the Northeast region, monthly satellite-derived and TMY-derived averages for global, direct and diffuse irradiances shall be compared, and any large differences shall be investigated and explained. The contractor shall develop a TMY satellite interpolation technique, which shall include adding the interpolated satellite-TMY bias, and adding the difference between interpolated and actual satellite value at the considered location. The method shall be tested for the Pittsburgh, PA TMY2 data developed at NREL.

A fourth step will be to investigate a methodology to distribute monthly differences between nearby TMYs and Task 2 (average satellite modeled) estimates based on hourly values. The methodology shall be based on modifying the time series of existing TMYs so that artificial TMYs correct to local monthly mean radiation estimates can be created. The methodology shall be tested for the Pittsburgh, PA TMY data.

Status/Accomplishments: Subcontractor has submitted a detailed report showing the results of using time series statistics to modify an existing TMY based on satellite estimates of average solar insolation from a different location. A draft paper for the 2001 ASES Forum 2001 conference has also been submitted.

Planned FY 2001 Activities: This contract is ongoing through June of 2001.

PV Domestic Applications and Markets

Programming Support for Energy-10

Contract #: TAR-8-18416-01	**Contract Period:** 3/30/98–3/29/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">CDI Corporation
P.O. Box 840354
Dallas, TX 75284-0354</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Norm Weaver
Phone: 970-870-1710 Fax: 970-870-1710 E-mail: norm_weaver@nrel.gov</td></tr>
<tr><td rowspan="2">Technical Monitor:
J. Douglas Balcomb
Phone: 303-384-7507
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E-mail: doug_balcomb@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $30,000
2000: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this subcontract was to provide programming services to develop the Energy-10 computer program, a tool for designing low-energy buildings. The funding support from the PV in Buildings Task was to develop the PV module that will be incorporated into the software. The PV module will evaluate both the system electrical output as well as the impact on other building energy loads, such a thermal and lighting loads, of a building-integrated PV system.

Approach/Background: Energy-10 is a PC-based building energy simulation program that focuses on the integration of daylighting, passive solar design, low-energy cooling, and energy-efficient equipment into both residential and nonresidential high-performance buildings. Developed specifically as a design tool, the program facilitates quick evaluations. Its simulation engines perform whole-building energy analysis for 8760 hours per year that include. The target audience for the program is building designers, architects, heating, ventilation, and air-conditioning engineers, utility officials, and architecture and engineering students and professionals. It is the people in this audience that has the most influence on whether or not PV is included in the building design. By incorporating PV into Energy-10 will introduce the possibility of using building-integrate PV systems, help the designers evaluate the impact the PV system will have on the building, and provide a tool for designers to optimize the building-integrated PV system design.

Status/Accomplishments: Work with CDI concluded in March 2000; however, work on the project continued. A beta version of Energy-10 with photovoltaic system design capability will be reviewed in November 2000. Reviewer comments will be incorporated into Energy-10 version 1.4.

Planned FY 2001 Activities: No planned activities with CDI.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Renewable Energy Analysis, Applications, and Domestic Market Opportunities

Contract #: ACQ-9-29770-01	**Contract Period:** 9/1/99–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Clean Power Research, L. L. C. 10 Glen Ct. Napa, CA 94558	
	Organization Type: IN	**Congressional District**: 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. Hoff **Phone:** 707-224-9992 **Fax:** 707-224-9993 **E-mail:** tomhoff@clean-power.com	
Technical Monitor: C. Herig **Phone**: 303-384-6546 **Fax**: 303-384-6490 **E-mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $70,000 2000: $0	**Cost Share Funding:**

Project Objective: The objective of this work is to research and analyze the economics, financial mechanisms, business opportunities and intangible value propositions for consumers, building industry, and utilities, as the energy industry changes through restructuring.

Approach/Background: Energy service and supply are rapidly changing. Relationships of electric service providers, regulatory/legislative bodies, the financial and building industry are transitioning with this change. State and local environmental and economic health are considered in electric utility industry restructuring resulting in policies favorable to renewables. Both utilities and builders/developers are defining micro-grids as reliable low cost approaches to meeting new load. And micro-grids meet the environmental and reliability concerns of policy makers. The following tasks will be completed in this subcontract:

- Expand a web based PV value tool which can be used by policy makers, builders/developers, consumers, and utilities to the additional three top value states, IL, NC, HI
- Estimate the size of the market for PV in new homes using micro-grids
- Perform two case studies
-

Status/Accomplishments:

PV Value Tool

Clean Power Estimator is an economic evaluation software program for customer-owned clean energy systems. The program gives a personalized estimate of the costs and benefits of a PV system for a specific homeowner. The program was tailored to work for residential customers in 2,000 cities through Illinois, Hawaii, and North Carolina. The following agencies received versions to post on the Internet: (1) Illinois Department of Commerce and Community Affairs/Renewable Energy Resources Program; (2) Hawaii's Energy, Resources, and Technology Division, Energy Branch; and (3) North Carolina Solar Center.

Note: all of the following reports are available in full on the Internet at: www.clean-power.com.

The Market for Photovoltaics in New Homes Using Micro-Grids

Policy makers have used economic incentives to create a near-term market for grid-connected photovoltaics (PV). How will this market be affected if these incentives disappear? This work estimates the U.S. market without incentives for PV in new single-family homes in subdivisions. It evaluates grid-connected and grid-independent micro-grids (with one-third of the electricity from PV) and grid-connected PV-only systems (with all the electricity from PV, net metered output). Results indicate that the PV market is larger for grid-independent micro-grids than for grid-connected PV-only systems for PV prices above $2,000/kW. The grid-independent micro-grids market ranges from 5 to 120 MW/year at a PV price of $6,000/kW; the variation is due to uncertainty in the utility interconnection cost savings.

Contract #: ACQ-9-29770-01

Case Study: Building Integrated Photovoltaics At the New York City Transit's Corona Maintenance Shop and Car Wash Facility
This report presents a screening methodology to evaluate building integrated photovoltaic (BIPV) systems. The screening methodology is useful in several ways. First, it provides a way to determine the feasibility of a BIPV system without incurring the cost of a detailed engineering study. Second, it can be used to identify a general set of conditions under which to select the various technology types. The methodology was applied to BIPV systems on the New York City (NYC) Transit's Corona Maintenance facility.

BIPV systems are attractive because they have both energy value and area value components. The energy value is based on the PV system power rating (kW) and the area value is based on the PV system size (ft^2). BIPV systems can be broadly categorized as low-efficiency and high-efficiency systems. Low-efficiency systems use low-efficiency thin-film PV or sparsely populated crystalline modules (i.e., a lot of space between the cells in the module). High-efficiency systems typically use standard crystalline modules (i.e., the crystalline cells are placed close together).

This work determined that a general set of conditions exist where high-efficiency BIPV systems are more cost-effective than low-efficiency BIPV systems. Assume that: 1) the goal is to maximize net present value; 2) there are no tax effects or economic incentives; 3) different PV systems are compared in the same orientation and application; 4) PV technologies have the same price ($/kW) and technical performance characteristics; and 5) PV technologies have the same positive area-related savings. Results suggest that high-efficiency systems are more cost-effective than low-efficiency systems only when the system is economically justified without any area savings and the system is area-constrained; low-efficiency systems are preferable under all other conditions. The rationale for this is as follows. Systems ***without*** area constraints have the same energy value and differ only in their area value when they are designed to have the same power rating; the low-efficiency system has higher area value because it covers more area. Systems ***with*** area constraints have the same area value and differ only in their energy value; the high-efficiency system has a higher power rating and is only preferred if the energy value (without area savings) exceeds PV cost.

Case Study: The Benefits of Distributed Resources to Local Governments: An Introduction
Numerous publications, reports, and case studies have demonstrated that distributed resources provide benefits to both the resource owner and the electric utility. This report begins to examine the benefits that distributed resources provide to the government. The report discusses how local governments benefit from distributed resources. It includes the following benefits: provide direct benefits when used in government buildings; improve the environment; guide economic development; ensure electrical system reliability for constituents; protect constituents from high electricity prices; and provide disaster relief support.

The report suggests some actions that local governments can take to encourage the use of distributed resources. They include: integrate bundled systems of energy efficiency and renewables into government buildings where they are cost-effective; eliminate biases in the tax system that favor traditional electricity supply over distributed resources; and include distributed resources as part of their overall planning process, particularly in the areas of disaster preparedness and economic development.

Major Reports Published in FY 2000:
T. E. Hoff and C. Herig. "The Market for Photovoltaics in New Homes Using Micro-Grids", preliminary NREL Report. January 2000

T.E. Hoff and C Herig. "Building Integrated Photovoltaics At the New York City Transit's Corona Maintenance Shop and Car Wash Facility", preliminary NREL Report. July 2000.

T. E. Hoff and C. Herig. "The Benefits of Distributed Resources to Local Governments: An Introduction", preliminary NREL Report. September 2000

Major Articles Published in FY 2000:
T. E. Hoff and C. Herig, "The Market for Photovoltaics in New Homes Using Micro-Grids", American Solar Energy Society's Solar 2000, June 2000

PV Domestic Applications and Markets

Iowa Comprehensive PV Survey and Dissemination Program

Contract #: DE-FG03-00SF22119	**Contract Period:** 9/1/00–8/31/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148	Iowa Department of Natural Resources 502 East 9th Street Des Moines, IA 50319	
	Organization Type: ST	**Congressional District**:
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave, SW Washington, DC 20585	**Principal Investigator (s)** J. Moehlmann **Phone:** 515-281-7018 **Fax:** 515-281-6794 **E-mail:** jennifer.moehlmann@dnr.state.ia.us	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2203000	**Cost Share Information**:
	DOE Funding Allocation: 2000: $154,000	**Cost Share Funding:**

Project Objective: To increase the use of photovoltaic (PV) technologies in new and existing construction by designing a program that will more fully engage institutions of higher learning, architects and engineers, construction companies, developers, and energy service providers in the appropriate application of PV technologies. This will be accomplished by surveying and training project development professionals.

Approach/Background: The first phase of this project involves the identification of any barriers that may exist during the design, construction, and marketing phases which limit the consideration and eventual implementation of PV technologies. The Department will form an advisory committee, which will be made up of Department engineers, planners, private sector engineers, architects, educators, builders and realtors. Together, they will develop a comprehensive set of surveys that will be sent to institutions of higher learning, architects, engineers, developers, realtors and construction companies in the Midwest region (Iowa, Minnesota, Wisconsin, Illinois, Missouri, Nebraska). Questions contained in the surveys will be designed to measure the respondents' PV technical knowledge, personal perceptions about PV technologies, and whether the respondent would recommend the implementation of PV technologies in his or her building projects. The responses to the survey will be collected and analyzed by the Department. A report will be completed which provides detailed PV barrier identification, and geographic significance. The report will also display the survey results using the Energy Bureau Geographic Information System (GIS). By entering information obtained from the survey results into the GIS database, other environmental, financial, or political conditions may be evaluated for their effects on barrier levels, or their effects on possible remedies. Because the Department maintains a GIS database on current renewable energy projects, future evaluation of the Departments efforts to remove market barriers in year two of this project would be feasible.

The final step in phase one will involve the creation of a strategic plan. The advisory committee will be responsible for the development of a strategic plan to identify the methods and materials to best facilitate the involvement of building professionals, and gain their support for the implementation of PV technologies in building projects. The strategic plan will serve as a "how to" manual, outlining specific steps that need to be taken to reduce market barriers, based on information taken from the survey.

Contingent upon continued funding, during the second phase of this project, the Department will utilize the recommendations contained in the strategic plan to develop effective tools and materials to reduce the current barriers to the implementation of PV technologies in new and existing building construction. The recommendations from the strategic plan will determine the specific action the Department takes in developing program tools and materials.

The Department will use a variety of methods to complete the dissemination process of developed PV materials. In the case of educational institutions, curriculum and materials will be developed and delivered with the cooperation of the institutions themselves. Professional associations, fraternal organizations and licensing agencies will be utilized to channel information to licensed engineers and architects. Unions, trade associations and professional publications will be used to disseminate information to construction contractors, developers and realtors.

Contract #: DE-FG03-00SF22119

Status/Accomplishments: The work is beginning in FY 2001.

Planned FY 2001 Activities: The Department will assemble the advisory committee, develop the survey, compile responses, publish the final report and create a strategic plan.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

PV Domestic Applications and Markets

Assistance to the State Legislatures on Photovoltaic Energy Issues

Contract #: DE-FG03-00SF22120/A000	**Contract Period:** 9/1/00–9/1/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148	National Conference of State Legislatures 1560 Broadway, Suite 700 Denver, CO 80202	
	Organization Type: ST	**Congressional District:** 1
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave. SW Washington, DC 20585	**Principal Investigator (s)** Matthew Brown **Phone:** 303-880-2200 x318 **Fax:** 303-863-8003 **E-mail:** matthew.brown@ncsl.org	
Technical Monitor: Same as Program Manager	**B&R Code**: EB22	**Cost Share Information**: none
	DOE Funding Allocation: 2000: $27,000	**Cost Share Funding:**

Project Objective: States have had a number of policies in place over the years to encourage photovoltaics. As state legislatures attempt to make decisions about energy policy, many are not well informed about the new and developing technologies that could have a significant influence on the future of the nation's energy system. This project will help state legislators to understand PV technology and its costs. It will also help them understand the most effective policies that they may put in place to address photovoltaic issues. The significance of reaching this audience with credible and non-biased information is tremendous at this time in which states have assumed tremendous responsibility for determining the energy policy of their states.

Approach/Background: The activities described in this proposal serve a unified goal of infusing the state legislative process with high quality information that will allow each state to make decisions that are appropriate to its own circumstances—yet based on expert knowledge and experiences in other states. This proposal emphasizes the central concern of most state decision-makers—the ability of electric consumers to derive a long-term benefit from the restructuring of the electric industry.

This project will provide state decision-makers with information about renewable energy -- particularly photovoltaics -- and energy efficiency technologies and policies in the context of electric industry restructuring. Through their role as state policymakers, legislators have the ability to use this information to stimulate increased energy efficiency and renewable energy use while simultaneously accelerating the adoption of new energy efficiency and renewable energy technologies.

NCSL, as an arm of the 50 state legislatures, has the ability to bring this information to state legislators and their staff in a credible way that is tailored to the needs of state legislatures. NCSL is uniquely positioned to be this informational resource. As such, this project is designed specifically to increase state legislators' understanding of energy efficiency and renewable energy technologies.

Relationship to Other Tasks
This project will enable NCSL to provide this detailed assistance to the legislatures on photovoltaics issues. This project is a continuation of an ongoing DOE-funded effort to provide legislatures with unbiased, well-thought-out analysis and information.

Status/Accomplishments:
Deliverables
Publications
NCSL publications reach a large legislative audience, including state energy environment and transportation committees, legislative leadership and key staff. Publications are also made available to federal officials and other interested parties. One state legislative report will be published in hard copy and electronic format. The report will be divided into the following areas: Introduction, Assessment of the photovoltaics' current and future potential, Policy Issues, Glossary of Terms.

Contract #: DE-FG03-00SF22120/A000

In addition, NCSL will develop a Power Point presentation based on the information presented in the State Legislative Report. This presentation will offer slides, with speaker notes, that a legislator or legislative staff person could use in a discussion of photovoltaic energy issues during a legislative hearing.

Tasks for Developing the Publications
Task 1—Literature Review
Task 2—Interviews
Task 3—State Legislative Policy and Program Review
Task 4—Produce State Legislative Report on Photovoltaics and State Legislative Policy
Task 5—Dissemination of the Report

Planned FY 2001 Activities: These activities are described above in "Approach/Background."

Major Reports Published in FY 2000: These are only a few of the dozens of reports that NCSL publishes annually on a variety on issues.

T. Gagliano, (2000), "Expanding Wind Power in Four States," 18 pp. NCSL, vol. 25 number 10, Denver CO

T. Gagliano, (2000), "Commercial Wind Power and Bird Species," 4pp. NCSL, vol. 25, number 11, Denver, CO

T. Gagliano, (2000), "Wind Power Development: Policy Options," 5pp. NCSL, vol. 25 number 12, Denver, CO

M. Brown, J. Woelfel (2000), "Tax and Landowner Revenues From Wind Power Development," 7 pp. NCSL, Vol. 25, number 5, Denver, CO

Major Articles Published in FY 2000: none

Domestic PV Applications and Markets

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Thornton **Phone:** 303-384-6469 **Fax:** 303-384-6490 **E-mail:** mr_pv@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E-mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $1,310,000 2000: $1,828,300	**Cost Share Funding:**

Project Objective: The goal of the Domestic PV Markets and Applications Project is to foster widespread acceptance of PV in numerous market sectors where significant penetration has not been attained. These sectors include the insurance and disaster mitigation industries, residential and commercial buildings, electric utilities and the agricultural/ranching industry.

Approach/Background: Tasks within this project area include:
- Training, Education and Technical Assistance - This subtask supports the Photovoltaics Program through training, education and technical assistance for domestic applications. The client base includes other NREL research and development activities, the DOE and other federal agencies and programs, the U.S. photovoltaic industry, and specific application sectors, such as the insurance industry.
- Market and Policy Value Analysis - With the energy industries competitive transitioning and the high capitol cost of PV, past work has shown an acceleration of domestic grid-tied PV through state and local policy funding. This task will continue to develop value analysis for policy justification. However, as often happens in accelerated markets, market support infrastructure is lagging. This task also identifies infrastructure weaknesses or opportunities and supports development through value analysis, and assessment tools.
- PV:BONUS Support - The DOE Golden Field Office asked the labs (NREL and SNL) to provide technical support to the PV:BONUS2 program, which began its second phase at the start of FY99. This program is supporting a variety of building-integrated products, and most of the projects are with companies which have had, or do now have, PVMaT subcontracts. The technical support for these seven DOE agreements is being managed in the same manner as the PVMaT technical support teams.
- Photovoltaics in Buildings (PVB) - In partnership with industry, the task fosters the widespread acceptance of PV-integrated buildings by overcoming technical and commercial barriers and by facilitating the integration of PV into the built environment for the PV and buildings industries and their customers. All activities are conducted in cooperation with current PV/buildings activities at the National Center for Photovoltaics (NCPV), both at NREL and SNL, the NREL Center for Buildings and Thermal Systems (CBTS), and in other federally funded locations such as the Florida Solar Energy Center (FSEC) and the Southwest Technology Development Institute (SWTDI).

Status/Accomplishments:
- Conducted three consumer workshops at National Western Stock Show, Denver, two during Earth Day and one at Smithsonian Institution, Washington, D.C.
- Hosted the FEMA 2000 *Technology Partnerships for Emergency Management* workshop in June 2000.
- Conducted the NCPV Program Review, April 2000.
- Provided technical assistance to San Jose, CA, Lakewood, CO, and Stanford, CT on using PV to manage emergencies.
- MSRI Support including targeted analysis and presentations for twelve partnerships
- Overall EIA/NEMS coordination and support. Presentation at AEO conference. Reviewer for EIA-NEMS analysis on residential and commercial buildings sector (results showed 40% of PV roadmap w/o policies and 400% with policies and price decline acceleration
- Local Governments and DG Presentation, Report, and Review of BTS subcontractors report
- Financing and Consumer’s Buying workshops at SW Renewable Energy Fair
- Presentation for Florida economic development meeting with utilities, energy office and FSEC.

Contract #: DE-AC36-98-GO10337

Status/Accomplishments (continued):
- Presented international policy analysis and presentation for Solar in Seattle event.
- Developed report for Local Governments Commission PV rooftop deployment strategy.
- Provided reprint material for Batteries Digest Newsletter upon request from Solar 2000 presentation.
- Invited article in EPRI's Signature, Winter 1999-2000, Vol 10 No. 1, "Mini-Grids, Big Opportunities."
- Invited lecture at Western Resources annual engineering meeting.
- Two oral presentations "Remote Monitoring of PV Performance Using Geostationary Satellites" and "Customer Sited PV – US Markets Developed from State Policies" at 16th European PV Solar conference and exhibition, Glasgow, UK
- Developed one pager on PV during power outages
- Completion of the beta review version the building energy software tool, Energy-10, that incorporates PV in
- building systems evaluation.
- Construction of theSolar/Energy-Efficient Demonstration Building.
- Construction of two high-performance buildings with PV systems (Zion National Park Visitor Center in Springdale, UT and the
- Big Horn Center in Silverthorne, CO).
- Developed regulations and a request for proposals for the upcoming collegiate Solar Decathlon competition.
- Secured the sponsorship of BP as a partner to DOE in the Solar Decathlon.

Planned FY 2001 Activities:
- Deploy *Solar Independence* exhibit in Washington, D.C.
- Plan for *Solar Decathlon*.
- Support PV Bonus Initiative
- Continued support to communities to build disaster management infrastructure.
- Support completion by AIA of design report about the "Solar Wall" competition.
- Continue support of Solar Decathlon.
- Continue investigations into utility reliability and restructuring issues.

Major Reports Published in FY 2000:
C. Herig, (1999), "Distributed Generation, " 4 pp. DOE/GO-10098-657, Golden, CO: National Renewable Energy Laboratory.

R. Nahan and A. Hicks, (2000), "The Solar Decathlon," 4 pp., DOE/GO-102000-1076, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000:
Thornton, "Renewables on Main Street," *Public Works Management and Policy*, Vol. 4, No. 3, January 2000, pp. 224-236.

A. Deering, and J. Thornton, "Solar Solutions for Natural Disasters," Risk Management, February 2000, pp. 28-33.

Hayter S.J., P.A. Torcellini, "Photovoltaics for Buildings: Case studies of High-Performance Buildings with PV." NCPV Program Review Meeting 2000. National Renewable Energy Laboratory. Denver, CO. April 17 - 19, 2000.

Hayter S.J., P.A. Torcellini, "High-Performance Building Design: Keys to Success." NCPV Program Review Meeting 2000. National Renewable Energy Laboratory. Denver, CO. April 17 - 19, 2000.

Thomas, H.P., S.J. Hayter, R.L. Martin, L.K. Pierce, "PV and PV/Hybrid Products for Buildings." Proceedings of the *16th European Photovoltaic Solar Energy Conference and Exhibition*. Glasgow, Scotland, Great Britain. May 1 - 5, 2000

PV Domestic Applications and Markets

American Solar Challenge

Agreement #: DE-FG36-00GO10527	**Project Period:** 4/1/00–9/30/03

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	New Resources Group 101 West Main Street Freeman, MO 64746	
	Organization Type: IN	**Congressional District:** 4
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dan Eberle **Phone:** 816-899-5511 **Fax:** 816-250-5430 **E-mail:** deberle@formulasun.org	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** New Resources Group
	DOE Funding Allocation: 2000: $200,000	**Cost Share Funding:** 2000: $404,335

Project Objective: The Formula Sun American Solar Challenge (ASC) is a biennial competition to design, build and race solar-powered cars in a ten-day, cross-country event. The ASC will be held from July 15, 2001 through July 25, 2001, beginning in Chicago, IL and terminating near Los Angeles, CA.

Approach/Background: The ASC is a biennial, competition to design, build and race solar-powered cars. The ten-day, cross-country event will be held from July 15, 2001 through July 25, 2001 and follow the historic Route 66, beginning in Chicago, Illinois and ending near Los Angeles, CA. Historically, solar car racing in the U.S. has featured exclusively North American post secondary (college and university) teams. However, the ASC has opened entry to schools, companies, universities, clubs and individuals worldwide. The American Solar Challenge will pit cars powered only by the sun's energy against each other in a competition that only the brightest, most creative and best organized team can be expected to win. At almost 2300 miles, it will be the longest solar car race in the world. Since it follows the old Route 66 and coincides with the 75th anniversary of that famous road, it will be a highly visible event and provide a dramatic, high technology, futuristic contrast to the nostalgic events surrounding the anniversary. In the past, sponsors of solar car races, both domestic and international, have received significant amounts of very positive publicity that has enhanced the sponsors' public image. This race has the potential to be the most visible solar car race ever.

The mission of the American Solar Challenge is to promote and celebrate educational excellence and engineering creativity and champions the creative integration of technical and scientific expertise across a range of exciting disciplines. The mission includes the promotion of: 1) renewable energies, specifically photovoltaics; 2) educational and engineering excellence; 3) environmental consciousness; and 4) public education and awareness of the potential of emerging technologies.

The ASC is comprised of the following components: pre-race development, pre-race support, the race, and post race assessment and support. DOE is supporting the American Solar Challenge by providing funding to New Resources Group, the race organizer, to support the planning, management, and conduct of the race. DOE will also conduct public outreach and community relations before and during the race. Details on the American Solar Challenge can be obtained at www.formulasun.org/ascindex.html.

Status/Accomplishments: New Resources Group (NRG) established the Formula Sun American Solar Challenge (ASC) Headquarters, which is the principal contact for all inquiries. New Resources Ground, in the role of ASC organizer, established the Formula Sun American Solar Challenge (ASC) Headquarters, finalized the race regulations, and developed the American Solar Challenge website at *http:/www.formulasun.org/ascindex.html.* NRG continues to update and maintain the website, field inquiries, and select sites for the qualifying rounds. The qualifying rounds are to be held at the Kansas Speedway in Kansas City, KA and near Western Michigan University in Kalamazoo, MI on May 7-11 and July 9-13, respectively. NRG drove Route 66 and established the race route. Additionally, NRG has continued seeking sponsorship for the race and has commitments from five main sponsors including DOE as well as sponsors and supporters at various levels.

Agreement #: DE-FG36-00GO10527

Planned FY 2001 Activities: During FY 2001, NRG will continue to maintain the race Headquarters, generate educational materials, maitain and enhance the website, conduct race planning, hold qualifiers, and conduct the ten-day, cross-country event.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

U.S. Representation in the IEA PVPS Task 7, "Photovoltaic Power Systems in the Built Environment"

Contract #: AAR-0-30461-01	**Contract Period:** 6/13/00–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Solar Design Associates
Harvard, MA 01451-0242</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Steven J. Strong
Phone: 978-456-6855 Fax: 978-456-3030 E-mail: sjstrong@solardesign.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Sheila Hayter
Phone: 303-384-7519
Fax: 303-384-7540
E-mail: sheila_hayter@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
2000: $12,445</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this subcontract was to support representation by the US on the International Energy Agency PV Power Systems Task 7, "Photovoltaic Power Systems in the Built Environment." US involvement with this task leads to a better understanding of international PV in buildings activities and an opportunity for the US to become competitive in the worldwide PV in buildings industry.

Approach/Background: The International Energy Agency (lEA) is an organization that promotes the collaborative research, development, and demonstration of new energy technologies between nations. IEA PVPS Task 7, "Photovoltaic Power Systems in the Built Environment," is a 5-year effort involving approximately 15 countries. The objective of the task is to enhance the architectural quality, technical quality, and economic viability of PV systems in the built environment and to assess and remove non-technical barriers for their introduction as an energy-significant option. The US participated in the previous related task, lEA SHC Task 16, "Photovoltaics in Buildings." This task concluded in the spring of 1996. The US has also been involved with lEA PVPS Task 7 since its inception in the fall of 1996.

Status/Accomplishments: During FY 2000, the IEA PVPS Task 7 sponsored an international design competition to stimulate development of ideas for PV in buildings products and applications. Steven Strong participated on the jury for this competition in the March 2000. Steven Strong communicates the research, development, and application activities that are occurring around the world to both professional architecture designers and architecture students in the U.S. by giving workshops and teaching classes on PV in buildings to these groups. He also gives numerous presentations each year as an invited speaker to conferences, design charrettes, and other industry meetings. As a result of other U.S. involvement with IEA PVPS Task 7, the document, "Building-Integrated Photovoltaic Designs for Commercial and Institutional Structures. A Sourcebook for Architects," was published in February 2000. Also completed in FY00 was the draft to the report, "U.S. Guidelines for the Economic Analysis of Building Integrated Photovoltaic Power Systems."

Planned FY 2001 Activities: None under the subcontract described in this summary.

Major Reports Published in FY 2000:
P. Eiffert and G. Kiss, (2000), "Building-Integrated Photovoltaic Designs for Commercial and Institutional Structures. A Sourcebook for Architects," 89 pp. NREL/BK-520-25272, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS Two - PV String Inverters

Agreement #: DE-FC36-97GO10261	**Project Period:** 9/30/97–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	Advanced Energy Systems, Incorporated (AES) Riverview Mill Wilton, NH 03086 **Organization Type:** IN	 **Congressional District:** 2
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dr. Robert H. Wills **Phone:** 603-654-9322 **Fax:** E-mail: rwills@advancedenergy.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: $44,999 1999: $171,316 1998: $90,833 2000: $0	**Cost Share Information:** Advanced Energy Systems, Inc. **Cost Share Funding:** 1997: $13,527 1999: $171,316 1998: $90,833 2000: $0

Project Objective: Advanced Energy Systems, Inc. proposes to design and manufacture a low cost String Inverter System (SIS), which will minimize the cost of the electrical BOS (i.e., the inverter and the PV output circuit wiring). The SIS is an inverter and associated wiring that is designed to operate with a single string of photovoltaic (PV) modules. By using a single string, the need for an expensive string-combiner is eliminated. The paralleling of multiple strings is accomplished on the utility or AC side of the system, lending to inexpensive installation costs.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Advanced Energy Systems (AES) was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. The key concept is a String Inverter Module or SIM rated at 250 V dc input, at about 4 amps. Its output is 12OV, 8 Amps or 1 kW per module. These power modules use similar construction and packaging to AC module micro-inverters. Up to four SIMs can be mounted in one enclosure which also houses DC source circuit fuses and disconnects, and the AC output circuit breaker. The SIM units are cooled via an integral natural convection "chimney" built into the enclosure - no fans are used and all electronic components are isolated from the environment. In the second part of the project, Advanced Energy Systems will develop low cost wiring and interconnection components for the complete PV system including cables, connectors, disconnect and GFI protection devices. SIM refers to the standardized, modular systems designs coming out of this work as String Inverter Systems (SISs). Advanced Energy Systems has proposed a six (6) month Phase 2 (July 1, 1998 through December 31, 1998) followed by a two (2) year Phase 3 period (January 1, 1999 through December 31, 2000). However, due to limited FY2000 funding, the project was discontinued December 31, 1999.

Status/Accomplishments: During Phase 1, AES designed and constructed a prototype unit which will be simple and inexpensive to manufacture and incorporates the inverter, DC source circuit string combiner, DC ground fault interrupter and disconnect, and an optional AC output circuit breaker, all in one enclosure, named this unit the "GC-1000". The GC-1000 is cooled via an integral natural convection duct built into the back mounting plate - no fans are used and all electronic components are isolated from the environment. During Phase 2, AES refined the inverter design, developed prototypes, which were UL tested and certified, and field tested pre-production units. Due to limited funding, the project was discontinued December 31, 1999. AES completed and submitted the Final Report.

Planned FY 2001 Activities: none

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS Two - Ballast-Mounted PV Arrays

Agreement #: DE-FC36-97GO10257	**Project Period:** 9/30/97–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	Ascension Technology, Incorporated 235 Bear Hill Road Waltham, MA 01773 **Organization Type:** IN	 **Congressional District:** 7
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Edward C. Kern Jr. **Phone:** 617-684-6101 **Fax:** E-mail: ekern@ascension.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: $44,160 1999: $0 1998: $43,328 2000: $0	**Cost Share Information:** Ascension Technology, Incorporated **Cost Share Funding:** 1997: $11,200 1999: $0 1998: $43,500 2000: $0

Project Objective: Ascension Technology for the development of analytic and experimental capabilities for quantifying the balance between driving (wind, seismic) forces and the restraining (gravitational/frictional) forces that must exist for the ballast-mounting approach to succeed. Ascension Technology and its partners to address wind loading on solar panels and the suitability of using frictional forces between ballast trays and roofing materials to resist wind on the PV arrays. The primary goal of the project is to capture the potential cost savings made possible by ballast-mounting by showing under what conditions it can satisfy wind loading concerns with a secondary goal is to address the more geographically constrained concern regarding withstanding seismic forces.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Ascension was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. Ascension Technology and its partners to address wind loading on solar panels and the suitability of using frictional forces between ballast trays and roofing materials to resist wind on the PV arrays. Ascension Technology to will validate analytic methods for predicting wind speed thresholds for ballasted PV arrays sliding across roofs and develop means to improve the frictional resistance of ballast mounting techniques. Additionally, under Phase 2, Ascension Technology will develop and test new array attachment concepts as successors to our present ballast tray and flat Roof-Jack products.

Status/Accomplishments: In Phase 1 of this project, Ascension Technology developed the analytic and experimental capabilities for quantifying the balance between driving (wind, seismic) forces and the restraining (gravitational/frictional) forces existing for the ballast-mounting approach to succeed. Ascension evaluated wind forces on roof-mounted arrays using improved analytical tools, developed a force-measuring instrument and began to take PV array wind force measurements in the field. Phase 2 included the validation of the analytical methods for predicting wind speed thresholds for ballasted PV arrays to prevent sliding and overturning of the arrays. An analytical model was been developed to guide the configuration of arrays and a means to improve the frictional resistance of ballast mounted trays was developed. Ascension completed a full-scale demonstration at a coastal Massachusetts test site. The demonstration quantified coefficients for a single-ballast-mounted photovoltaic module and contributed to the development of an analytical model to determine the minimum ballast requirements for various module configurations and wind speed. Under Phase 2, Ascension developed and tested a new array attachment concept as an improvement to Ascensions traditional ballast tray products.Due to limited funding, the project was discontinued on December 31, 1999. Ascension completed and submitted the Final Report.

Planned FY 2001 Activities: none

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS Two - Solarex Thin Film Photovoltaics

Agreement #: DE-FC36-97GO10245	**Project Period:** 9/30/97–6/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	BP Solar 630 Solarex Court Frederick, MD 21703 **Organization Type:** IN	**Congressional District:** 6
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** John H. Wohlgemuth **Phone:** 301-638-4375 **Fax:** 301-698-4201 **E-mail:** wohlgej@bpsolarex.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: $57,368 1999: $521,588 1998: $164,436 2000: $408,723	**Cost Share Information:** Solar **Cost Share Funding:** 1997: $43,680 1999: $525,777 1998: $165,518 2000: $411,413

Project Objective: With the support of subcontractors Kawneer, Solar Design Associates (SDA) and Velux, Solarex (now BP Solar) will develop building-integrated photovoltaic products using tandem-junction amorphous silicon modules. Major objectives of the program include: 1) developing a commercial photovoltaic curtain wall module (Spandrel Module); 2) developing a commercial photovoltaic sunshade for curtain walls (PowerTint Window); and 3) developing an opaque PV sunshade (PowerShade).

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which BP Solar was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development.

Under PV:BONUS One, the team of BP Solar, Kawneer and Solar Design Associates (SDA) developed a crystalline silicon photovoltaic curtain wall module that integrated into Kawneer's standard curtain wall system and commercialized and is sold through Kawneer's network of salesman and dealers. During PV:BONUS One, a potential demand for a Building-Integrated Photovoltaic (BIPV) product based on thin film PV modules was identified. Advantages of using thin film PV modules in BIPV applications include: 1) cosmetics; 2) lower cost per unit of area than crystalline modules; and potential for a controlled amount of light transmission through the module.

Under PV:BONUS Two, BP Solar supported by Kawneer, SDA, and Velux, propose to develop BIPV products including curtain walls, skylights and sunshades using tandem junction amorphous silicon plates now being produced by BP Solar in its Toano, VA factory. The commercial products will be developed in conjunction with Kawneer, mounting directly into Kawneer curtain wall framing and installed by glazers using the same methods used to install curtain walls. The residential products will be developed in conjunction with Velux, a major worldwide manufacturer of skylights, for installation directly into the skylights and roof windows manufactured in the Velux factory in South Carolina.

Status/Accomplishments: BP Solar, competitively selected, was awarded Phase 2 funding July 1, 1998 for continued development of these three thin film PV products. During Phase 1, BP Solar reduced the number of products developed under PV:BONUS Two from five to three and completed conceptual designs on each. Phase 2 accomplishments during FY19999 included: 1) development of a water jet process to cut plates after deposition for size flexibility; 2) completed demonstration of thin film processing on heat strengthened glass; 3) developed a laser ablation process to remove thin film layers (holes or lines in almost any pattern); 4) developed BIPV software; and 5) initiated planning for a demonstration at the University of Wisconsin at Green Bay.

During FY00, BP Solar developed a laboratory process for the fabrication of amorphous-Silicon (a-Si) thin film modules using heat-strengthened glass. The process is undergoing trial runs at the Toano factory for implementation in the first quarter of 2001. During Phase 2, the BP Solar team has developed a process that allows thin film modules to transmit up to 10% of the incident light while producing PV electricity. The process has been qualified and equipment has been ordered for the production line.

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Status/Accomplishments (continued): Viracon, as part of the BP Solar team, successfully incorporated double glass thin film modules into insulated glass (IG), thereby allowing the modules to serve as walls or sloped glazing. Kawneer, as part of the BP Solar team, has developed a design for a pre-engineered PV sunshade, which is now under test. Under Phase 2, BP Solar developed and implemented a process that allows plates to be cut after fabrication, thereby allowing for flexibility in size. This process has been implemented on a commercial basis with various sizes of plates available for sale. Commercial goals met during FY2000, included: 1) concluded commercial agreements between BP Solar, Solar Design Associates and Kawneer; 2) BP selected the PowerView product for integration into the new gas station design rolled out around the world in the 4th quarter of 2000; and 3) Viracon has been awarded a contract to deliver PowerView integrated glass units for installation spring 2000 on a new building on the University of Wisconsin campus.

Planned FY 2001 Activities: Under Phase 3, BP Solar plans to finalize a commercial agreement with Viracon and identify sales channels for the PV IG product; obtain UL approval of the PowerView and SunShade systems; support installation and monitoring of the University of Wisconsin at Green Bay project; monitor the performance of the PowerView modules in at least 10 BP gas stations; develop a marketing plan for the SunShades and identify a demonstration project; complete implementation of the heat strengthened and PowerView products in the Toano factory; and complete development and qualification of the edge connector.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS One - Integrated Modular Homes

Agreement #: DE-FC36-93CH10568	**Project Period:** 8/1/93–6/30/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Robert Hassett
Phone: 202-586-8163
Fax: 202-586-8148
E-mail: Robert.Hassett@ee.doe.gov</td><td colspan="2">Fully Independent Residential Solar Technology (FIRST)
66 Syndertown Road
Hopewell, NJ 08525-2705</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 12</td></tr>
<tr><td>Directing Organization:
Golden Field Office
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Lyle Rawlings
Phone: 609-466-4495 Fax: 609-466-3631</td></tr>
<tr><td rowspan="2">Project Manager:
Lizana Pierce
Phone: 303-275-4727
Fax: 303-275-4753
E-mail: lizana_pierce@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Fully Independent Residential Solar Technology (FIRST)</td></tr>
<tr><td>DOE Funding Allocation:
1994: $193,589 1997: $24,660
1995: $275,265 2000: $0
1996: $177,265</td><td>Cost Share Funding:
1994: $237,000 1997: $125,683
1995: $295,964 1998: $75,000
1996: $164,124 2000: $0</td></tr>
</table>

Project Objective: The prime objective of the project is to design, develop, and introduce to the residential market a line of integrated, modular solar homes designed for photovoltaic power. The intent of the project is to optimize home designs for least-cost construction, high performance, reliability, and to put in place the necessary marketing and distribution networks, financial products, and utility sector encouragement to ensure product success.

Approach/Background: The product concept is a factory-manufactured home which is designed from the ground-up to integrate PV power, high-efficiency appliances and light, passive solar heating and cooling architecture, and offers solar hot water as an option. The home, including the solar systems, wiring and controls, key appliances, and lights, will be produced by a major manufactured housing company, which specializes in modular homes.

Status/Accomplishments: Phase 1 (6/1/93-6/1/94) included design and initiation of pilot home construction. Phase 2 included final design and completion of six pilot homes. Phase 3 planned activities include: the implementation of PV-integrated modular homes into sustainable communities and low-income housing projects; establishment of partnerships with the EPA Energy Star Home Program for "Energy Star Mortgages"; investigation of PV/wind hybrid systems; development of a 48 V direct-current ballast for compact fluorescent lamps; and development of large, lightweight, roof-integrated modules. Nine townhouses in a Philadelphia low-income housing project, seven homes for the New Alchemy Farms Sustainable Community (Cape Cod, MA) and completion of the Long Island home are planned during Phase 3. FIRST installed a factory-built home featuring photovoltaic hardware and passive solar/energy efficient design features in the Washington area during the Solar Energy Forum held April 1997. A low-income home was completed (September 1999) in Jersey City in conjunction with a minority housing development and training corporation who may utilize the PV-integrated home concept in future developments. As a result of this modular home, Atlantic City has incorporate “efficient, renewable energy, and recycled homes” into CityScapes a twenty-two (22) home development project in Atlantic City, New Jersey. Three integrated, modular solar homes have been completed as part of the New Alchemy Farms Sustainable Community with eighteen planned for the Philadelphia low-income housing project. The three new Alchemy homes resulted in substantial lower costs ($20 per foot less) than conventional homes in the community. Large-area module development has been completed with prototypes planned for November 1997. BP Solar is considering including the roof-integratable large-area module into their product line. The pre-framed large-area modules incorporate numerous cost reduction advancements by using a plastic framing assembly which allows interlocking of the modules, reduces weight, provides water-tight seals, simplifies plug wiring, negates grounding requirements, and reduces the installation time.

FIRST continued to work with First Solar in development of a roof-integrated PV module and continued to work with Advanced Energy Systems (AES) on development of an inverter. Final approval from the Philadelphia Redevelopment Authority has been received on the Philadelphia Solar Townhouse Project a low-income housing project consisting of eleven (11) solar townhomes. Closing for the project is expected in December 2000 with construction to begin soon thereafter.

Planned FY 2001 Activities: Complete construction of the 11 PV integrated modular homes as part of Philadelphia's low-income housing project.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS Two - PowerRoof 2000

Agreement #: DE-FC36-97GO10247	**Project Period:** 9/30/97–9/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	PowerLight Corporation 2954 San Pablo Avenue Berkeley, CA 94710 **Organization Type:** IN	**Congressional District:** 9
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Thomas L. Dinwoodie **Phone:** 510-540-0550 **Fax:** 510-540-0552 **E-mail:** td@powerlight.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: $60,844 1999: $397,132 1998: $57,162 2000: $399,313	**Cost Share Information:** PowerLight Corporation **Cost Share Funding:** 1997: $ 67,000 1999: $560,834 1998: $101,041 2000: $492,959

Project Objective: PowerLight Corporation, in cooperation with AstroPower; BP Solar; BP Solar; and Siemens Solar, propose to development of an innovative Building-integrated PV roofing system called PowerRoof . PowerGuard is the first core product in the PowerRoof family and has been successfully developed under prior programs. The PowerRoof 2000 proposal targets development of two next-generation core PowerRoof building products, HeatGuard and PowerTherm . Each builds upon the proven technological approach of the PowerGuard solar electric roofing system.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which PowerLight was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. The HeatGuard PV roofing assembly is a patent-pending core product in the PowerRoof line. In addition to generating clean solar electricity, Building-integrated HeatGuard PV systems provide roof protection from solar thermal loads in the cooling season and block radiant building losses in the heating season. This yields significant reductions in building HVAC loads - leading to reductions in energy consumption, energy costs, and system equipment sizing. The PowerTherm PV roofing system pursues existing PowerLight patent claims for hybrid PV/thermal. PowerTherm is a Building-integrated PV/thermal hybrid system designed to couple the benefits of PV power with the collection of thermal energy. The parallel development of HeatGuard and PowerTherm as extensions of the PowerGuard approach is essential, as detail refinement of both projects will yield mutually beneficial technological advancements.

Status/Accomplishments: Under Phase 1, PowerLight accomplished the following: 1) received, prototyped, and tested leading advanced thin film materials into PowerRoof assemblies from seven leading manufacturers; 2) optimized and validated HeatGuard to improve the contribution to the building thermal envelop by reducing the rooftop solar absorptance to zero; 3) developed the PowerTherm concept prototype; 4) identified hybrid products using the HeatGaurd and PowerTherm systems. Phase 2 Fiscal Year (FY) 1999 accomplishments associated with the PowerTherm system include: 1) development of software for simulating PV/thermal hybrid performance; 2) validated simulation results through preliminary field-testing; 3) finalized preliminary PowerTherm tile design; and 4) developed a PowerTherm system prototype. During FY1999, PowerLight identified radiant barriers and optimized the sloped tile design for the HeatGuard system, evaluated the field performance of the sloped tile design, and established the value of the HeatGaurd radiant barrier through Energy -10 simulations.

During Phase 2 (FY2000), PowerLight's accomplishments included: 1) completion of four (4) advanced thin-film commercial demonstrations totaling 54.8 kW; 2) development of four versions of the flat HeatGuard prototypes, finalizing the HeatGuard design, and fabrication of a 20 kW system planned for installation September 2000; and 3) developed two basic versions of PowerTherm and one advanced PowerTherm product and installed and tested prototypes in Kona, Hawaii and Sonoma, California. The PowerRoll, PowerLight's advanced PowerTherm product, uses Uni-solar's flexible roll-to-roll PV system with laminated tubing. The PowerRoll is currently designed for the thermal and electrical loads needed for pool heating. PowerRoll samples have been submitted to the Florida Solar Energy Center (FSEC) for certification testing.

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Planned FY 2001 Activities: During Phase 3 (October 1, 2000 through September 30, 2001), PowerLight has proposed wind tunnel testing, Underwriter's Laboratory (UL) testing and listing, and FSEC certification of the PowerTherm product. PowerLight also plans to initiate the ICBO certification process for both the PowerTherm and HeatGuard products and initiate certification processes in Japan and Europe. For the PowerTherm product, PowerLight has also proposed a 25 kW demonstration to obtain performance data, advanced lamination process research to reduce manufacturing costs and increased life, and design and development of alternative plumbing interconnects to minimize field installation costs. Limited Phase 3 activities are associated with the HeatGuard product as the design has been finalized, requires no additional IEEE, IEC, UL or wind tunnel testing, and modifications to the manufacturing line are minimal. Other activities planned during Phase 3 include: 1) refine PowerTherm and HeatGuard system packaging; develop installation manual for the PowerTherm system; develop operations and maintenance (O&M) manuals for both product lines; develop a network of installer; and complete an education and training program for qualified installers and facility engineers.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS Two - Photovoltaic Powered Electrochromic Windows

Agreement #: DE-FC36-97GO10251	**Project Period:** 9/30/97–9/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	Sage Electrochromics, Incorporated 2150 Airport Drive Faribault, MN 55021	
	Organization Type: IN	**Congressional District:** 6
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Neil Sbar **Phone:** 507-333-0078 **Fax:** 507-333-0145 **E-mail:** nsbar@sage-ec.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Sage Electrochromics, Incorporated
	DOE Funding Allocation*: 1997: $60,000 1999: $120,000 1998: $200,331 2000: $175,000	**Cost Share Funding:** 1997: $42,918 1999: $138,065 1998: $230,409 2000: $184,430

* DOE Funding Allocation only represents funds provided by the PV Program.

Project Objective: Sage Electrochromics, in conjunction with BP Solar, propose to develop and commercialize photovoltaic (PV) powered electrochromic (EC) "smart windows" EC windows control the amount of sunlight and solar heat by dynamically switching between darkened and clear states and anywhere in-between. They provide a unique opportunity to realize significant energy savings and reduce peak electrical demand in buildings. The low-power DC voltage required to power the EC window glazing can be supplied by PV solar cells incorporated in the double pane insulating glass unit (IGU) so that no external hard-wired connections are needed.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which SAGE was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. The project is segmented into three phases over 60 months. In Phase 1, Sage proved the viability of the PV-EC concept and fabricated several 0.1 m^2 windows demonstrating operational performance, including wireless control, over a range of solar conditions. In Phase 2, Sage plans to achieve the capability to fabricate limited numbers of full-sized demonstration PV-EC prototype windows, which will be used for field demonstration and performance verification. The participant group expanded to include Glass Technologies, world leader in large-area sputtering technology and high performance architectural window fabrication, and Libbey-Owens-Ford, leading producer of conductive glass substrates. During Phase 3, the development of equipment, processes, partnerships, and distribution channels to initiate commercial production and introduction of the PV-EC window product for sale into targeted building markets will be finalized.

Status/Accomplishments: In Phase 1, Sage proved the viability of the PV-EC concept and fabricated several 0.1 m^2 windows demonstrating operational performance, including wireless control, over a range of solar conditions. The results support a marketing strategy that targets skylights and overhead glazing as first applications. Phase 1 defined the capabilities of this product, which led to defining a large size PV-EC window product that can be used for a variety of architectural window applications. Under Phase 2 (FY1999), Sage has: 1) developed variable control of the EC device and simplified construction; 2) built remotely-controlled PV-EC prototypes; 3) displayed an electrochromic window at Epcot; 3) defined the first product as a skylight; 4) completed pilot line industrial coater for dispositioning of substrates; 5) designed and built large-area solution coater and heater; and 6) processed skylight sized substrates in pilot line.
During FY2000, Sage installed and operated the pilot line for producing full-sized electrochromic windows (5 ft^2), conducted duration testing of the first pilot line EC devices at NREL, and demonstrated wireless window control. The first generation prototype PV-EC was demonstrated September 2000. Sage concluded agreements with leading Skylight and Sunroom manufacturers for the development, testing, and market introduction of overhead glazing products and is concluding agreements with leading window companies to develop, market and sell Sage's Switchable EC Window Systems. Sage completed an agreement with a leading controls manufacturer (Honeywell) to develop control systems for the electrochromic windows and forged a working relationship for the fabrication and testing of the integrated glass units (IGU's) with the world's largest producer of low-e IGU's for residential application for the fabrication and testing of the integrated glass unit.

Agreement #: DE-FC36-97GO10251

Status/Accomplishments (continued): During the period, a utility agreed to purchase SageGlass for installation into the skylight of a Children's Science Museum in San Francisco. Sage also demonstrated the world's largest all-ceramic lithium-based EC window at the International Home Builder's Show in Dallas, January 2000.

Planned FY 2001 Activities: Under the EC technology and product development task, Sage will continued film and device development, development of switching protocol, evaluation of alternative substrate cleaning systems, and complete pilot line production of up to 60 full-size switchable windows for test and evaluation. Under the PV-EC product development task, Sage plans to develop and produce 2nd generation PV-EC prototypes, continue durability testing of the PV-EC units and controls, and begin limited customer trials. Currently, Phase 2 activities are fully funded through September 30, 2001. However, Sage has proposed additional development activities to produce a full function, wireless, PV-powered window system resulting in an incremental funding request.
Phase 3, currently planned to begin in FY2002, is proposed as a two-year phase focused on expanded production and yield of PV-EC windows for commercial sales, extended customer evaluations, and demonstrations of control protocols and energy management capabilities.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS One - AC PV Module and Curtain Wall Application

Agreement #: DE-FC36-93CH10572	**Project Period:** 6/1/93–6/30/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Robert Hassett
Phone: 202-586-8163
Fax: 202-586-8148
E-mail: Robert.Hassett@ee.doe.gov</td><td colspan="2">Solar Design Associates (SDA)
P.O. Box 242
Harvard, MA 01451-0242</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
Golden Field Office
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Steven Strong
Phone: 978-456-6855 Fax: 978-456-303 E-mail: sjstrong@solardesign.com</td></tr>
<tr><td rowspan="2">Project Manager:
Lizana Pierce
Phone: 303-275-4727
Fax: 303-275-4753
E-mail: lizana_pierce@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Solar Design Associates (SDA)</td></tr>
<tr><td>DOE Funding Allocation:
1994: $625,000 1997: $333,374
1995: $1,953,736 2000: $0
1996: $1,077,176</td><td>Cost Share Funding:
1994: $605,315 1997: $362,442
1995: $1,967,635 2000: $0
1996: $1,171,098</td></tr>
</table>

Project Objective: The objective of the project is to develop and commercialize a large-area photovoltaic (PV) module with a dedicated, integrally-mounted, DC to AC power inverter, with an electrical output of 60 Hz AC power for compatibility with the utility grid. In addition, an integrated PV curtain wall product specifically for commercial building facades will be developed for commercialization. The AC photovoltaic module will nominally be 4 x 6 feet (24 square feet) in size and designed for direct building integration into the vertical facades and sloped-roof construction of residential, commercial or institutional buildings, replacing the traditional building skin.

Approach/Background: Under Phase 1 and 2 of PV:BONUS One, a large-area PV module with a dedicated, integrally-mounted, DC to AC power inverter, whose electrical output is 60 Hz AC power which is fully compatible with the utility grid was developed. The module's output is connected directly to the building's AC distribution system without need for any DC wiring, string combiners, DC ground-fault protection or additional power conditioning equipment. The AC module is nominally 4 x 6 feet (24 square feet) in size and designed for direct building integration into the vertical facades and sloped-roof construction of residential, commercial and institutional buildings, replacing the traditional building skin. A framed version of the AC module has also been developed for systems employing tracker and rack mount systems.

Status/Accomplishments: In Phase 1, Solar Design developed a prototype of the AC module inverter, while Mobil Solar Energy Corporation worked on developing a nominal 50-Volt, 240-Watt, 24 square foot photovoltaic module. During the Phase I effort, Mobil Solar was closed by Mobil Oil and BP Solar Corporation, the largest US manufacturer of photovoltaics and the second-largest in the world, agreed to continue the development work in lieu of Mobil Solar. During Phase 2, the Kawneer Company, a leading manufacturer of architectural curtain wall systems, also joined the SDA team along with the Maryland Energy Administration and Baltimore Gas and Electric. In addition to designing and manufacturing a new large-area PV module to accept the SDA modular inverter, the BP Solar / SDA team also developed an integrated PV curtain wall system specifically for commercial building facades and sloped-roof glazing applications. One of the first applications of this new technology was the new entry canopy designed by SDA, for the natatorium complex at the Summer Olympic Games in Atlanta. Here, 18 large-area BP Solar AC modules with clear backskins are mounted in a custom, arched support structure by Kawneer, to form the skin of the canopy. The AC Module has received UL approval and is being marketed through BP Solar and Kawneer. High-visibility, high-leverage early demonstrations are presently under way at the Olympic village and at the Sacramento Municipal Utility District (SMUD) where the first two-rooftop residential AC modules systems of 4 kWh each were fielded. The integration of a large-area thin-film array is planned for the south face of the 12-story high cube at the new Discovery Center, a non-profit science center, was completed August 1999 and dedicated April 2000.

Planned FY 2001 Activities: Complete demonstration projects and submit the final report.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Building-Integrated Photovoltaics

PV:BONUS Two - Hybrid Photovoltaic/Thermal Collector

Agreement #: DE-FC36-97GO10250	**Project Period:** 9/30/97–9/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	Solar Design Associates, Incorporated (SDA) 252 Old Littleton Road Harvard, MA 01451-0242 **Organization Type:** IN	**Congressional District:** 5
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Steven J. Strong **Phone:** 978-456-6855 **Fax:** 978-456-3030 **E-mail:** sjstrong@solardesign.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: $49,969 1999: $689,938 1998: $185,148 2000: $400,000	**Cost Share Information:** Solar Design Associates, Incorporated (SDA) **Cost Share Funding:** 1997: $82,762 1999: $867688 1998: $450,770 2000: $503,053

Project Objective: Solar Design Associates, Inc. (SDA), United Solar Systems Corporation, and SunEarth, Inc., propose to design, develop, demonstrate, manufacture and commercialize a Hybrid Flat-plate Photovoltaic/Thermal (PV/T) Collector to deliver both electricity and thermal energy. The PV/T collector design will employ liquid thermal transfer medium and closely resemble conventional flat-plat solar thermal collectors in size, appearance, installation and function. However, in place of the normal thermal absorber plate, it will employ a PV element of triple-junction amorphous silicon alloy solar cells made with United Solar's proprietary UNISOLAR technology whose material and thermal characteristics are uniquely well suited for combined PV/T applications.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Solar Design Associates was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. During Phase 2, Solar Design Associates (SDA), in conjunction with United Solar Systems Corporation, and Sun Earth, Incorporated, propose to design and develop a Hybrid Flat-Plate Photovoltaic / thermal (PV/T) Collector to deliver both electricity and thermal energy. The hybrid collector will be fabricated, demonstrated, and verified during Phase 3.

Status/Accomplishments: During Phase 1, SDA, in conjunction with United Solar Systems Corporation (USSC) and SunEarth, Inc., developed the conceptual design for the PV/T collector product and fabricated a full-scale conceptual PV/T collector based upon the standard SunEarth thermal collector. Under Phase 2 (FY99), SDA accomplished the following: 1) initiated thermal performance of the full-scale prototype at FSEC; 2) initiated outdoor exposure testing at UniSolar; 3) validated the bypass diode scheme; 4) recorded initial performance curve; 5) estimated thermal performance as a function of application; and 6) initiated UL listing. During FY2000, SDA finalized the majority of the PV/T material issues, defined the requirements for the PV/T stagnation tests, fabricated and shipped a full-size collector to Arizona for testing, and completed initial stagnation testing. During the same period, SDA defined UL testing requirements and developed plans for fabrication of a PV/T system for UL testing. Additionally, SDA completed discussions with SRCC for testing and certification of the PV/T system. SDA has also completed discussions with Montana State University for installation of a proof-of-concept demonstration system at the University in September 2000. The Boston Plumbers Union (Local #12) is expanding their union hall and is interested in installing a rooftop solar system using a combined PV/T collector. Due to uncertain appropriations in FY00 and subsequent delays in funding Phase 2, SDA has requested and been granted a Phase 2 extension through May 2001 to complete Phase 2 activities.

Planned FY 2001 Activities: SDA has requested and been granted a Phase 2 extension through May 2001 to complete Phase 2 activities. Remaining Phase 2 activities include: completion of UL and SRCC testing, UL listing, and SRCC certification of the PV/T; complete materials selection, manufacturing plan, and finalize manufacturing costs and selling prices; finalize marketing strategies; identification of education and training needs; and finalization of business and financial plans and business relationships.

Agreement #: DE-FC36-97GO10250

Planned FY 2001 Activities: Phase 3 is currently planned to begin in June 2001. Phase 3 activities include product demonstration and verification to include fabrication of initial pre-production units, qualification testing of initial commercialization production units, demonstration of the hybrid PV/T, implementation of education and training programs, and initial market introduction.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

PV:BONUS Two - Field Applied PV Membrane

Agreement #: DE-FC36-98GO10249	**Project Period:** 9/30/97–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E-mail**: Robert.Hassett@ee.doe.gov	United Solar Systems Corporation 1100 West Maple Road Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dr. Subhendu Guha **Phone:** 248-362-4170 **E-mail:** sguha@uni-solar.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** United Solar Systems Corporation
	DOE Funding Allocation: 1998: $213,205 2000: $300,854 1999: $400,026	**Cost Share Funding:** 1998: $214,800 2000: $300,854 1999: $403,239

Project Objective: United Solar Systems Corp. in collaboration with Energy Conversion Devices Inc. the National Association of Home Builders, Phasor Energy, Arizona Public Service, Southern California Edison Co., Southern Cal Roofing, ATAS International, Elk Corp and San Diego Gas & Electric intend to develop a field applied, flexible photovoltaic (PV) membrane product for the 'built-environment". The UNI-SOLAR PV Membrane, a flexible PV laminate, will ship directly to the site for field application or to a building product company for integration with their own products. It uses United Solar multi-junction a-Si stainless steel PV cells laminated in flexible UL approved materials.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which United Solar System Corporation was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. For the commercial sector, a 250 watt, 30" x 18' PVM design is planned for retrofitting onto flat commercial roofs and existing metal roof shade structures (covered parking). For residential and light commercial markets with sloped roofs, a narrower 125 watt, 16" x 18', PVM is needed for conform to conventional metal roofing shapes. For concrete tile roofs, prevalent in the southwest, the 125 watt PVM will be designed as a PV "Shingle Membrane" for use in an integrated manner with flat tiles.

Status/Accomplishments: During Phase 1, the conceptual design of the product has been completed and key product development tasks identified including PV Membrane size, electrical characteristics, termination designs, mounting methods for flat commercial roofs, covered parking, metal and tile shingle roofs. The PVM uses United Solar Triple-Junction PV cells on a flexible substrate, laminated in UL approved weather resistant materials to provide a flexible PV "membrane". During Phase 2 (FY1999), Uni-Solar accomplished the following: 1) completed the Photovoltaic Membrane (PVM) design; 2) fabricated prototypes; 3) verified the prototype performance at NREL; 3) resolved roofing/building interface issues; 4) developed a peel and seal field installation method; 5) finalized PVM termination design; 6) obtained UL recognition; 7) established PVM manufacturing process; and 8) initiated outdoor testing.

Phase 2 accomplishments in FY2000 included: 1) the completion and fabrication of PVM prototypes; 2) verification of PVM performance at NREL; 3) studied compatibility of the Peel and Stick adhesive with Galvalume materials; 4) tested and approved for code compliance a field installed termination; 5) PVM modules undergoing testing using IEEE test protocol in Troy, MI and Mexico; 6) established the manufacturing process for producing PVM with Peel and Stick adhesive; 7) UL recognition obtained for the roofing laminates with UL listing pending ; and 9) developed a draft application guide for field installation. On May 3, 2000, United Solar Systems introduced the Field Applied Flexible Roofing Laminate as a new Uni-Solar product. Additionally, a 2 kW installation at the Lesley Science Center in Ann Arbor Michigan was completed.

Agreement #: DE-FC36-98GO10249

Planned FY 2001 Activities: Under Phase 3, planned for October 2000 through September 2001, Uni-Solar has proposed product demonstration, product verification, and marketing.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Utility On-Grid Photovoltaic Applications

Agreement #: DE-FC36-94GO10007	**Project Period:** 8/16/94–12/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Dan Ton **Phone:** 202-586-4618 **Fax:** 202-586-8148 **E-mail:** Dan.Ton@ee.doe.gov	Edison Technology Solutions 2151 Walnut Grove Avenue Rosemead, CA 91770	
	Organization Type: IN	**Congressional District:** 28
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Steve E. Taylor **Phone:** 626-302-8946 **E-mail:** taylorse@sce.com	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Edison Technology Solutions
	DOE Funding Allocation: 1994: $ 500,000 2000: $0 1995: $1,500,000 1996: $ 500,000	**Cost Share Funding:** 1994: $2,000,000 2000: $0

Project Objective: The major objective of the SCE program is to validate the use of PV as a circuit-specific peaking support resource. The ultimate benefit of a successful on-grid PV program would be more rapid commercialization of the potentially large domestic on-grid PV market.

Approach/Background: The proposed application involves using PV to meet peak load requirements on selected SCE electric distribution circuits. The circuits of interest are old, underground 4 kV circuits, which have reached the limit of their load-carrying capability. The circuits serve residential areas, which have seen recent growth in peak load requirements, so that the circuits will soon exceed their limit during the summer peak load period. Without PV, the main alternative is to replace the circuits by excavating city streets and landscaping to install new underground, high-capacity cable. Since SCE estimates that the replacement of underground cable costs approximately $600,000 per mile, installing PV to meet the peak load requirements on these circuits results in the deferment of this significant cable replacement expense. SCE estimated that replacement of about 200 miles of underground 4 kV circuits in their system could be deferred by the use of grid-connected PV. This would require approximately 25 MW of PV to meet the peak loads on these circuits. The program has been proposed in two separate phases. During Phase I, a feasibility assessment was performed to address issues such as load and solar resource coincidence, load growth, alternatives to PV, and the size, scope, configuration, and available roof space for PV systems. Some initial installation and testing were performed on a pilot scale to establish data for the areas to be considered for the project. Phase II includes final design, procurement, installation, and monitoring.

Status/Accomplishments: The PV installation at the Discovery Science Center was completed and dedicated April 2000. The 20 kW system is installed on a cube shaped structure and generates approximately 10% of the Centers annual electricity consumption. Data collection, monitoring, and analysis continued for the following sites: 1) covered reservoir (98.3 kW) at Huntington Library; 2) rooftop application (112 kW) at Monterey Hills Elementary School; 3) patio cover (5.76 kW) at University of California, Irvine, 4) rooftop systems (31.5 kW) at Knotts Berry Farm Amusement Park; 5) Pacific Park Solar Farris Wheel (41.3 kW) at Santa Monica Pier; 6) covered lunch/assembly area (10.9 kW) at Glenmeade Elementary School in Chino Hills; 7) covered lunch/assembly area (12.6 kW) at Alamitos Intermediate School located in Orange County, CA; 8) rooftop system (9.45 kW) at Boys Republic in Chino Hills; 9) rooftop application (4.8 kW) at Montara Avenue Elementary School; 10) affordable housing site rooftop system (7.2 kW) at Elizabeth Court Apartments in Cudahy; 11) PV system (1.6 kW) at Straw Bale Greenhouse, Cal Poly at Pomona; 12) affordable housing site carport (4.8 kW) at Elizabeth Court Apartments in Cudahy; and 13) carport system (31.2 kW) at Santa Monica Civic Auditorium.

Planned FY 2001 Activities: Continue data collection, monitoring, and analysis.

Major Reports Published in FY 2000: Quarterly project reports.

Major Articles Published in FY 2000: none

PV for Utility Applications

Technology Experience to Accelerated Markets in Utility Photovoltaics (TEAM-UP)

Agreement #: DE-FC36-93CH10560	**Project Period:** 10/1/92–12/31/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Dan Ton
Phone: 202-586-4618
Fax: 202-586-8148
E-mail: Dan.Ton@ee.doe.gov</td><td colspan="2">Solar Electric Power Association (formally known as Utility Photovoltaic Group)
1800 M Street, NW, Suite 300
Washington, DC 20036-5802</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: NA</td></tr>
<tr><td>Directing Organization:
Golden Field Office
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Jeffrey Serfass
Phone: 202-857-0898 Fax: 202-223-5537 E-mail: Jserfass@ttcorp.com</td></tr>
<tr><td rowspan="2">Project Manager:
Lizana Pierce
Phone: 303-275-4727
Fax: 303-275-4753
E-mail: lizana_pierce@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Utility Photovoltaic Group (UPVG)</td></tr>
<tr><td>DOE Funding Allocation:
1994: $1,000,000 1998: $2,000,000
1995: $8,891,000 1999: $3,800,000
1996: $5,400,054 2000: $1,499,110
1997: $300,000</td><td>Cost Share Funding:
1994: $209,000 1998: $5,330,102
1995: $9,337,727 1999: $11,282,804
1996: $5,400,054 2000: $9,085,607
1997: $7,942,410</td></tr>
</table>

Project Objective: The Utility PhotoVoltaic Group's (UPVG's) objectives is the establishment of an accelerated market for suppliers of photovoltaic systems that allows investments in larger manufacturing facilities, thus reducing photovoltaic unit costs through economies of scale, creating even broader market potential. TEAM-UP, a multi-year hardware initiative, provides cost-share for small-scale applications and grid-connected programs, as well as, focusing on commercialization strategies for photovoltaic systems in the utility industry. The TEAM-UP program is intended to help develop sustainable markets and provide the needed experience that leads to business opportunities for many of the participants. The prime objective of TEAM-UP is to document the business and technical experiences of the TEAM-UP ventures and document and report trends and results. This includes a categorization of the various business models along with some of the keys to success and pitfalls. The intent is to discuss general trends and results that provide value for replication of successful PV system installations and programs.

Approach/Background: Created in September 1992, the Utility PhotoVoltaic Group's original Program Development Plan addressed the large potential for applications of photovoltaic systems for electric utilities and their customers. The first activity focused on technology transfer and promotion to accelerate today's potential economic applications of photovoltaic systems for the benefit of electric utilities and their customers, while the other parallel program was the formulation and exploitation of strategies that would result in high-volume purchases of photovoltaic systems for emerging applications. Phases 1 and 2 of the agreement focused on these two parallel activities, whereas Phase 3 included the implementation of utility market acceleration strategies.

Implementation of the hardware initiative, TEAM-UP, began during Phase 3 with funding for grid-connected projects and support of market/buyer teams for grid-independent applications. During Phase 3, 4, and 5 there have been three Rounds of solicitations and awards of cost-share funding for twenty two (22) PV projects initiated. Of these two rounds of awards, eighteen (18) are grid-connected projects, which represent 4.6 MW of photovoltaic installations valued at nearly $44 million. During Phase 6, which includes Round Three awards, there were an additional fourteen (14) projects funded, all grid-connected ventures that have installed an additional 2.8 MW of PV systems valued at $26 million. Additionally, TEAM-UP was instrumental in securing cost-share funding from non-government sources for more that 80% for all of 32 grid-connected projects. For the off-grid projects, four (4) teams were formed which served as market development and/or buyer teams for off-grid applications of photovoltaics, including remote residential service, water pumping applications, and lighting applications. The first three Rounds of TEAM-UP projects will total more than 7.4 MW of PV systems in over 1100 installations in 34 states across the U.S. resulting in over $70 million worth of PV projects. There are over 130 partners involved in all the projects. The Round One installations were completed in September of 1998, Round Two installations were completed in September 1999, and October 2000 marked the completion of installations under Round Three.

Agreement #: DE-FC36-93CH10560

Approach/Background (Continued): The goal of the Phase Six Program Plan is to demonstrate and validate the use of photovoltaics by electric utilities, energy service organizations, and their customers. The organization, in response to the significant changes in the electric supplier, energy service provider, and utility industries, changed the name of the organization in October 2000 from the UPVG to the Solar Electric Power Association (the "Association"). The goals of the Association are to: 1) expand electric energy service provider use of domestic photovoltaic systems, thereby increasing demand for PV; 2) encourage utilities and energy service organizations to take advantage of the economic development potential, business opportunities, and environmental benefits offered by PV technology; 3) facilitate the development of community interaction with local energy service providers to remove barriers to building-integrated PV; and 4) further the replication of successful TEAM-UP ventures.

Status/Accomplishments: The TEAM-UP program has issued funding awards to 36 teams for $15.0 million of DOE funds. Private funds support the ventures at a cost-share ratio of 4 private dollars to every dollar of DOE funds. Through these efforts ventures have installed more than 7.4 MW of PV systems in over 1100 installations in 34 states across the U.S. resulting in over $70 million worth of PV projects. All PV systems have been installed as of the end of October 2000.

Planned FY 2001 Activities: All TEAM-UP PV system installation program activities are planned for completion by December 31, 2000. FY 2001 activities include the completion of the Final Report.

Major Reports Published in FY 2000:

Solar Electric Power Association, (previously Utility PhotoVoltaic Group), " Large Systems Cost Report", document distributed at the UPEx 2000 conference, October 2000.

Solar Electric Power Association (October 2000) "Solar Commercialization Workshops, Summary Report".

Major Articles Published in FY 2000:

S. Hester**,** M. Fioravanti, T. Willey, A. Mervis, A. Chang**, "**TEAM-UP Results Costs, Performance, and Business Experiences", *28th IEEE PV Specialists Conference*, Anchorage, AK, 17-22 September 2000.

S. Hester, J. Serfass, M. Fioravanti, W. Bensley, "A Utility Perspective of PV Commercialization"**,** Program and Proceedings: NCPV Program Review Meeting 2000, 16-19 April 2000, Denver, CO, BK–520-28064, (2000).

Photovoltaic Market Valuation and Load Matching

Contract #: XAD-8-17671-1	**Contract Period:** 11/21/97–6/1/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	State University of New York Albany, NY 12222	
	Organization Type: CU	**Congressional District:** 21
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** R. Perez **Phone:** 518-437-8751 **Email:** perez@asrc.cestm.albany.edu	
Technical Monitor: Christy Herig **Phone**: 303-384-6546 **Fax**: 303-384-6491 **E-mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: State University of New York., NYSERDA
	DOE Funding Allocation: 1998: $85,000 2000: $19,640 1999: $70,000	**Cost Share Funding:** 1998: $50,000 2000: $9,839 1999: $50,000

Project Objective: Building upon accomplished PV load matching and customer-sited valuation tasks, the current objectives of this subcontract are:

1. Determination of the value and effective capacity of PV in New York City
2. Prepare publications and documents based on previous research objectives

Approach/Background:
Determine PV effective capacity for the New York metropolitan area using 97-99 load data to be obtained from the New York ISO. Site/time specific PV output is to be determined from satellite data archived at ASRC under a distinct NREL contract. Several benchmarks are to be used to quantify PV's effective capacity: (1) Effective Load Carrying Capability, used in previous tasks of this contract, (2) solar load controller minimum temperature adjustment to insure 100% PV availability during all top loads.

Determine the availability of PV coincident with instances if high market prices in New York ISO regions based on NY ISO data starting in November 1999.

Status/Accomplishments
A detailed article including selected results from this task is under final preparation. This will be presented at the 2000 ASES Forum in Washington, DC.

A report on the valuation on PV in reference to ISO market prices is under preparation. The results of this report will be used as justification for NYSERDA to assist in an accelerated deployment of grid-connected PV in the New York metro region.

Planned FY 2001 Activities: none

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000:
Herig, C., R. Perez and S. Letendre, (2000): Concerns over grid reliability – New opportunities for PV. Proc. UPEX 2000, Utility Photovoltaic Working Group Meeting, Baltimore, MD

Perez, R., M. Kmiecik, C. Herig and D. Renné, (2000): Monitoring PV performance using geostationary satellites, Proc. 17th European PV Conference, Glasgow, Scotland

Perez, R., M. Kmiecik, D. Renné and C. Herig, (2000): Remote Monitoring of PV Performance Using Geostationary Satellites, Proc. ASES-2000 Conference, Madison, WI

Lampi M. and R. Perez, (2000): Assigning a capacity value to distributed renewable resources in restructured electric markets – the case of New York State, ASES-2000 Conference, Madison, WI

Contract #: XAD-8-17671-1

Perez, R., J. Schlemmer, B. Bailey and K. Elsholtz, (2000): The Solar Load Controller -- End-use maximization of PV's peak shaving capability. ASES-2000 Conference, Madison, WI

Perez R., (2000): Drivers for Distributed Generation. Proc. Building Energy 2000 NESEA Conference, Yale University, New Haven, CT

PV for Utility Applications

User-Scale Applications - Photovoltaics (USAPV)

Agreement #: DE-FG36-93CH10587	**Project Period:** 9/27/93–6/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	User-Scale Applications – Photovoltaics One Upper Pond Road Parisippany, NJ 07054 **Organization Type:** IN	**Congressional District:** 11
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Eva Gardow **Phone:** 973-455-8347	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1994: $352,740 2000: $0 1995: $303,864	**Cost Share Information:** User-Scale Applications – Photovoltaics **Cost Share Funding:** 1994: $352,740 2000: $0 1995: $658,030

Project Objective: The prime objectives of the USAPV program is three fold as follows: 1) develop the necessary marketing business plans and regulatory framework to integrate photovoltaic technology into the portfolio of products and services offered by the utility, 2) develop the necessary standards for and understanding of PV technology such that PV becomes one of several solutions employed by utilities to solve operational problems and meet distribution system peak demands, and 3) introduce at least 10 MW of new PV demand within the northeastern United States.

Approach/Background: USAPV was originally proposed and sponsored by Congressman Dean Gallo (R-NJ) as a program that would encourage greater visibility and opportunity for the integration of PV technology in New Jersey and the northeastern United States. The New Jersey Board of Regulatory Commissioners (NJBRC) has been in the forefront of regulatory reform in the promotion of demand side management programs and is an advocate of PV applications in New Jersey. Both the NJBRC and NJDEPE strongly support and endorse the project. Furthermore, regulatory support may promote a broader acceptance and visibility for this PV initiative in the utility industry. User Scale Applications - Photovoltaics (USAPV) will implement cost shared demonstrations of utility-owned, end-user and distributed applications of photovoltaic technology. USAPV's objective is to leverage federal funds with private funding from utilities customers, PV industry, state regulatory agencies, and other participating organizations. USAPV will monitor and evaluate projects, each cost-shared on a minimum of a 50/50 basis. USAPV will establish priorities for demonstration projects and will be responsible for their management, data collection and reporting. USAPV will be managed by a Steering Committee with representation from the participating utilities, New Jersey Department of Environmental Protection and Energy (NJDEPE), and U.S. DOE with advisement from a Technical Review Committee representing PV experts from National Laboratories and utilities, industry, and research organizations.

Status/Accomplishments: Jersey Central Power & Light and Atlanta Electric initially sponsored projects on a 50/50 cost share basis for the implementation of projects in the areas of fluorescent and outdoor lighting, and isolated load applications. Nine projects have been completed through those two utilities. Three additional utilities, Metropolitan Edison Company, Potomac Electric Power Company, and New York Power Authority have completed projects under USAPV grants. Two additional projects, Taunton Municipal Lighting Plant and Tampa Electric Company have been completed. Award of an agreement to the Liberty Science Center for the “Solarscapes Project” which includes the installation of a hands-on interactive exhibit and a nighttime visual lighting display, as well as an ongoing educational program. USAPV is currently reviewing three additional applications for funding.

Planned FY 2001 Activities: Review and award funding for two to three of the proposals. During FY 2001, USAPV will complete installations at the Liberty Science Center and under the pending agreements.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

PV for International Applications

PV International Market and Applications Development

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401 **Organization Type**: FF	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** C. Hanley , D. Lew , P. Lilienthal , M. Ross, L. Roybal, B. Stafford, J. Stone**, J. Strachan, R. Taylor , W. Wallace **Phone:** **303-384-6470 **Fax:** **303-384-6481 **E-mail**: **jack_stone@nrel.gov	
Technical Monitor: Jack Stone **Phone**: 303-384-6470 **Fax**: 303-384-6481 **E-mail:** Jack_Stone@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1997: $1,447,000 2000: $1,275,700 1998: $1,721,000 1999: $1,750,000	**Cost Share Information**: none **Cost Share Funding:**

Project Objective: The activities of the NREL and Sandia PV International activities will support the four EE/RE strategic goals for its international activities: 1) Address emerging global environmental and energy issues; 2) Promote trade and market development; 3) Promote energy and environmental security; and 4) Conduct cooperative research and development. The overarching strategic objective for the NREL and Sandia international activities will be to accelerate the establishment of self-sustaining EE/RE markets and businesses in developing and transition countries. Existing bilateral agreements and memorandums of understanding (MOUs) will continue to be supported. Activities will be broadly classified into policy, technology, and markets.

Approach/Background: International activities funded by the DOE PV Program will be aligned with the primary functions of the DOE PV Program to partner with industry and academia to foster an environment leading to profitable and sustainable markets. The NREL and Sandia activities will be carried out in countries in the developing world chosen for their government's commitment to renewable energy and the potential of a large market for U.S. industry. Activities will include, but not be limited to, providing technical assistance, demonstrating technical feasibility of new technologies, providing education and training to government and NGO personnel, developing test protocols which place American products on a leveled playing field with foreign companies, and business development including facilitating joint venture agreements between foreign and U.S. companies. Technical assistance will be used to leverage in-country program activities by providing support for the development and implementation of international projects. The credibility of the U.S. government, through MOUs developed at the highest levels of the governments, will be utilized to maintain a presence for the United States in these countries which can effectively counter the activities of the foreign competition which place U.S. companies at a disadvantage. High level policy benefits will be utilized to assist developing countries with clean development to encourage their cooperation with international environmental goals (climate change, emission trading) and other foreign policy initiatives that benefit from international support. Also, the U.S. is providing development assistance in numerous countries through AID, UNDP, World Bank and other funding agencies for which our technical assistance and training activities can make the efforts of those other agencies more effective.

Status/Accomplishments: US/China website at www.nrel.gov/china became operable 12/99 and has been continuously updated to reflect new events (such as the US/China Renewable Energy Forum Proceedings which is completely available on the website) and new reports (such as the Commercialization of Solar PV Systems in China report). Small system test facility planned and construction completed. Building has been fitted out and testing of selected systems has begun. Tests results will be provided to US industry to assess competitive products available in other countries. The IPV Test Facility, construction is completed and fitted with 2.9 KW of PV power with 5KW-inverter power station. 120Vac distribution is in progress along with communication system. Data acquisition systems are being studied for application. HOMER and ViPOR have been substantially enhanced. The help files for both models have been substantially improved. Their web pages have been redesigned and training draft materials have been developed. A subcontract was issued to TERI to perform an impact study of the Ramakrishna Mission Project, report completed. Lessons learned are applicable to other developing countries. The Ramakrishna Missions battery charging station is being studied for better performance. Some change in the design may be applicable. UV water purification is under study for safe drinking water in developing countries. Alternatives to rechargeable lanterns vs. battery charging for small lighting systems. Solar refrigeration to CURE project and health clinics. Solar home systems being tested by stand alone IPV Test Facility. The Tata Energy Research Institute issued their final report on the impact of the project in the Sundarbans. Restarted cooperative programs in India, performed impact study in the Sundarbans.

Contract #: DE-AC36-98-GO10337

DOE continues to obtain large impacts at low cost, through leveraging funds from USAID/Mexico. The new Annex VII, Policy and Planning, was signed between DOE and SDPC in 5/00.

The China program had the following accomplishments during FY00:

- Rural Electrification Training – Brightness rural electrification program staff from the Beijing Jikedian Renewable Energy Development Center, northwestern provincial Planning Commissions, and the State Development Planning Commission attended a two-week training at NREL and in Southern California in 5/00 on rural electrification and renewable energy policy. Seven companies and institutions presented at this training course and two letters of intent for further cooperation were signed between the Chinese and US organizations. DOE/NREL co-sponsored a 2-week training with MOA for local technicians and government staff at the Asia-Pacific Solar Energy Training Center in Lanzhou during 11/99 with US company trainers.
- PV dissemination projects – By the end of 2000, 341 US/Chinese household PV/wind systems will be installed in this pilot project between DOE/NREL and the Inner Mongolia New Energy Office. As a result of this activity, local officials in Dongwu County have completed a feasibility study and plan for 4,000 hybrid systems to be installed over the next 5 years. A PV school and home project near Beijing was established in 10/99 to educate local people in solar energy and to demonstrate examples of the US/China bilateral cooperation pilot projects that have been implemented in remote areas around the country. In cooperation with APEC, 2 companies have installed 200 solar home systems in the Lhasa prefecture to identify business development strategies for PV installations in Tibet.
- Rural Electrification Survey and Analysis – In China, rural electrification options analysis report was drafted and reviewed and will be published in early 2001.
- Business Development Reports –*Renewable Energy Markets In China: An Analysis of Renewable Energy Markets in Guangdong, Jiangxi, Jilin and Yunnan, with Updated Information from Beijing* was published in 12/99 as an NREL report. *Commercialization of Solar PV Systems in China* was published on the website in 6/00 as an English version and will be published in hard-copy in China as a bilingual report in early 2001.
- Conferences and Workshops – DOE/NREL successfully held a US/China Renewable Energy Forum for April 19-20, 2000 in DC with participation from approximately 125 people, including 50 Chinese delegates and 24 US companies. A CDROM of the proceedings was released in June 2000. The Forum was followed with clean energy exhibitions and a study tour to NREL and renewable energy facilities in CA. The US/China Renewable Energy Business Workshop and study tour was conducted by DOE/NREL with 13 US companies in China during 11/99. This workshop and study tour was fruitful in assisting US companies with potential new customers, distributorships, and partnerships.
- Policy and Planning – NREL assisted development of Annex VII – *Policy and Planning* - to the Bilateral Protocol, focusing on renewable energy policy and support of the Brightness Rural Electrification Program. This was signed between DOE and SDPC in May 2000.
- Outreach and Reporting– NREL completed the China website at www.nrel.gov/china in 12/99 and maintains a database of US and Chinese businesses and contacts. The US/China Summary of Protocol Activities for the past four years was released as a bilingual report and CDROM in 4/00.

Planned FY 2001 Activities: Re-engage U.S. renewable energy presence in India following lifting of sanctions. Follow through of DOE commitments, continue MoU, continue engagement in the country's large PV markets in the world's largest democratic country. Continues DOE commitments under Bilateral Protocol. Maintain key DOE/NREL role in developing US industry presence and market share in the world's largest country and one of the largest renewable energy markets. Replicate Mexico program in Central America. Successfully leverage non-DOE funding in countries where the Mexico experience can be duplicated. Continue modeling and testing activities Builds on NREL's recognized expertise and capabilities to the benefit of U.S. industry. There are 437 HOMER users in 47 countries. The models are leading to major projects in the Philippines, Australia, and South Africa.
NREL will support organization of renewable energy sessions and participation at the proposed Clean Energy Symposium & Exhibition and Symposium on Carbon Management Science and Technology to be held in Beijing in 8/01.

Major Reports Published in FY 2000:
"Ramakrishna Mission Initiative Impact Study", Final Report, A. Chaurey, TERI, New Delhi, India, June, 2000, NREL Report NREL/SR-520-28601

Draft report of *Off-Grid Renewable Energy Options for Rural Electrification in Western China* prepared and reviewed

Proceedings of US/China Renewable Energy Forum, Washington, DC, 19-20 April 2000

Published *Commercialization of Solar PV System in China* on website in 6/00. Bilingual hard-copy is being published in China.

Major Articles Published in FY 2000:
J. Stone, H. Ullal, A. Chaurey, and P. Bhatia, "Ramakrishna Mission Initiative Impact Study — A Rural Electrification Project In West Bengal, India", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

PV for International Applications

Thin-Film Technology Validation Study

Contract #: AAD-0-30604-03	**Contract Period:** 12/99–12/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Bakaert ECD Solar Systems LLC 1675 West Maple Road Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dr. T. C. Tripathi **Phone:** 91-11-913-79207 **Fax:** 91-11-436-0764 **E-mail:** advtct@ren02.nic.in	
Technical Monitor: Jack L. Stone **Phone**: 303-384-6470 **Fax**: 303-384-6481 **E-mail**: jack_stone@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Ministry of Non-Conventional Energy Sources, government of India
	DOE Funding Allocation: 2000: $15,875	**Cost Share Funding:** 2000: $15,875

Project Objective: Undertake a detailed technology validation project for state of the art thin-film modules of the a-Si triple tandem type.

Approach/Background: Approximately 3 kilowatts were competitively procured for installation and testing at the Solar Energy Centre in New Delhi, India. The sample modules were characterized at NREL and will be measured at the Solar Energy Centre to validate their characterization techniques.

Status/Accomplishments: The modules have been shipped to India and will be installed early in 2001

Planned FY 2001 Activities: Installation of the modules will be completed and testing will continue for an indeterminate amount of time to evaluate the performance of thin-films in the Indian environment.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

PV for International Applications

Thin-Film Technology Validation Study

Contract #: ADG-0-30626-01	**Contract Period:** 9/00–10/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	BP Solar 989 Corporate Drive Linthicum, MD 21090	
	Organization Type: IN	**Congressional District:** 3
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dr. T. C. Tripathi **Phone:** 91-11-913-79207 **Fax:** 91-11-436-0764 **E-mail:** advtct@ren02.nic.in	
Technical Monitor: Jack L. Stone **Phone**: 303-384-6470 **Fax**: 303-384-6481 **E-mail**: jack_stone@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Ministry of Non-Conventional Energy Sources, government of India
	DOE Funding Allocation: 2000: $30,000	**Cost Share Funding:** 2000: $30,000

Project Objective: Undertake a detailed technology validation project for state of the art thin-film modules of the a-Si double tandem and cadmium telluride types.

Approach/Background: Approximately 5 kilowatts of each technology type were competitively procured for installation and testing at the Solar Energy Centre in New Delhi, India. The sample modules were characterized at NREL and will be measured at the Solar Energy Centre to validate their characterization techniques.

Status/Accomplishments: The modules have been shipped to India and will be installed early in 2001

Planned FY 2001 Activities: Installation of the modules will be completed and testing will continue for an indeterminate amount of time to evaluate the performance of thin-films in the Indian environment.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

China Program Web site Development and Communications

Contract#: TDH-9-29120-01	**Contract Period:** 9/20/99-9/20/01

Sponsoring Office Code: EE-13	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Julie Cardinal 5225 White Willow Drive, M210 Fort Collins, CO 80528	
	Organization Type: IN	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Julie Cardinal **Phone:** 970-206-1296 **E-mail:** Julie_Cardinal@nrel.gov	
Technical Monitor: Debra Lew **Phone:** 303-384-7522 **Fax:** 303-384-7419 **E-mail:** Debra_Lew@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None
	DOE Funding Allocation: 1999: $24,500 2000: $5,500	**Cost Share Funding:**

Project Objective: This project was designed to support the U.S. renewable energy industry in developing business opportunities in China. The main objective is to develop and maintain an English-language website, that will provide information on Protocol activities, new business opportunities, new policies, and market and industry reports that have been developed by NREL. This project will also support business development through developing a database of US and Chinese company contacts for distribution of timely business-related information and through supporting communications outreach to US companies. In addition to the website, this project supports the development of additional resources to disseminate information including the US/China Renewable Energy Forum and conference proceedings and periodic mailings of US/China renewable energy publications.

Approach/Background: The website is developed and maintained to disseminate information widely to US businesses by posting DOE/NREL China activities, pilot projects and reports on the internet. A database has also been established which contains US companies that are interested in China markets. Other information that is disseminated both through the website and periodic electronic and hard-copy mailings includes business and market information, conference proceedings, and events.

Status/Accomplishments:
- The website is complete and available at www.nrel.gov/china. It is updated regularly.
- A database of US companies, Chinese contacts, and others who are interested in China renewable energy is maintained.
- The US/China Renewable Energy Forum Proceedings were prepared and mailed to participants on CD-ROM within 2 months of the Forum.

Planned FY 2001 Activities:
- Maintain and update the website with new publications, information, and events calendars.
- Maintain database of US contacts interested in China renewable energy and Chinese renewable energy companies.
- Distribute electronic news and events updates and publications
- Develop communication materials for US/China renewable energy activities.

Major Reports Published in FY 2000:
Proceedings of US/China Renewable Energy Forum, Washington, DC, 19-20 April 2000.

Major Articles Published in FY 2000: none

PV for International Applications

Renewable Energy Business Development in China

Contract#: AAX-8-17679-01	**Contract Period:** 2/26/98–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Center for Renewable Energy Development 1811 Jinyu Mansion 129 Xuanwumen Xidajie Beijing, 100031, P.R.C.	
	Organization Type: ZZ	**Congressional District:**
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J. Li **Phone:** 011 8610 6641 7350 **Fax:** 011 8610 6641 1401 **E-mail:** lijf@public.bta.net.cn	
Technical Monitor: Debra Lew **Phone:** 303-384-7522 **Fax:** 303-384-7419 **E-mail:** Debra_Lew@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1997: $94,933 1998: $39,870 1999: $70,157 2000: $0	**Cost Share Funding:**

Project Objective: To establish a framework for specific collaboration in order to promote renewable energy business development between the U.S. and China. To hold workshops and study tours, leveraging other events, which will bring US and Chinese businesses together for future partnerships and cooperation. To support information dissemination through websites and newsletters business related data from the US and China for mutual exchange with companies in both countries. To proactively support the development of renewable energy projects in China and project participation by U.S. and Chinese companies.

Approach/Background: Joint cooperation with the Center for Renewable Energy Development in Beijing is conducted to generate a number of information products to exchange between China and the U.S. for the purpose of promoting business cooperation and the development of opportunities. Joint efforts are also conducted to support market-conditioning efforts in financing and policy. Whenever possible, CRED and NREL will leverage other events in order to bring US and Chinese businesses together at least cost. Exchange visits, workshops and study tours are used to reach these goals.

In order to bring relevant market information to US businesses, CRED has assisted in development of market and technology assessments, which are published as reports and distributed widely through the US business community. Websites and newsletters are also used to disseminate information.

Status/Accomplishments:
- Published *Commercialization of Solar PV System in China* on website in 6/00. Bilingual hard-copy is being published in China.
- A US/China Renewable Energy Business workshop and study tour was held in 11/99 to bring 13 US companies to China for the purpose of increasing US markets for renewable energy products and services in China. This workshop and study tour resulted in several potential deals, partnerships and distributorships for US wind and PV suppliers.

Planned FY 2001 Activities: A Chinese language website to provide information on business opportunities and policies will be finalized and updated. The bilingual report *Commercialization of Solar PV System in China* will be published in early 2001.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Rural Electrification Using Photovoltaics in Northwestern China

Contract#: AAX-8-17680-01	**Contract Period:** 12/5/97–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Chinese Ministry of Agriculture No. 11 Nongzhanguan Nanli Beijing 100026, P.R.C.	
	Organization Type: ZZ	**Congressional District:**
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J. Li **Phone:** 011 86 10 6419-2610 **Fax:** 011 86 10 6500-2448 **E-mail:** lijingm@agri.gov.cn	
Technical Monitor: Debra Lew **Phone:** 303-384-7522 **Fax:** 303-384-7419 **E-mail:** Debra_Lew@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Chinese Ministry of Agriculture
	DOE Funding Allocation: 1996: $100,000 2000: $0 1998: $50,000 1999: $45,000	**Cost Share Funding:** 1996: $80,000 2000: $0

Project Objective: In general, there are several objectives. To expand the use of PV renewable energy systems throughout western and northwestern China for solar home lighting, educational school systems, etc. by expanding the knowledge base for solar applications in rural China, especially through the Gansu Project. To perform technical and economic analysis for rural electrification options to identify the most cost effective way on a life cycle basis for supplying rural electrification needs in China. To characterize the market for solar rural electrification systems in Qinghai and Xinjiang provinces in western China. To provide technical assistance for the Asia-Pacific Solar Energy Training Center being supported by the Ministry of Agriculture in Lanzhou in Gansu.

Approach/Background: Rural electrification options analyses will be conducted on data which has been collected in surveys for Xinjiang and Qinghai provinces in northwestern China. The analyses will characterize the best options for supplying rural electrification needs in this remote region of China and will provide a characterization of the existing market for solar PV systems. Technical assistance will be supplied to the regional testing and training facility in Lanzhou to support the resources of the Chinese Ministry of Agriculture in extending the training services available to several provinces in western China.

Status/Accomplishments:
- Provided analysis support for University of Delaware’s final report on rural electrification options.
- Two-week training session held for 30 technicians and local government officials from northwest China at the Asia-Pacific Solar Energy Training Center in Lanzhou in 11/99.
- Installation of demonstration systems at a village near the Great Wall in Beijing, showing the PV technology and its applications at a school and household in 10/99.

Planned FY 2001 Activities: Final report summarizing project activities.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

PV for International Applications

Thin-Film Technology Validation Study

Contract #: AAD-0-30604-04	**Contract Period:** 12/99–12/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Energy Photovoltaics, Inc. 276 Bakers Basin Road Lawrenceville, NJ 08648	
	Organization Type: IN	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dr. T. C. Tripathi **Phone:** 91-11-913-79207 **Fax:** 91-11-436-0764 **E-mail:** advtct@ren02.nic.in	
Technical Monitor: Jack L. Stone **Phone**: 303-384-6470 **Fax**: 303-384-6481 **E-mail**: jack_stone@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Ministry of Non-Conventional Energy Sources, government of India
	DOE Funding Allocation: 2000: $15,019	**Cost Share Funding:** 2000: $15,019

Project Objective: Undertake a detailed technology validation project for state of the art thin-film modules of the a-Si double tandem type.

Approach/Background: Approximately 3 kilowatts were competitively procured for installation and testing at the Solar Energy Centre in New Delhi, India. The sample modules were characterized at NREL and will be measured at the Solar Energy Centre to validate their characterization techniques.

Status/Accomplishments: The modules have been shipped to India and will be installed early in 2001

Planned FY 2001 Activities: Installation of the modules will be completed and testing will continue for an indeterminate amount of time to evaluate the performance of thin-films in the Indian environment.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

PV for International Applicatons

PV Power Systems International Conference Support

Contract #: BE-8906	**Contract Period:** 1/12/99–1/3/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Fred Morse Associates, Inc. Washington, DC	
	Organization Type: IN	**Congressional District**: N/A
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS-0753 Albuquerque, NM 87185-0753	**Principal Investigator (s)** Fred Morse **Phone:** 202-483-2393 **Fax:** 202-265-2248 **Email:** fredmorse@morseassociatesinc.com	
Technical Monitor: Ward I. Bower **Phone**: 505-844-5206 **Fax**: 505-844-6541	**B&R Code**: EB22	**Cost Share Information**: none
	DOE Funding Allocation: 2000: $54,600	**Cost Share Funding:**

Project Objective: Support, through Organizing Committee and U.S. industry, the Third International Executive Conference on PV Power Systems in Competitive Electricity Markets.

Approach/Background: Serve on international organizing committee and contact appropriate U.S. industry and utility personnel to participate, speak, and lead conference proceedings.

Status/Accomplishments: A successful IEA PVPS Executive Conference: Il Valore del Sole was held in Venice, Italy on November 3-5, 1999. Over 150 international invitees participated. A committee of US (state) government participation provided input for a Government Perspectives report on “Policy Options to Encourage PV Markets” report.

Planned FY 2001 Activities: Government Perspectives report

Major Reports Published in FY 2000:
Government Perspectives report entitled “Policy Options to Encourage PV Markets”

Major Articles Published in FY 2000: none

PV for International Applications

Mexico Support

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Sandia National Laboratories
Renewable Energy Office</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Michael P. Ross
Phone: 505-844-3301 Fax: 505-844-7786 E-mail: mpross@sandia.gov</td></tr>
<tr><td rowspan="2">Technical Monitor:
Joe R. Tillerson
Phone: 505- 844-1806
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E-mail: jrtille@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $210,000
2000: $100,000</td><td>Cost Share Funding:
2000: $775,000</td></tr>
</table>

Project Objective: The objective is to accelerate the acceptance of commercially viable renewable energy technologies for off-grid productive-use applications in Mexico. This work is done in partnership with U.S. and Mexican industry, and the goal is the establishment of sustainable and growing new markets for renewable energy technologies.

Approach/Background: The program is implemented through the development of partnerships with in-country institutions who have ongoing and funded activities wherein renewable technologies can help them to achieve their goals. Examples include rural development and conservation organizations. Through the provision of technical assistance, training, and the implementation of pilot projects, the Sandia team works with these partners—and suppliers of systems—to help them build the institutional capacity to implement renewable energy projects.

Status/Accomplishments:
To date over 400 renewable energy systems have been installed representing a cumulative value of over 14 million kWh projected over a 20 year lifetime of the systems. 96% of these systems locally sustained and are functioning well. Each system installation was accompanied by training in which about 40 people on average were trained. The program is now entering a phase of replication and capacity building. Pilot projects are at a minimal. Replication refers to the replication of the program's successful system projects and demonstrations by program partners in Mexico on a large-scale. Capacity building is the proper training of our partners to carryout such system projects and programs. Focus is in 4 areas: agriculture (FIRCO has already started their $31 million RE for Agriculture program), protected environmental areas (working with SEMARNAP), tele-education (working with the Secretariat of Public Education with Telesecundaria projects), and off-grid, rural electrification (assisting the World Bank and the Secretariat of Energy to develop their Off-Grid, Rural Electrification Pilot Project in the states of Chihuahua and Quintana Roo).

Planned FY 2001 Activities:
Agriculture (FIRCO): Assist in organizing 28 PV water pumping workshop courses - each in a separate state plus an additional 4 regional courses, and 4 wind water pumping courses in southern Mexico. Produce and deliver one set of technical specifications for both PV and wind water pumping systems. Produce and deliver one set of training materials (master copy) for the PV and Wind workshops. Participate in at least 14 of the 28 PV water pumping workshops and 2 of the regional PV water pumping workshops by performing classroom concept and design presentations, and on-site installation, operation, and maintenance training. Participate in 3 or 4 wind water pumping courses by performing classroom concept and design presentations, and on-site installation, operation, and maintenance training. Provide technical assistance to FIRCO for PV and water pumping systems – design, installation, operation, and maintenance, outside of the trainings. Also technical assistance for new applications such as greenhouses and milk cooling. Provide technical assistance to FIRCO and local counterparts in the development of one or more pilot financing activity.

Off-Grid Rural Electrification: Identifying and defining applications of renewable energy technologies for this project in both the states of Quintana Roo and Chihuahua. Training of Secretariat of Energy program implementers (subcontractors in the states of Quintana Roo and Chihuahua), which includes verification testing and specification discussions. Evaluation of the Chihuahua home lighting systems that were installed in several communities in the state of Chihuahua. Evaluation will include system status, customer satisfaction surveys, and maintenance reports.

Contract #: DE-AC04-94AL85000

Protected Environmental Areas: Identify and define general renewable energy opportunities in the various zones of protected areas. Assist SEMARNAP in the system sizing and design to electrify the initial 5 field stations that must be completed by December 2000. Train SEMARNAP and subcontractor technicians in the design, installation, operation, and maintenance of renewable energy systems for various applications.

Tele-education: Perform assessments on presently installed PV systems and on the various operating power loads of Telesecundarias. Define and design a modular package design and provide technical specifications for Telesecundarias, recommending basic power system configurations and capacity/sizing. Develop system/component specifications for use in the public solicitation or limited solicitation Process. Advise on the companies that should be invited to submit bids, if limited solicitation is preferred. Train Telesecundaria technicians at the national and state levels in the selection, design, procurement, installation, operation, and maintenance of renewable energy systems that will be used in the rural schools. Assist Telesecundarias with the recommendation of energy efficient electronics and equipment models to reduce overall system cost by limiting power requirements. Provide assistance/advice concerning post-installation system acceptance tests.

Other: Collecting system information on existing pilot systems and replicated systems (installation site, specifications, maintenance, etc.) for program database. Evaluating database information to support communications. Document program activities, the progress of program partners, and to outreach to the public in the form of monthly reports, newsletters, webpage updating, external publications, and seminar presentations. Assess partner needs in Mexico and form a strategy plan. Assist program partners who are implementing large-scale replication programs with the development of a database management system that is compatible to the Mexico Renewable Energy Program database for tracking replicated projects. Finalize a national renewable energy training strategy in Mexico. Monitor and assess potential opportunities for large-scale replication projects of solar thermal water heating technology in Mexico, especially in planned governmental programs to implement such systems in low-income housing. Assist the Center of Energy Investigations/Mexican National Autonomous University (CIE/UNAM) in the development of an in-country renewable energy assistance center that is situated in the state of Morelos reaching into the neighboring states. Assist SEMARNAP and its counterparts to identify one or more potential sources of external funding for investment in the infrastructure for protected areas. Assist as an essential team member of the World Bank and Mexican Secretariat of Energy in the preparation and eventual approval of the Off-Grid Rural Electrification Project by the World Bank and the Global Environmental Facility (GEF). Contribute to the refurbishment and transfer of the Xcalak community hybrid system. Monitor and evaluate existing hybrids in Quintana Roo and Baja California Sur.

Major Reports Published in FY 2000:
E. Richards, C. Hanley, R. Foster, G. Cisneros, C. Rovero, L. Büttner, L. Ojinaga, S. Graham, C. Estrada, and O. Montufar, "Photovoltaics in Mexico: A Model for Increasing the Use of Renewable Energy Systems, "Advances in Solar Energy: An Annual Review of Research and Development, Volume 13, ISBN: 0-89553-256-5, ASES, Boulder, Colorado, 1999.

Major Articles Published in FY 2000:
C. Hanley, M. Ross, G. Cisneros, R. Foster, C. Briones, "Developing Sustainable Renewable Energy Markets in Mexico: Results and Future Challenges." ISES Millennium Solar Forum Proceedings, ANES, Mexico City, September 30 - Oct 3, 2000.

Thin-Film Technology Validation Study

Contract #: AAD-0-30604-02	**Contract Period:** 9/00–10/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Siemens Solar Industries 4650 Adhor Lane Camarillo, CA 93010	
	Organization Type: IN	**Congressional District:** 23
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dr. T. C. Tripathi **Phone:** 91-11-913-79207 **Fax:** 91-11-436-0764 **E-mail:** advtct@ren02.nic.in	
Technical Monitor: Jack L. Stone **Phone**: 303-384-6470 **Fax**: 303-384-6481 **E-mail**: jack_stone@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Ministry of Non-Conventional Energy Sources, government of India
	DOE Funding Allocation: 2000: $15,390	**Cost Share Funding:** 2000: $15,390

Project Objective: Undertake a detailed technology validation project for state of the art thin-film modules of the copper indium diselenide type.

Approach/Background: Approximately 3 kilowatts were competitively procured for installation and testing at the Solar Energy Centre in New Delhi, India. The sample modules were characterized at NREL and will be measured at the Solar Energy Centre to validate their characterization techniques.

Status/Accomplishments: The modules have been shipped to India and will be installed early in 2001

Planned FY 2001 Activities: Installation of the modules will be completed and testing will continue for an indeterminate amount of time to evaluate the performance of thin-films in the Indian environment.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

SWRES Mexico Support

Contract #: AT-7335	**Contract Period:** 6/4/96–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Southwest Technology Development Institute (SWTDI) Las Cruces, NM 88003-0001	
	Organization Type: CU	**Congressional District**: 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS-0752 Albuquerque, NM 87185-0752	**Principal Investigator(s)** Robert Foster **Phone:** 505-646-3948 **Fax:** 505-646-3841 **E-mail:** rfoster@nmsu.edu	
Technical Monitor: Michael P. Ross **Phone:** 505-844-3301 **Fax:** 505-844-7786 **E-mail:** mpross@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1998: $250,000 1999: $250,000 2000: $200,000	**Cost Share Funding:**

Project Objective: Provide technical and strategic support to the Mexico Renewable Energy Program (MREP).

Approach/Background: Provide renewable energy system technical support and training for MREP projects (pilot) and for partner projects (replication) in Mexico.

Status/Accomplishments:
- Technically assisted new system installations and trainings in 9 separate Mexican states.
- Trained 23 FIRCO trainers in PV water pumping system design, installation, operation, and maintenance.
- Developed a CD-ROM based PV water pumping guide.
- Trained 363 persons in 9 separate courses on the topics of PV water pumping, PV systems, and Mexican PV codes.
- Provided market and systems information and feedback in US industry.
- Updated and maintained the MREP webpage.
- Updated and maintained the MREP system installation and maintenance database.
- Provided monthly reports on all activities, project reliability studies, and market trend assessments.
- Monitored and reported on the Sunwize hybrid icemaker in Chorreras and the Solus direct drive PV refrigerator.

Planned FY 2001 Activities:
- Feasibility study on the Xcalak hybrid system.
- Telesecundarias PV System Analysis Results in Chihuahua.
- Feasibility report detailing recommendations for developing a distance learning program.
- Programmatic impact report.
- General program articles suitable for publishing in appropriate magazines and journals.
- Technical assistance and training to program partners (e.g. FIRCO, SEMARNAP, SEP).
- Act as primary contact point with the states of Baja California Sur and Chihuahua.
- Maintain program Spanish and English internet homepage.
- Maintain program database of installed program systems and partner systems.
- Monitor performance of: PV refrigerator, hybrid icemaker, Chihuahua lighting systems.

Contract #: AT-7335

Major Reports Published in FY 2000:
E. Richards, C. Hanley, R. Foster, G. Cisneros, C. Rovero, L. Büttner, L. Ojinaga, S. Graham, C. Estrada, and O. Montufar, "Photovoltaics in Mexico: A Model for Increasing the Use of Renewable Energy Systems," Advances in Solar Energy: An Annual Review of Research and Development, Volume 13, ISBN: 0-89553-256-5, ASES, Boulder, Colorado, 1999.

R. E. Foster, "Destilación Solar," Procedimientos del IV Seminario Binacional de Ahorro de Energía y Medio Ambiente, Colegio de Ingenieros Mecanicos, Electricistas, Electronicos y Ramas Afines del Estado de Chihuahua, A. C., Ciudad Juárez, Chihuahua, December 1-3, 1999.

Major Articles Published in FY 2000:
C. Hanley, M. Ross, G. Cisneros, R. Foster, C. Briones, "Developing Sustainable Renewable Energy Markets in Mexico: Results and Future Challenges." ISES Millennium Solar Forum Proceedings, ANES, Mexico City, September 30 - Oct 3, 2000.

A. Ellis, L. Estrada, C. Newcomb, D. Corbus, "Costa de Cocos Wind-Diesel Hybrid Power System." ISES Millennium Solar Forum Proceedings, ANES, Mexico City, September 30 - Oct 3, 2000.

L. Ojinaga, C. Rovero, R. Foster, A. Trespalacios, "Programa de Financiamiento para Energía Renovable en Chihuahua, México." ISES Millennium Solar Forum Proceedings, ANES, Mexico City, September 30 - Oct 3, 2000.

L. Estrada, R. Foster, A. Cota, "First Year Performance and Reliability of the Chorreras PV Hybrid System Ice-Maker in Chihuahua, Mexico." ISES Millennium Solar Forum Proceedings, ANES, Mexico City, September 30 - Oct 3, 2000.

O. Carrillo, "Difusión y Enseñanza de Tecnología de Energía de Renovables por Multimedia." ISES Millennium Solar Forum Proceedings, ANES, Mexico City, September 30 - Oct 3, 2000.

PV for International Applications

Ramakrishna Mission Initiative Impact Study

Contract #: AAD-0-30604-01	**Contract Period:** 12/99–12/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Tata Energy and Resources Institute 1600 Wilson Boulevard, Suite 500 Arlington, VA 22209	
	Organization Type: NP	**Congressional District**: 8
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dr. Pankaj Bhatia **Phone:** 703-841-1136 **Fax:** 703-243-1865 **E-mail:** teri@igc.org	
Technical Monitor: Jack L. Stone **Phone**: 303-384-6470 **Fax**: 303-384-6481 **E-mail**: jack_stone@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 2000: $39,950	**Cost Share Funding:**

Project Objective: Undertake a detailed evaluation study of the impact of PV systems installed in eight villages in the Sundarbans region of West Bengal, India. This study included social and economic impact on the system beneficiaries. The systems were installed under the auspices of a cost shared international cooperation between the Ministry of Non-Conventional Energy Sources (MNES), the government of India and NREL/DOE, the government of the United States. Three hundred PV powered domestic lighting systems have been successfully operated in the Sundarbans region of West Bengal since 1997. This study details the impact of these systems on the beneficiaries, including student study time, kerosene consumption and savings, effectiveness of supply and after sale service, nature and frequency of occurrence of faults in the systems, technical evaluation of the systems including detailed battery charging patterns, satisfaction of users, and summary of payment collection. The Ramakrishna Mission has been an excellent choice as the NGO responsible for administering the project and training the teams responsible for installing and maintaining the systems. Other applications such as battery charging stations, common area lighting, water pumping, and vaccine refrigeration were also evaluated.

Approach/Background: New global industries are emerging to provide electricity to the 2 billion people in the world who do not currently have access to adequate energy and communication services. For those villagers who are remote from the electric power grid or where there is an inadequate energy supply due to poor distribution and transmission, photovoltaics (PV) provides a reasonable alternative to traditional fossil fuels or batteries. In addition to being viable in single dwelling installations, mini or micro grids can also be used to service the small communities. Photovoltaic systems can be sized appropriately to meet the demand. There are many problems associated with providing a high tech solution to the end users who tend to be financially poor and minimally educated. This paper addresses a rural electrification project carried out under the auspices of a Memorandum of Understanding (MoU) between the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and India's Ministry of Non-Conventional Energy Sources (MNES). It has been designed to address these problems and to provide a sustainable approach for extending the application of the lessons learned to other areas of the world. The Ramakrishna Mission (RKM) is a well respected humanitarian NGO with operations worldwide. The RKM was chosen by MNES and NREL as the operating agent in the Sundarbans region of West Bengal. This area is an isolated region consisting of many islands with no access to conventional electrical services. The RKM provides a banking service as well as providing installation, training, and servicing and repair. Eight villages were chosen to receive various PV systems, including home lighting, common area lighting, water pumping, vaccine refrigeration, battery charging, and electrification of a weaving center. Beneficiaries were required to make a down payment on their PV systems, and repay low interest loans on the remaining amounts. Some 300 homes have received one fifty watt polycrystalline silicon PV panel and a battery/charge controller. Several youth clubs were provided lighting and TV connections. The entire project was funded with matching funds from India and the United States in equal amounts of $200,000.

Status/Accomplishments: NREL contracted with the Tata Energy Research Institute (TERI) in New Delhi to perform a before and after impact study in the region. Of particular interest were the impacts of PV lighting on student study habits, amounts of kerosene displaced, increased productivity (particularly by the women of the village), encouragement of entrepreneurship such as selling battery charging services, battery charge and discharge patterns, increased health maintenance from the lighting and vaccine refrigeration, and, of course, the reliability of the PV systems.

Contract #: AAD-0-30604-01

This impact study is the second done in the region after almost two years of use have passed. One hundred and fifty two domestic home lighting system users were surveyed. Of this group seventy six were evaluated for the first time. In addition to the individual home users, the systems in use at the village institutions were included. The systems performance has been surprisingly very good in view of the harsh environment such as monsoons, heat, and humidity. Of the 300 PV modules used by the home systems, two have been stolen and the rest are fully functional. Two of the 300 batteries have been removed and will be replaced. Two of the 300 charge controllers are non-functional. The acceptance of the PV systems is very high. However, 73% of the households surveyed reported a need for higher capacity systems mainly for additional lights, entertainment and fans. In almost all households, school age children study under the PV powered lights whereas before kerosene lamps had been the only option. Some 93% of the households report that security against theft is an important advantage. The average household reports a savings of approximately 7 liters of kerosene per month. The subsidized price of kerosene is Rs.3.50 per liter or Rs.10-12 per liter on the open market. Batteries typically represent the weak link for domestic PV systems. The set points for the charge controllers were purposely fixed so that the users couldn't set the charge and discharge rates beyond the recommended values. The battery charging patterns are typically 10-15 Ah per day. The condition of the surveyed batteries was found to be very good, including the casing, terminals and battery box. PV modules were found to be in good condition. There have been some problems with repositioning of the modules from true south due mainly to the instability of mounting on thatched roofs. Some shadowing has occurred over the past several years due to rapid growth of the area trees.

One of the objectives of the RKM initiative was to make it self-sustaining and capable of being replicated, not only in the surrounding villages, but also in other developing countries in the world. MNES in conjunction with the West Bengal Renewable Energy Development Agency (WBREDA) has installed an additional 2000 systems in the Sundarbans, making this one of the largest and successful PV rural electrification projects in the world. One of the most important factors appears to be the association with RKM. The Mission has been very successful in training installers and providing maintenance on site. In addition, they have maintained the financing and repayment schedules for the beneficiaries. Payment collection as been 88%. The village with the poorest record is attributable to the lack of a local technician, hence, customer satisfaction is low.

Planned FY 2001 Activities: Pending availability of funds, the PV system beneficiaries will continue to be monitored. A technology evaluation project utilizing thin-film, PV modules/systems will be proposed. A detailed training program will be required for installation and maintenance of these state-of-the-art PV systems.

Major Reports Published in FY 2000:
"Ramakrishna Mission Initiative Impact Study", Final Report, A. Chaurey, TERI, New Delhi, India, June, 2000, NREL Report NREL/SR-520-28601.

Major Articles Published in FY 2000:
J. Stone, H. Ullal, A. Chaurey, and P. Bhatia, "Ramakrishna Mission Initiative Impact Study — A Rural Electrification Project In West Bengal, India", *28th IEEE PV Specialists Conference,* Anchorage, AK, 17-22 September 2000.

Evaluation of Intermediate Applications for Photovoltaics in the United States and Developing Countries

Contract#: XCU-7-16806-01	**Contract Period:** 6/1/97–10/31/00

<table>
<tr><td>Sponsoring Office Code: EE-13</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">University of Delaware
Center for Energy and Environmental Policy
Newark, DE 19716</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
J. Byrne
Phone: 301-831-8405 Fax: 302-831-3098 E-mail: jbbyrne@udel.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Debra Lew
Phone: 303-384-7522
Fax: 303-384-7419
E-mail: Debra_Lew@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1996: $125,000 2000: $0
1998: $ 22,575
1999: $ 47,908</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The project focus is to complete the rural electrification survey and analysis project in China.

Approach/Background: In FY 1999, the subcontractor collaborated with the Chinese Ministry of Agriculture (MOA) and the Chinese Ministry of Sciences to collect data and perform analyses from a technical and socio-economic survey of several counties in Inner Mongolia, Xinjiang, and Qinghai provinces in China. Analyses consisted of evaluating rural electrification options and performing market characterizations for the northwestern region of China. MOA also visited the University of Delaware for training in analysis techniques and conducted some analysis of the survey data during this visit.

Status/Accomplishments:
- Draft report of *Off-Grid Renewable Energy Options for Rural Electrification in Western China* prepared and reviewed.

Planned FY 2001 Activities: Publication of final report as hardcopy and on website.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Outreach and Program Management

Solar Energy Information Materials - Million Solar Roofs Initiative

Contract #: DE-FG01-99EE10705	**Contract Period:** 9/29/99–6/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.doe.gov	American Solar Energy Society (ASES) 2400 Central Avenue, Suite G-1 Boulder, CO 80301	
	Organization Type: NP	**Congressional District**: 2
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator** Larry Sherwood **Phone:** 303-443-3130 **Fax**: 303-443-3212 **Email**: LSherwood@ases.org	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2202	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $96,305 2000: $0	**Cost Share Funding:**

Project Objective: This project was initiated as part of the Million Solar Roofs Initiative and aimed at providing Million Solar Roofs Partnerships and others with high quality, consistent solar energy information materials.

Approach/Background: The American Solar Energy Society (ASES) and the North Carolina Solar Center (NCSC) will jointly research and report on existing solar information materials and then develop a series of print and web-based brochures for different solar technology applications.

Status/Accomplishments:
- Conducted survey of Million Solar Roofs partners on their content of the printed materials and future website, and how the partners might use the materials to enhance their MSRI programs.
- Surveyed existing relevant public information brochures and websites.
- Developed 7 draft public information brochures on Million Solar Roof Initiative technologies.
- Began to develop companion website.

Planned FY 2001 Activities:
- Complete final reviews for 7 public information brochures and deliver final art for printing.
- Complete companion website

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Outreach

Photovoltaic Systems Monitoring Program

Agreement#: DE-FG01-99EE35087	**Contract Period:** 6/1/99–9/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Dan Ton **Phone:** 202-586-4618 **Fax:** 202-586-8148 **E-mail**: Dan.Ton@ee.doe.gov	State of California, California Energy Commission (CEC) 1516 Ninth Street, MS-1 Sacramento, CA 95814	
	Organization Type: ST	**Congressional District:** 5
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Sanford Miller **Phone:** 916-653-2834 **Fax:** 916-653-2543 **E-mail**: smiller@energy.state.ca.us	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code**: EB2202	**Cost Share Information**: CEC
	DOE Funding Allocation: 1999: $135,249 2000: $0	**Cost Share Funding:** 1999: $135,250 2000: $0

Project Objective: The objective of the project is to collect and analyze data on PV and other emerging renewables (ER) capacity additions and performance, so that policy makers and industry stakeholders can have consistent, comparative information on the trends in sizes, capacity factors and electricity production over the crucial transition period. This data forms the fundamental and primary measure of assessing technology development. When analyzed in conjunction with other information (such as financial incentives, electric industry restructuring), this information can provide insights for program and policy development. This information and analyses will assist stakeholders (financiers, developers, energy service companies) directly involved with emerging renewable power project development and marketing. It can also be used to provide end-users with more information on PV technologies.

Approach/Background: The analysis will be primary based on the empirical data on system types, capacity additions and electricity production resulting from California's $54 million Emerging Renewables Buydown Program. Recipients of Buydown Program will be asked to participate in the monitoring program. Monitoring equipment will be installed at the premises to record daily operating information including generation and customer demand. Customers will also be requested to complete questionnaires on customer satisfaction. The survey and operating data will become part of a baseline for evaluation of market acceptance, dependability and reliability analyses.
The monitoring program results will eventually become a part of the baseline information that can:

- Enable assessment of seasonal and weather-based variations in production by geographic region;
- Enable assessing future production when PV and other ER systems are operated in response to competitive market conditions;
- Permit analysis of capability of various system sizes to meet customer demands;
- Offer insights into cost-effective requirements necessary for systems to gain market acceptance; and,
- Provide better understanding how expanded development of small, distributed generation systems will affect the electricity marketplace

Status/Accomplishments: The California Energy Commission (CEC) has completed Phase 1 of the project which included monitoring installation of data acquisition systems (DAS) and monitoring of 15 PV systems. A draft Phase 1 report has been completed. During the period, CEC obtained system performance data from Southern California Edison. This data will supplement the data obtained by CEC and incorporated into the Phase 1 results. Phase 2 will include re-installation of the DAS and monitoring of an 15 additional systems. To complete Phase 2, the CEC requested and was granted a one-year extension of the grant.

Planned FY 2001 Activities: During FY 2001, CEC will re-install the 15 data acquisitions systems on 15 existing PV systems and perform monitoring and data collection. Submittal of the Phase 1 draft report is expected December 2000.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Photovoltaics for You (PV4You)

Contract #: DE-FG01-99EE35084	**Contract Period:** 7/9/99–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **PPhone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.doe.gov	Interstate Renewable Energy Council P.O. Box 1156 Latham, NY 12110	
	Organization Type: NP	**Congressional District**: 21
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** J. Weissman **Phone:** 617-323-7377 **Fax:** 617-325-6738 **Email:** WeissmanPV@aol.com	
Technical Monitor: Same as Program Manager	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $600,000 2000: $0	**Cost Share Funding:**

Project Objective: To develop and distribute information on PV and to educate key stakeholder groups including state government agencies, local government offices, consumer representative agencies, school officials and students. PV4You brings stakeholders together to build awareness and understanding; identifies barriers to the deployment of photovoltaics and strategies to overcome them; and provides assistance leading to accelerated adoption of off-grid and grid-connected PV.

Approach/Background: This project consisted of six core actions. 1) Ongoing support and assistance for the PV4You State working groups and network. 2) PV4You Outreach to Cities Project encourages incorporation of PV into city programs for affordable housing, job training, and the environment. 3) The PV4You National Consumer Project provides assistance and information to on PV to consumer agencies. 4) The PV4You Solar Schools Project is to educate teachers, students, and school officials about solar energy. 5) The PV4You National Public Education Project is aimed at keeping PV4You stakeholder network well informed give them the tools to increase awareness of PV among public and private decision makers. 6) The PV4You Project on PV Interconnection to the Grid provides general and technical information on interconnection issues to key stakeholders.

Status/Accomplishments: The PV4You program continues to reach hundreds of state and local officials, key energy players and communities with monthly communications, web-based material, and meetings targeted at different stakeholder groups. The PV4You *Schools Going Solar* Project deals with hundreds of teachers, students, and communities and supports a special web site www.schoolsgoingsolar for school and community officials. The PV4You National Consumer Project deals with state-appointed consumer representatives throughout the country and supports a special web site www.spratley.com/ncp/, which operates PV Net, an electronic bulletin board message center. The *Going Solar* public education campaign hosts a network of over 200 organizations and agencies and offers a web site at www.goingsolar.org bringing brochures, fact sheets, videos, public service announcements and more to sample and download, then copy and distribute. Along with energy news and tools, resources, and easy-access information, the www.irecusa.org web site hosts a special section on interconnection issues and includes the “Connecting to the Grid” Guide, monthly Interconnection Newsletters, the State-By-State Interconnection Table, and an on-line library.

The PV4You *Connections* newsletter was published twice – in the Fall of 1999 and the Spring of 2000. This publication has grown to 20 pages with 4 sections: State News, School Beat, City Side, and Across the Nation. Twelve issues of the PV4You Monthly Memo, the Schools Going Solar Letter, and the Interconnection Monthly Newsletter were published electronically. Six issues of the PV4You Consumer Letter were published.

Four Workshops were held. An Interconnection Workshop was held in Richmond, Virginia at Old Dominion Electric Cooperative on September 30, 1999. On April 26, 2000, the Ohio Communities Going Solar Workshop was held in Columbus, Ohio. On May 15, 2000, the New Jersey Communities Going Solar Workshop was held in Trenton, New Jersey. On June 16, 2000, the Interconnection of Renewables to the Grid Workshop was held at the Dane County Expo Center in Madison, Wisconsin.

Contract #: DE-FG01-99EE35084

On Sunday, June 18, 2000, IREC and the PV4You Program held its annual meeting. This all-day event attracted over 50 attendees representing cities and states, the federal government (DOE and EPA), the National Renewable Energy Laboratory, national solar organizations, and other interested parties.

The 1999 PV4You Bibliography INDEX was published in December. The INDEX cites some of the market-related, photovoltaic documents published in 1999.

Two National PV Stakeholders (formerly called PV-COMPACT) meetings were held – one on October 3, 1999 and the other on March 4, 2000.

The *Going Solar* Model Education Kit was released in December 1999. One hundred and fifty kits were assembled and distributed to the PV4You state and local networks, national stakeholders, and ASES state and student chapters.

PV4You Program team members participated in the following events:

- NARUC Summer Meeting – July '99
- NASEO Annual Conference – September '99
- UPEx Conference – IREC Session with PV4You Project Staff - *Trends In Policy And Community Issues* – October '99
- NESEA Teachers Conference - *Teaching Today's Skills with Tomorrow's Technologies* – November '99
- NASUCA Annual Conference –November '99
- NARUC Annual Conference – November '99
- Renewable Energy Session at the *Design & Construction 2000 – Sustainable Products Trade Show* in Philadelphia – Nov '99
- PTI UC Energy Task Force 3 day meeting. January 2000
- Green Energy Parks Conference. January 2000
- NESEA Building Energy 2000 Conference. March '00 in New Haven
- Green Building Conference & PTI Conference. April '00
- National Science Teachers Association. April – Exhibit & Session.
- ASES Solar 2000 Conference. June '99
- NASEO Winter Meeting. February '00
- NARUC Winter Meeting. March '00
- NACO Winter Meeting. March '00
- NASUCA Summer Meeting. June '00

Planned FY 2001 Activities:
There are no planned activities under this contract since it is ending December 31, 2000. Activities from October-December 2000 are covering final administrative and program tasks.

Major Reports Published in FY 2000:
Third Edition of the PV4You "Connecting to the Grid: A Guide to PV Interconnections Issues." Spring 2000. Authors: Chris Larsen, Bill Brooks, and Tom Starrs.

Major Articles Published in FY 2000:
Utility Interconnection: Keep it Standardized, Stupid! Authors: Tom Starrs, Kelso Starrs & Associates, LLC and Chris Larsen, North Carolina Solar Center. ASES 2000 Solar Conference. June 2000.

"PV Goes To School." June 2000 Issue of the CADDET Renewable Energy Newsletter. Author: Vicki Mastaitis.

"Energy Supply Disruptions When Disaster Strikes: PV Supplying Power for the Community." June 2000 PTI PRISM electronic newsletter. Author: Jack Werner.

Photovoltaics for You (PV4You)

Contract: # DE-FGO3-00SF22116	**Contract Period:** 9/1/00–8/31/03

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.doe.gov	Interstate Renewable Energy Council P.O. Box 1156 Latham, NY 12110	
	Organization Type: NP	**Congressional District**: 21
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** J. Weissman **Phone:** 617-323-7377 **Fax:** 617-325-6738 **Email:** WeissmanPV@aol.com	
Technical Monitor: Same as Program Manager	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $0 2000: $550,000	**Cost Share Funding:**

Project Objective: To develop and distribute information on PV and to educate key stakeholder groups including state government agencies, local government offices, consumer representative agencies, school officials and students. PV4You brings stakeholders together to build awareness and understanding; identifies barriers to the deployment of photovoltaics and strategies to overcome them; and provides assistance leading to accelerated adoption of off-grid and grid-connected PV.

Approach/Background: This project covers six core outreach areas: 1. On-going support and assistance for the PV4You state groups and stakeholder outreach activities and the national stakeholder network and forums. 2. Provide educational assistance to state-appointed consumer representatives in understanding technical aspects of photovoltaics in newly competitive electricity markets and residual regulated monopolies. 3. Assist community leaders in linking the development of photovoltaic options to local government needs such as distributed power and off-grid applications and to encourage the use of photovoltaics as part of solutions to community issues. 4. Educate teachers, students, school officials and the public about solar energy and the benefits of locating solar hardware on schools and integrating the hardware with math and science studies and other subjects. 5. Keep the national PV4You network well informed, up-to-date and prepared with educational tools and materials to facilitate photovoltaic market growth. 6. Provide both general and technical information and support where efforts are being made to simplify and streamline the interconnection of PV systems to the utility grid.

Status/Accomplishments: This contract has just started so activities are forthcoming.

Planned FY 2001 Activities: The following outreach and educational projects will carry on: PV4You Schools *Going Solar*, the PV4You National Consumer Project, the *Going Solar* educational campaign, the PV4You Project on PV Interconnection to the Grid. PV4You will work, coordinate, and collaborate with state, local and community stakeholders and with national organizations. Deliverables and activities include:

- 12 News & Update Memos for the PV4You State, Local, and National Networks (electronic: monthly).
- 12 Interconnection Issues Newsletters (electronic: monthly).
- 12 Schools *Going Solar* Newsletters (electronic: monthly).
- 6 PV Consumer Letters (hardcopy & electronic: every other month or released for conferences).
- 12 *Going Solar* (Public Education) Newsletters (electronic: monthly).
- 1 edition of the PV4You *CONNECTIONS* Newsletter (hardcopy/Spring 2001) with four sections: State News, City Side, School Beat, and Across the Nation.
- Maintenance and upgrade of 4 web sites (irecusa.org, schoolsgoingsolar.org, spratley.com/ncp, and goingsolar.org)
- 2 Interconnection Workshops (to be scheduled).

Contract: # DE-FGO3-00SF22116

Planned FY 2001 Activities (continued):
- Annual Meeting for state and city officials and the PV4You Network (April 22, 2001).
- Coordination with national organizations and stakeholders (on-going).
- Periodic Consumer Conference Calls (3-4 per year).
- Needs Assessment Survey for NASUCA members.
- *Going Solar* community-friendly, public service educational material.
- 2 Articles and Papers.

Major Reports Published in FY 2000: n/a

Major Articles Published in FY 2000: n/a

Outreach

PV Program Information Dissemination to Enhance PV's Commercial Potential

Contract #: DE-FG01-99EE35083	**Contract Period:** 5/12/99–5/12/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.hq.gov	National Association of Regulatory Utility Commissioners 1100 Pennsylvania Ave. NW STE 603 Washington, DC 20004	
	Organization Type: NP	**Congressional District**: NA
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Andrew Spahn **Phone:** 202-898-2217 **Fax:** 202-898-2213 **Email:** aspahn@naruc.org	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2202	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $ 50,000 2000: $ 0	**Cost Share Funding** 2000: $ 50,000

Project Objective: To develop and distribute information that will enhance PV's commercial potential through the National Association of Regulatory Utility Commissioners (NARUC) participation in a national photovoltaic collaborative whose goal is to develop and distribute photovoltaic (PV) educational materials and tools targeted to the needs of State and local officials.

This project's specific objectives are:
- To facilitate the participation of state regulators and key staff in the PV Compact's Coordination Council and Working Groups;
- To enable regulators to work with other stakeholders to develop and distribute critical educational information and tools about PV and the need for interconnection rules and standards that will make it possible for continued growth of PV resources; and
- To enable those regulators and key staff participating in the PV Compact to disseminate the information developed by the PV Compact among other state regulators and key staff nationwide.

Approach/Background: This project includes several activities that will assist state public utility regulators as they work with other stakeholders in a photovoltaics collaborative. The project facilitates participation of state regulators in PV Compact meetings, facilitates work on interconnection regulation issues, and enables dissemination of information from PV compact and interconnection work to state regulators nationwide.

NARUC has developed three specific tasks that it will undertake to accomplish the above project objectives. These tasks are: 1) Participate in the PV Compact's Coordination Council; 2) Participate in the PV Compact's Working Groups; and 3) Communicate with the Regulatory Community. These are described briefly below.

Task 1: Participate in the PV Compact's Coordination Council
Regulatory commissioners and key staff will need to prepare for and attend the PV Compact's Coordination Council meetings. We anticipate three (3) meetings of the Coordination Council during FY 2000. Five (5) State public utility commissioners, commission staff, and other NARUC representatives will be permanent members to the PV Compact, in addition to occasional participation of other commissioners and staff who may attend meetings as observers from time to time.

Several consulting tasks are required. The consultant should provide analytic and research support for the regulators. The consultant should coordinate communications between and among the regulators involved in the PV Compact. By means of regular conference calls, faxed materials, and individual communications, the consultant should provide the communications links so the regulators can reach consensus among themselves on the issues to be addressed at PV Compact Coordination Council sessions. To maximize the benefits of the regulators' participation in these sessions, the consultant should also provide follow-up support to the regulators on issues which require attention after PV Compact Coordination Council meetings.

Task 2: Participate in the PV Compact's Working Groups
Reasonable, fair, and predictable interconnection standards and policies will be the focus of the PV Compact's Interconnection Rules and Standards Working Group. State regulators will need to take a leadership role in the work of this Group. It is crucial that NARUC representation is involved in this important endeavor (including the tasks related to technical interconnection standards as well as non-technical interconnections contracts, terms, and conditions).

Contract #: DE-FG01-99EE35083

Restructuring policy issues will be addressed by a focused working group. Specific issues to be addressed by this Working Group include: restructuring legislation and regulation, restructuring standards, net metering, system benefit charge rules, and other distributed energy technologies. Implementation of State mandated policies regarding PV and other renewables offer opportunities for coordination, cooperation, and synergies as States work together to implement wires charges and portfolio standards. In the thirty States with net metering legislation or policies, there are implementation issues that can be assisted with coordinated approaches developed under the PVCompact framework.

PV faces the same regulatory issues as are faced by other forms of distributed resources. These may arise in either traditional, vertically integrated utilities under State commission regulation or be found where States are implementing restructuring of their electric utilities. Distributed resources such as PV face similar market and institutional barriers as those facing DSM. Whether in utilities focusing on new internal business units or in states with markets restructured to provide for generation customer choices, relationships between customers who can cut loads or produce their own electricity and the regulated distribution wires business are new, complex, and slow to emerge.

State regulators will also be key players in the PVCompact Education Working Group due to their roles and responsibilities for educating consumers of their choices in electric restructuring. Regulators will also need to be involved in the PVCompact review of the proposals and products of the other Working Groups.

Similar consulting support will be required to help with the analytic, research, communications, and coordination tasks regulators will face as participants in the PV Compact Working Groups.

Task 3: Communicate with the Regulatory Community
A key task for the regulators will be to actively communicate the progress achieved in the work of the PV Compact to the regulatory community and to bring to the PV Compact the concerns of regulators. This communications process will be critical in ensuring the acceptance of PV energy in the electric sector in each state.

Status/Accomplishments:

- NARUC organized the regulatory aspects of the PV Stakeholders Issues Forum/ 2000 PV Experience Conference - October 1-5, 2000 in Baltimore, MD
- NARUC organized the regulatory aspects of the PV Stakeholders Meeting - March 4, 2000 in Washington, DC
- NARUC organized a Renewable Energy Panel (focusing on regulatory aspects of PV implementation) in conjunction with the NARUC Distributed Resources Workshop in Santa Fe in June, 2000.
- NARUC experts participated in the Annual Conference of the American Solar Energy Society in Madison, Wisconsin, in July, 2000. This annual meeting is another key venue for coordination between regulators
- and the rest of the PV community.

Planned FY 2001 Activities:

- One (1) PV Compact Coordination Meetings – Location TBD

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Outreach

PV Program Information Dissemination to Enhance PV's Commercial Potential

Contract #: DE-PS01-00EE10722-1B	**Contract Period:** 5/1/00–4/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.hq.gov	National Association of Regulatory Utility Commissioners 1100 Pennsylvania Ave. NW STE 603 Washington, DC 20004 **Organization Type**: NP	**Congressional District**: NA
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Andrew Spahn **Phone:** 202-898-2217 **Fax:** 202-898-2213 **Email:** aspahn@naruc.org	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2202	**Cost Share Information**: None.
	DOE Funding Allocation: 2000: $ 102,852	**Cost Share Funding** 2000: $ 50,000

Project Objective: To develop and distribute information that will enhance PV's commercial potential through the National Association of Regulatory Utility Commissioners (NARUC) participation in a national photovoltaic collaborative whose goal is to develop and distribute photovoltaic (PV) educational materials and tools targeted to the needs of State and local officials.

This project's specific objectives are:

- To facilitate the participation of state regulators and key staff in the PV Compact's Coordination Council and Working Groups;
- To enable regulators to work with other stakeholders to develop and distribute critical educational information and tools about PV and the need for interconnection rules and standards that will make it possible for continued growth of PV resources; and
- To enable those regulators and key staff participating in the PV Compact to disseminate the information developed by the PV Compact among other state regulators and key staff nationwide.

Approach/Background: This project includes several activities that will assist state public utility regulators as they work with other stakeholders in a photovoltaics collaborative. The project facilitates participation of state regulators in PV Compact meetings, facilitates work on interconnection regulation issues, and enables dissemination of information from PV compact and interconnection work to state regulators nationwide.

NARUC has developed three specific tasks that it will undertake to accomplish the above project objectives. These tasks are: 1) Participate in the PV Compact's Coordination Council; 2) Participate in the PV Compact's Working Groups; and 3) Communicate with the Regulatory Community. These activities are below.

Task 1: Participate in the PV Compact's Coordination Council
Regulatory commissioners and key staff will need to prepare for and attend the PV Compact's Coordination Council meetings. We anticipate three (3) meetings of the Coordination Council during FY 2000. Five (5) State public utility commissioners, commission staff, and other NARUC representatives will be permanent members to the PV Compact, in addition to occasional participation of other commissioners and staff who may attend meetings as observers from time to time.

Several consulting tasks are required. The consultant should provide analytic and research support for the regulators. The consultant should coordinate communications between and among the regulators involved in the PV Compact. By means of regular conference calls, faxed materials, and individual communications, the consultant should provide the communications links so the regulators can reach consensus among themselves on the issues to be addressed at PV Compact Coordination Council sessions. To maximize the benefits of the regulators' participation in these sessions, the consultant should also provide follow-up support to the regulators on issues which require attention after PV Compact Coordination Council meetings.

Task 2: Participate in the PV Compact's Working Groups
Reasonable, fair, and predictable interconnection standards and policies will be the focus of the PV Compact's Interconnection Rules and Standards Working Group. State regulators will need to take a leadership role in the work of this Group. It is crucial that NARUC

representation is involved in this important endeavor (including the tasks related to technical interconnection standards as well as non-technical interconnections contracts, terms, and conditions).

Restructuring policy issues will be addressed by a focused working group. Specific issues to be addressed by this Working Group include: restructuring legislation and regulation, restructuring standards, net metering, system benefit charge rules, and other distributed energy technologies. Implementation of State mandated policies regarding PV and other renewables offer opportunities for coordination, cooperation, and synergies as States work together to implement wires charges and portfolio standards. In the thirty States with net metering legislation or policies, there are implementation issues that can be assisted with coordinated approaches developed under the PVCompact framework.

PV faces the same regulatory issues as are faced by other forms of distributed resources. These may arise in either traditional, vertically integrated utilities under State commission regulation or be found where States are implementing restructuring of their electric utilities. Distributed resources such as PV face similar market and institutional barriers as those facing DSM. Whether in utilities focusing on new internal business units or in states with markets restructured to provide for generation customer choices, relationships between customers who can cut loads or produce their own electricity and the regulated distribution wires business are new, complex, and slow to emerge.

State regulators will also be key players in the PVCompact Education Working Group due to their roles and responsibilities for educating consumers of their choices in electric restructuring. Regulators will also need to be involved in the PVCompact review of the proposals and products of the other Working Groups.

Similar consulting support will be required to help with the analytic, research, communications, and coordination tasks regulators will face as participants in the PV Compact Working Groups.

Task 3: Communicate with the Regulatory Community
A key task for the regulators will be to actively communicate the progress achieved in the work of the PV Compact to the regulatory community and to bring to the PV Compact the concerns of regulators. This communications process will be critical in ensuring the acceptance of PV energy in the electric sector in each state.

Status/Accomplishments:
No work has been completed under this agreement, however it is anticipated that activities will produce the following deliverables:

- Regulatory input into PV Compact documents that outline critical issues associated with PV.
- Regulatory input into PV Compact documents that will be used to educate consumers about photovoltaics.
- Participation of State regulators and staff in meetings of the PV Compact's Coordination Council and Working Groups.
- Regular reports on the PV Compact's work provided at meetings of the NARUC Committee on Energy Resources and the Environment.
- An annual written report for regulators that includes a summary of PV Compact activities and specific recommendations for future regulatory actions to enhance the development of PV resources.

Planned FY 2001 Activities:

- NARUC will organize and participate in three (3) PV Compact Coordination Meetings – Location TBD
- NARUC will actively participate in the 2001 Photovoltaic Experience Conference & Exhibition (UPEx '01) Sacramento, CA

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Removing CC&R Barriers to Residential and Commercial Solar Energy

Contract #: DE-FG01-99EE10704	**Contract Period:** 9/15/99–9/15/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.doe.gov	Pace University School of Law 78 North Broadway White Plains, NY 10603	
	Organization Type: CU	**Congressional District**: 19
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Fred Zalcman **Phone:** 914-422-4082 **Fax:** 914-422-4180 **Email:** fzalcman@law.pace.edu	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2202	**Cost Share Information**: Pace University School of Law
	DOE Funding Allocation: 1999: $88,470 2000: $0	**Cost Share Funding:** 1999: $14,280 2000: $0

Project Objective: This project was initiated as part of the Million Solar Roofs Initiative and aimed at removing barriers to building-related solar energy use. The specific objective are to:

- Improve understanding of codes covenants and restriction and how they may adversely impact solar installations.
- Provide a legal and conceptual framework for recognizing legitimate local aesthetic and economic interests without unduly restricting solar installations.
- Offer practical advice to homeowners and businesses on navigating the design approval process.
- Assess the effectiveness of existing laws intended to restrict the preclusive effect of codes covenants and restrictions.

Approach/Background: The Pace University project team's goal is to educate and influence the many parties interested in or affected by local codes covenants and restriction. They will develop a handbook and a model workshop. They will demonstrate these resources at a series of at least four workshops in communities that have strong barriers to solar energy.

In preparing these deliverables, the project team's basic legal research has been supplemented by the practical experiences of those most familiar with the effects of architectural controls on solar use. In February 2000, a telephone survey of 13 solar contractors in Arizona, California and Florida was conducted. Solar contractors and other companies who sell solar systems directly to the homeowner must work with both the prospective solar system purchaser and, in many cases, the association's approval entity in order to complete the sale and install the system consistent with the rules of the association. These interviews offered important insights which were applied in the recommendations and approaches offered in workshops and in the homeowner handbook.

Status/Accomplishments:
The Pace University's project team has delivered a draft final handbook entitled "Bringing Solar Energy to the Planned Community". The final handbook will be delivered to DOE in mid-December. The emphasis throughout this Handbook is in providing accurate, authoritative and practical information that the homeowner can use in seeking design approval for his system. This fills a distinct need, as relatively little has been written about the interaction of residential solar system design and the community's aesthetic review process. The Handbook and workshop materials provides the following resources:

- an overview of the law of restrictive covenants and the myriad ways they may impact solar energy systems. The information is primarily intended to address the questions that homeowners will have about CC&Rs, but will be useful as well to the legal practitioner unfamiliar with solar systems, the law of public and private land use restrictions, or both.
- a "roadmap" to guide the homeowner through the steps leading up to Architectural Review Committee approval. The Handbook suggests ways to improve the prospects for the solar homeowner reaching an amicable resolution with the Architectural Review Committee.
- several proactive strategies that can be taken by Million Solar Roof Partnerships to overcome local barriers. These strategies fall into two main categories – legislative and education – and are based on successful strategies being implemented in areas of the country where CC&R restrictions have been most acute.

Contract #: DE-FG01-99EE10704

Status/Accomplishments (continued):

- a reference guide to the state laws that have been enacted to limit the demands the association can place on solar systems through its CC&Rs, as well as a model state law.
- several form letters and legal documents. This should be used in conjunction with the legal strategies set out in the Handbook. The homeowner can customize these documents to the particular facts surrounding his interactions with the Architectural Review Committee.
- contact information for organizations and individuals the homeowner may wish to consult regarding planned solar systems.

Major Reports Published in FY 2000:

F. Zalcman, T. Starrs, L. Nelson, M. Neary, and C. Kettles, (2000), "Overcoming Private Land Use Restrictions to Solar Energy Systems", 7 pp., American Solar Energy Society Solar 2000 Conference Proceedings, Boulder, CO.

Outreach

Renewable Energy Technology Analysis (RETA)

Contract #: DE-FG01-99EE35085	**Contract Period:** 6/9/99–6/8/03

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail:** Richard.King@ee.doe.gov	Pace University Law School 78 North Broadway White Plains, NY 10603-3710	
	Organization Type: CU	**Congressional District**: 19
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** S. Swanson **Phone:** 802-652-0056 **Fax:** 802-658-0563 **Email:** Samswanson@aol.com	
Technical Monitor: Lynne Gillette **Phone**: 202-586-1495 **Fax**: 202-586-8148 **Email**: Lynne.Gillette@ee.doe.gov	**B&R Code**: EB22	**Cost Share Information**: Pace Univ. School of Law
	DOE Funding Allocation: 2000: $199,970	**Cost Share Funding:** 2000: $117,372

Project Objective: In coordination with other groups working on PV outreach, Pace University will

- provide objective information aimed at converting consumer preferences for "green" electricity into actual purchases of PV
- provide technical support to environmental organizations and, with the support from the Director of PV4U, to other PV stakeholders, including consumer groups, utility regulatory agencies, and retail electricity service providers
- provide focused technical support to environmental organizations that have the potential to address obstacles to PV use in states which offer the greatest opportunity to achieve significant PV commercialization benefits.

Approach/Background: The RETA Project aims to tap support within the extensive number of environmental NGO's nationally to promote increased use of PV. Pace University will provide technical support to a variety of stakeholders through the PV Clearinghouse to assist these organizations in their efforts to remove market barriers to PV. The RETA Project is contributing to the environmental organization based consumer information campaign to advance investments in Solar and other clean renewable power sources. The development of the web-based analysis tool "Power Scorecard" (see www.powerscorecard.org) was a major focus of work in FY 2000, but is now complete. The Power Scorecard helps consumers identify and select electricity options that depend on PV and other low environmental impact electricity generation.

Status/Accomplishments: During this period the RETA Project made completing and launching the Power Scorecard consumer education tool a top priority. This enabled the RETA Project to move the Power Scorecard forward to the threshold of public release. The RETA Project largely achieved the Power Scorecard education objectives supported by this grant -- i.e, the development of a consumer education tool that helps consumers

- understand the environmental benefits of PV based electricity supplies
- identify the electricity service options that use PV supplies
- purchase electricity supplies that use PV to serve their customers.

The development of the solar components of the tool is complete

During 2000 the RETA Project

- completed the development of the **Power Scorecard** environmental education tool,
- completed a demonstration test of the rating tool using retail electricity service products offered residential consumers in California and Pennsylvania,
- obtained sponsor support from six major environmental education organizations,
- designed the Internet web site that hosts this rating tool, consulted with many diverse stakeholders on the rating system design, and
- announced the public release of rating tool on the web site www.powerscorecard.org for retail electricity services in California and Pennsylvania.

As explained below the Power Scorecard will be sustained subsequently by its environmental organization sponsors.

Contract #: DE-FG01-99EE35085

Status/Accomplishments (continued):
PV Clearinghouse: During FY 2000 the RETA Project worked with the recently established Independent System Operator (ISO) for the New York Power Pool to develop practices to recognize the potential capacity value offered by distributed PV installations and other intermittent resources base electric generators. This work is designed to ensure that PV will receive fair economic treatment in the new competitive wholesale electricity markets. The RETA Project supported a Florida environmental organization in its effort to promote the development of "green pricing" programs that enable consumers to by PV generated electricity from their utility. The RETA Project collaborated with PV4You and other PV market stakeholders in efforts to improve the effectiveness of the efforts of the individual stakeholders in accelerating the market penetration of PV technology.

Planned FY 2001 Activities: Having achieved the development of the Power Scorecard and having obtained sustaining sponsorship from some of the nation's largest and most influential environmental organizations, the Pace Law School Energy Project decided to move the Power Scorecard to other sources of funding and to redirect the RETA Project. In the future the Power Scorecard will be sustained by the sponsors – i.e., the Pace Law School Energy Project, Environmental Defense, Izaak Walton League of America, Natural Resources Defense Council, Northwest Energy Coalition, and the Union of Concerned Scientists.

The RETA Project has shifted its focus to address the PV Clearinghouse which provides technical support to environmental organizations to assist their efforts to promote the increased use of solar energy to meet our nation's electricity needs. In a June 27, 2000 conversation with US DOE's James E. Rannels, Director of the Office of Solar Energy Technologies, and Lynne Gillette, Photovoltaics Program Manager in the Office of Solar Energy Technologies, we reported these plans to make these changes in the RETA Project work program.

During FY 2001 the RETA Project will address the following objectives:

- Provide technical support to environmental organizations that have the potential to address obstacles to PV use.
- Assist the Center for Environmental and Energy Research at Alfred University with developing issues requiring attention in the emerging competitive retail electricity market in New York State.
- Ensure that solar PV and other intermittent renewable energy electricity generators will be treated fairly in the emerging competitive wholesale electricity market.
- Develop guidelines and tools for environmental education organizations preparing to carry out solar PV marketing programs.
- Provide collaborative support to the *PV Compact* and to NGO efforts in other states.

Major Reports Published in FY 2000:
Sam Swanson, Tom Bourgeois, Mollie Lampi, John Williams and Fred Zalcman with Environmental Defense, Izaak Walton League of America, Natural Resources Defense Council, Northwest Energy Coalition, and Union of Concerned Scientists. "*Power Scorecard Methodology Report*." Pace Law School Energy Project. 2000

Environmental Defense, Izaak Walton League of America, Natural Resources Defense Council, Northwest Energy Coalition, Union of Concerned Scientists, Pace Law School Energy Project, and American Rivers. Power Scorecard Internet Web Site – www.powerscorecard.org

Major Articles Published in FY 2000:
Mollie Lampi, Pace University School of Law and Richard Perez, SUNY Atmospheric Sciences Research Center. "Assigning A Capacity Value To Distributed Renewable Resources In Restructured Electric Markets – The Case Of New York State." *American Solar Energy Society Conference*, Madison, WI June 2000.

Working with State and Local Officials to Assess Benefits and Design Policies to Further the Deployment of Photovoltaics in Economically Attractive Applications

Contract #: DE-FG03-00SF22117	**Contract Period:** 9/1/00–8/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">RAND Corporation
1700 Main Street
P.O. Box 2138
Santa Monica, CA 90407-2138</td></tr>
<tr><td>Organization Type: NP</td><td>Congressional District:</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Mark Bernstein
Phone: 310-393-0411, x6524 Fax: 310-393-4818 E-mail: markb@rand.org</td></tr>
<tr><td rowspan="2">Technical Monitor:
Lynne Gillette
Phone: 202-586-1495
Fax: 202-586-8148
E-mail: Lynne.Gillette@ee.doe.gov</td><td>B&R Code: EB22</td><td>Cost Share Information: None</td></tr>
<tr><td>DOE Funding Allocation:
2000: $216,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The project will provide information and outreach to state and local government officials, as well as key private sector officials, on the economic benefits and policy opportunities for using photovoltaic (PV) systems in economically attractive applications. The project will emphasize providing quality analysis to show the costs and benefits of PV applications, and will work closely with state and local officials to help them understand the opportunities and implications that follow from the analyses. The project proposes a pilot application of this effort at the national level as well as in four states. The project will recognize that each state has unique circumstances that will result in different costs and benefits for PV. Accordingly, different states may require different policy solutions.

Approach/Background: The project will be completed in four phases, with each phase building on the knowledge and experience accumulated in previous phases. Specifically, the project will attempt to do the following:

1. Develop a methodology for assessing the economic benefits of PV and how policies can impact the barriers to PV introduction. The methodology will include: how to assess the real economic opportunity for PV applications at the state and local levels; how to measure the benefits and costs to the state of increased penetration of PV; how to assess the impacts of different policy measures on the market for PV; and how to develop a set of policy recipes for state and local officials to follow to achieve benefits from PV applications.

2. The methodology will be applied nationally and then to one state as pilot analyses. The state will be chosen in consultation with DOE. During these pilot analyses, the following will occur: national and state-level measures of the benefits of PV will be developed; regional and local opportunities for cost-effective applications will be examined; policy options for state and local officials will be assessed; local outreach efforts will begin, focusing on state and local officials, public utility officials, legislators and the governor's office; techniques for cost/benefit analyses for various policy and state-level initiatives will be developed; and initial documentation on the opportunities for PV in the state will be prepared.

3. The previously developed methodologies —with potential revisions based on Phase II— will be applied to three additional states. These states would be chosen in consultation with DOE.

4. A report will be prepared on how to assess, evaluate, and measure the impacts and benefits of PV at the state and local level. The report will include a roadmap that other states can follow to perform similar assessments.

In total, this project will be the first time that comprehensive state and local level analyses have been conducted by innovatively applying conventional economic tools to more accurately assess the costs and benefits of PV. The project will recognize the variety of benefits that PV provides and attempt to link some of those benefits to economic growth in the state. The project will look at how policies impact the economics of PV, address barriers to the implementation of PV, and provide a framework for state and local level decision making.

Contract #: DE-FG03-00SF22117

Status/Accomplishments: The project team is currently in Phase 1 of this project. An initial outline of issues was prepared to help guide the literature review effort. This research effort is now underway and should pass its first milestone in mid-December.

Planned FY 2001 Activities: During FY 2001, the following milestones are planned:
- The initial research phase will be completed by the end of the second week in December 2000.
- The initial national and state level economic frameworks and data requirements will be identified in January 2001.
- The national-level analysis will be completed with initial documentation by mid-February 2001.
- The first state-level analysis will be completed with initial documentation by mid-April 2001
- Assuming that full funding for the project is transferred this year, the remaining state level analyses will initial documentation will be completed in roughly mid-June with the full report completed by the end of August.

Major Reports Published in FY 2000: none.

Major Articles Published in FY 2000: none.

Solar Energy Finance - Million Solar Roofs Initiative

Contract #: DE-FG01-99EE10707	**Contract Period:** 10/1/99–3/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **Email**: Lynne.Gillette@ee.doe.gov	Renewable Energy Development Institute (REDI) 75 N. Main Street, 234 Willits, CA 95490	
	Organization Type: NP	**Congressional District**: 1
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Keith Rutledge **Phone:** 707-459-1256 **Fax**: 707-459-0366 **Email**: keith@redinet.org	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2202	**Cost Share Information**: Renewable Energy Development Institute
	DOE Funding Allocation: 1999: $ 48,000 2000: $ 0	**Cost Share Funding:** 1999: $ 12,300 2000: $ 2,700

Project Objective: This project was initiated as part of the Million Solar Roofs (MSR) Initiative and aimed at providing MSR Partnerships and with the necessary tools for education on financing solar energy projects.

Approach/Background: The Renewable Energy Development Institute (REDI) will produce a Solar Energy Finance handbook that will include information on existing programs, case studies of various financing approaches for a diverse audience. They will also produce a “how-to-finance” booklet specifically for residential consumers. They will be developing model solar financing workshops and conducting four of these workshops in MSR partnership areas across the country.

Status/Accomplishments: Contract #: DE-FG01-99EE10707
Beginning in October 1999 REDI has compiled a vast collection of loan program descriptions, articles relating to lending, websites, contacts, forms and manuals for use in the Solar Finance Handbook. Electronic presentations covering topics related to solar financing for all sectors as well as software tools for financial analysis have also been included. The materials are assembled in electronic format onto a single CD-ROM disk for ease of access. The disc also includes a searchable electronic database for filtering documents in up to three separate fields to find all documents related to the chosen topics. The searchable database can be used in a self-executing file with Microsoft Access but has been designed specifically for use on the MSR website. This format will allow easy access by all and across all computer platforms as well as the ability to add, edit or delete by MSR partners as new programs come on-line or there are changes in existing programs.

During the months of August and September 2000 four regional financing workshops were held in Albuquerque, NM; Raleigh, NC; Seattle, WA; Long Island, NY. The all-day workshops covered a wide variety of lending issues as they pertain to solar loans as well as the full range of loan programs for each sector; residential, commercial and institutional. Workshop participants were surveyed regarding their knowledge of lending programs, the MSR program, solar technologies and were asked about barriers they were aware of and how we can work collectively to overcome them. While many of the workshop participants were interested mostly in the residential sector the workshop format provided a clear case for the need for financing in the commercial and institutional sectors as well. Feedback from the participants has been very favorable.

Follow-up conversations with a variety of the MSR partners has provided further information on new and planned lending programs across the country. The materials contained in the Financing Handbook will need to be continually updated as these programs are implemented and changes are made. For this reason the format of the materials will be best kept in an electronic format and made available over the Internet on the MSR website and/or on the DSIRE database.

Planned FY 2001 Activities:
All Financing Handbook and Workshop Materials are being reviewed, edited and will be compiled on the final draft of the CD-ROM for submission with the final report scheduled for delivery by the end of January 2001. Future workshops are already being planned with MSR partners for presenting local Solar Finance Workshops in their regions. The Bay Area Solar Coalition (BASC) has received a DOE MSR contract for one of these workshops. In addition, REDI staff has been in continual contact with many of the MSR partners in assisting with design and implementation of solar financing programs that fit their particular needs. Further work needs to be performed in the area of specialty lending such as a Native American loan program tailored to the unique aspects of this

community. Several states are in the process of designing or implementing financing programs to compliment utility restructuring and energy conservation incentive programs. REDI staff is working with MSR partners in researching existing programs, consulting on new program ideas and networking MSR partners with solar and finance industry contacts.

The MSR Solar Financing Workshops and Handbook need to be utilized by MSR partners in offering presentations in their communities. Materials should be customized by the MSR partners to fit their local programs and special needs. Targeted workshops to specific sector audiences such as homeowners associations, religious congregations, real estate professionals, lending professionals and government representatives need to be scheduled to spread the word about MSR and solar lending opportunities.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Outreach

Building a Market for Photovoltaics Through Electric Service Providers

Contract #: DE-FG01-99EE35086	**Contract Period:** 8/6/99–7/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E-mail**: Lynne.Gillette@ee.doe.gov	Solar Electric Power Association (previously known as Utility PhotoVoltaic Group) 1800 M Street, NW, Suite 300 Washington, DC 20036-5802 **Organization Type**: IN	**Congressional District**: NA
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Jeff Serfass **Phone:** 202-857-0898 **Fax**: 202-223-5537 **Email**: jserfass@ttcorp.com	
Technical Monitor: Same as Program Manager	**B&R Code**: EB2202	**Cost Share Information**: UPVG
	DOE Funding Allocation: 1999: $298,682 2000: $0	**Cost Share Funding:** 1999: $40,631 2000: $24,265

Project Objective: This education and outreach project “Building a Market for Photovoltaics Through Electric Service Providers” helped develop an integrated flow of information between electric utilities and other energy service providers, their customers, and key stakeholders in the solar industry, financial community and the architect/builder community. The project was initiated by the Utility PhotoVoltaic Group. The organization, in response to the significant changes in the electric supplier, energy service provider, and utility industries, changed the name of the organization in October 2000 from the UPVG to the Solar Electric Power Association (the “Association”). The information developed in this outreach effort started a process to break down existing market barriers and create a marked acceleration of the use of PV electricity.

Approach/Background: The Association relied heavily on the experiences and lessons learned as a result of their involvement with the TEAM-UP (Technology Experience to Accelerate Markets in Utility Photovoltaics) demonstrations. The main purpose for this project was to widely disseminate the results of TEAM-UP.

Status/Accomplishments: The project is complete. It reached all of its goals. Highlights include:
Website Enhancements: In the first half of CY2000, the Association made extensive revisions and contributions to its web site (www.solarelectricpower.org), including:

- Redesign of opening page to create ready access to the information about photovoltaics that resides within the site (the former opening page featured basic information about the Association)
- Posting more information on and analysis of TEAM-UP results and lessons learned
- Posting solar press releases from other organizations
- Creating an on-line version of the *Record* newspaper, with regularly posted updates
- ‘Streaming’ our 1997 video “Solar Power: Making the Dream Real” on the site (with free download of Real Player)
- New postings on and improvements to the web site, including renewing registrations with search engines to turn up the site as a top ten hit in categories including “solar electricity”, “solar power” and “photovoltaics” (the site was already #1, #2 and #8 in recent tests of the Lycos and Infoseek search engines)

These improvements have contributed to a <u>50 percent increase</u> in hits at our web site (from 15,409 in November 1999 to 31,148 in July 2000).

We issued a press release “Utility Study Shows Consumer-Friendly Products and Niche Use Opening Markets for Solar Electricity” on 15 Dec 99 electronically on PRNewswire and by email to press contacts. This resulted in contacts from reporters at Energy Daily, PV News, Restructuring Today, Utility Environment Report resulting in stories. The story was picked up by other wire services including Energy Central News and Environment News Service, resulted in stories on web sites such as GreenMountain.Com (lead story on main page in mid-December), and electronic news sources like Trends in Renewable Energy.

Most of the deliverables were met by the reports that were released in FY 2000, and are listed below.

Contract #: DE-FG01-99EE35086

Planned FY 2001 Activities: None, project complete.

Major Reports Published in FY 2000*:*
UPVG, (11/1999) "4.5 MW and Counting: Technical and Business Experiences of TEAM-UP Program Partnerships" This report was researched and written under the UPVG's Phase Five and Phase Six TEAM-UP contracts with the DOE. Actual printing, and widespread outreach on the results of the report, is covered under the Education and Outreach contract, as a major dissemination product on the experiences and lessons learned on installing PV.

T. Starrs, (7/2000) "Barriers and Solutions to Interconnection Issues for Solar Photovoltaic Systems". This paper describes the critical issues surrounding utility interconnection of customer-sited solar photovoltaic systems. It identifies the barriers to streamlined, simplified interconnection and describes how these barriers might be overcome in a manner that is fair and equitable to both utilities and their customers. It also summarizes recent actions on interconnection-related issues by utility policymakers, including legislatures, utility regulators, and utilities themselves. In addition, the paper addresses the benefits and costs to utilities of encouraging significant market penetration of customer-sited PV systems. The paper concludes that utilities choosing to embrace rather than oppose customer-sited PV installations may be able to benefit substantially from doing so, by maintaining or even enhancing revenues, reducing costs and capturing administrative efficiencies, and realizing significant public relations benefits that promote customer satisfaction and loyalty.

S. Strong (7/2000) "Buildings On Line" This paper describes the history of BIPV, the role of utilities, technical and non-technical barriers, incentives/encouragement for supporting BIPV, and business opportunities. This paper also presents numerous case studies.

E. Holt, (7/2000) "The Role Green Power in Increasing Demand for Solar Electricity." July 2000. This report covers programs with the longest experience, utility green pricing programs. It then examines the sale of solar electricity to customers in newly-competitive retail markets and the sale of solar electricity as bulk power supply in the wholesale electricity market. Third, it considers programs that sell or finance PV systems for on-site energy consumption. Finally, it describes a European model in which the utility facilitates the sale or exchange of solar electricity. In each case, the program or service is described, followed by quantified results wherever possible.

UPVG, (4/2000) "UPVG Record"

UPVG, (1999) "Schools Going Solar: Volume 2"

Multiple Authors, (2000) "UPEx'99 Proceedings" on CD-ROM.

Major Articles Published in FY 2000: none

Outreach

Interconnection Barriers – Solution for the Million Solar Roofs Initiative

Contract #: DE-FG01-99EE10706	**Contract Period:** 9/24/99–11/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Lynne Gillette
Phone: 202-586-1495
Fax: 202-586-8148
E-mail: Lynne.Gillette@ee.doe.gov</td><td colspan="2">Solar Electric Power Association (previously known as Utility PhotoVoltaic Group)
1800 M Street, NW, Suite 300
Washington, DC 20036-5802</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: NA</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
1000 Independence Ave., SW
Washington, DC 20585</td><td colspan="2">Principal Investigator (s)
Steve Hester
Phone: 202-857-0898 Fax: 202-223-5537 Email: shester@ttcorp.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Same as
Program Manager</td><td>B&R Code: EB2202</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $117,180
2000: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This project was initiated as part of the Million Solar Roofs Initiative and aimed at removing barriers to interconnecting building-related PV systems with the utility grid. The effort covers both technical and non-technical barriers and is aimed at identifying solutions to remove these barriers. It is a combined effort of UPVG and PVUSA. The specific objective is to help resolve technical and non-technical issues relating to PV interconnection to the utility grid. The organization, in response to the significant changes in the electric supplier, energy service provider, and utility industries, changed the name of the organization in October 2000 from the UPVG to the Solar Electric Power Association (the "Association").

Approach/Background: The Association/PVUSA project team's goal is to develop materials that will offer potential solutions for both the technical and non-technical barriers to interconnection. They developed a handbook and a model workshop. They demonstrated these resources at a series of four workshops in Million Solar Roof communities that have identified interconnection issues.

Status/Accomplishments: Four regional Workshops were held. Materials were developed and the materials were presented on March 22-23, 2000 in Atlanta, Georgia; on May 22-23, 2000 in Columbus, Ohio; on August 2, 2000 in Portland, Oregon; and on October 5, 2000 in Baltimore, Maryland.

The Workshop Notebook is an extensive document that is intended to help participants in Million Solar Roofs (MSR) partnerships across the United States and others to continue to address utility interconnection issues. The notebook manual provides MSR partners with a full set of materials necessary to fully understand PV system utility interconnection issues.

The manual includes "notes" versions of each workshop presentation speaker slides. Speaker notes below each slide provide background information on the slide contents. After a tutorial on PV and inverter basics, the presentations focus on two primary areas:

- a technical focus dealing with the codes and standards governing utility interconnection;
- a non-technical focus dealing with legal and regulatory issues.

The technical focus area contains three presentations.

1. *Technical Interconnection Issues: Codes and Standards*—This presentation is designed to provide the participant with a background of the relevant codes and standards that have been developed for the PV industry, and why they are important to interconnection issues.
2. *IEEE929-2000 Overview*—This presentation is a brief overview of the content of IEEE Standard 929. This is the key document for the utility interconnection of PV systems.
3. *Islanding Testing*—This presentation describes the key test specified in IEEE 929: the test for non-islanding inverters. This information is especially important for skeptical engineers worried that PV systems will compromise grid safety.

Contract #: DE-FG01-99EE10706

Status/Accomplishments (continued):
The non-technical focus area contains two presentations.

1. *Interconnection Experiences*—This presentation was written to provide some real-world examples of what can happen when interconnection issues are not simplified.
2. *Net-Metering and Interconnection*—This presentation addresses the non-technical barriers to interconnection and net metering and solutions for those barriers.

These presentations are interwoven in the workshop since they are interrelated and often must be dealt with simultaneously. In addition to these presentations, there is an extensive selection of other materials covering these topics in greater detail. Several of these resources also contain additional references.

Following the first section containing the workshop presentations is a section devoted to IEEE 929 entitled Technical Interconnection Issues. A full copy of the standard can be purchased at www.standards.ieee.org. There is also a description of the contents of the standard and the purpose behind each of the requirements in the standard. Following the IEEE 929 section are some brief sections showing the table of contents of the UL 1741 test standard (that document may be purchased through http://ulstandardsinfonet.ul.com/), a paper on the results of non-islanding testing conducted at Sandia National Laboratories written by Greg Kern of Ascension Technology, and a paper by Doug Dawson, formerly of Southern California Edison, on the state of various utility interconnection requirements in the fall of 1999.

Another section contains papers supporting the presentations in the non-technical focus area. The first of these papers is an update on net-metering developments as of the summer of 1999. The second paper addresses the need to keep interconnection requirements standardized for manufacturers, utilities, and governments. The next paper, *Allocating Risks: An Analysis of Insurance Requirements for Small-Scale PV Systems*, addresses the issues related to insurance requirements often found in interconnection agreements. The last two papers in this section deal with the broad topic of barriers and solutions to interconnection issues providing substantial background to the Net Metering and Interconnection presentation in this manual.

The fourth section contains several important resources. The first document is the booklet entitled, *Connecting to the Grid: A Guide to PV Interconnection Issues*. This guide provides an excellent overview of all the issues, both technical and non-technical, written in an easily understandable format. It discusses a broad range of PV implementation issues including building codes and local covenants. The second paper, *Making the Connection*, is published by the National Renewable Energy Laboratory and is actually a shortened version of the first edition of Connecting to the Grid, designed to reach a broad audience with a glossy and concise document.

Following these documents is the newly issues (after the four workshops) Interconnection Positions Statement of the Solar Electric Power Association, then a copy of the American Solar Energy Society's policy statement on PV interconnection issues. Both of these documents contain model interconnection agreements. This section ends with case study information from actual PV interconnection experiences.

The last section contains a variety of resources that relate to state implementation of net metering and interconnection. The first item is a table of all the state net metering programs updated as of the fall of 2000. The next two items are presentations by Chris Larsen of the North Carolina Solar Center providing a state-by-state update on progress on interconnection issues. These presentations are current as of the spring of 2000. So much is happening in this area that these presentations should be used for historical perspective rather than representing current activities in each state. The last three items are copies of net metering legislation from three different states, Virginia, Oregon, and Montana. These are examples of possible language that can be used for drafting laws in other states.

MSR partnerships should avail themselves of some excellent resources in addition to the materials in this Workshop manual. As MSR partners become better informed on these and other important implementation issues, the barriers to PV commercialization will begin to weaken. The main issue is getting the right information into the hands of the right people in a format that can be effectively articulated when needed. It is the goal of the workshop manual to help fulfill these information needs.

The Workshop manual will be issued in December 2000.

Planned FY 2001 Activities: none

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

TUSD PV for Schools

Agreement #: DE-FC36-99GO10465	**Project Period:** 9/1/99–6/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Dan Ton **Phone:** 202-586-4618 **Fax:** 202-586-8148 **E-mail:** Dan.Ton@ee.doe.gov	Tucson Unified School District (TUSD) 2025 East Winsett Tucson, AZ 85719 **Organization Type:** CU	**Congressional District:** 2
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Douglas Crockett **Phone:** 520-617-7086 **Fax:** 520-617-7130 **E-mail:** Dcrocket@tusd.k12.az.us	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E-mail**: lizana_pierce@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1999: $100,000 2000: $0	**Cost Share Information:** **Cost Share Funding:** 1999: $139,357 2000: $0

Project Objective: Tucson Unified School District (TUSD), in conjunction with the Tucson Coalition for Solar (TCS), will design and implement a program for establishing solar energy as a viable choice for satisfying community energy needs, specifically in schools. Through an integrated set of learning opportunities for students, teachers, school support staff, and the wider community of neighbors, family and local industry, the critical role of solar energy will be more firmly established in the Tucson metropolitan area. Further, a curriculum for the development of "solar learning opportunities" will be created to serve as a guide for other communities to design a solar initiative tailored to their needs and conditions, while building on the experience of others.

The purpose of the TUSD PV for Schools Initiative is to: increase community awareness of, and commitment to solar energy applications in schools and the community at large, by establishing a continuum of photovoltaic education for: middle to high school students and teachers; school faculty support staff and management; and the wider community. TUSD PV for Schools Initiative is a campaign designed to integrate photovoltaic technologies/applications into the immediate and wider school community. The immediate school community includes both support staff (administration, facilities managers, and maintenance staff), and curriculum (teachers, students and curriculum support personnel). The wider community includes the business and residents neighboring the schools, parents and extended family, the local union chapter of the school maintenance staff, and the community at large.

Approach/Background: Tucson Unified School District's (TUSD's) Photovoltaics (PV) for Schools Initiative was selected under the PV for Schools Supplemental Announcement. Under the Supplemental Announcement, DOE solicited Applications to develop and demonstrate a model for integrating photovoltaics into middle and high school buildings and education programs. The PV installations are intended to produce electricity for the reduction of utility costs and to serve as teaching aids for the introduction of renewable energy into each schools science programs. The activities to be undertaken under TUSD's PV for Schools project are: 1) developing capacity and enhancing political support for solar energy infrastructure through briefings for School Facilities' Managers, Board of Education, District Management and the interested public, maintenance staff and local union members, and the installation of 4kW in each of two schools; 2) establishing a solar energy awareness and value in the education continuum including a widespread solar education for the Stafford Middle School through the animated website at the "Sunsite/Funsite"; 3) building solar energy capacity in the education continuum by establishing a PV technical framework and skills within the Engineering Magnet Program at Palo Verde Engineering and Technology Magnet High School.

Status/Accomplishments: Tucson Unified School District (TUSD) was awarded and fully funded in FY99 under the "PV for Schools" solicitation. During FY2000, TUSD, along with Tucson Electric Power, completed a 4 kW solar ramada structure at Stafford Middle School, which was dedicated in April 2000. Additionally, TUSD provided a 1 kW PV system, donated by Arizona Electric Power Cooperative, to the Palo Verde Magnet High School auto shop for charging electric car batteries for the student racing team. An on-line Photovoltaic Module was developed for the Middle School Science curriculum. Seven teachers and 15 students have participated in the on-line course. Solar Code Training was conducted at the International Brotherhood of Electric Workers (Local #570) in March 2000. A Celebrate solar event was held at Stafford Middle School in conjunction with Earth Day 2000. The Earth Day Festival attracted over 100 participants. Three students were selected and attended the Arizona Solar Energy

Institute in Flagstaff, July 2000. A grant extension was requested and approved through June 2001 to allow UL listing of Global Solar's product, which is planned for installation at Palo Verde High School.

Planned FY 2001 Activities: During FY 2001, TUSD will install 4 kW at Palo Verde High School, conduct a Solar/Photovoltaic Energy Workshop for Middle School Science Teachers, and continue on-line photovoltaic courses.

Major Reports Published in FY 2000: none

Major Articles Published in FY 2000: none

Photovoltaics Program Technical Support

Contract#: AXE-9-29605-01	**Contract Period:** 4/12/99–4/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Jeffrey Mazer
Phone: 202-586-2455
Fax: 202-586-8148
E-mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">McNeil Technologies, Inc.
6564 Loisdale Ct., S-800
Springfield, VA 22150</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 8</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
K. DeGroat
Phone: 703-921-1632 Fax: 703-921-1610 E-mail: kdegroat@mcneiltech.com</td></tr>
<tr><td rowspan="2">Technical Monitor:
Robert McConnell
Phone: 303-384-6419
Fax: 303-384-6481
E-mail: robert_mcconnell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $139,851
2000: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Task 1: Gather information from the U.S. Department of Energy (DOE) Office of Science (OS) to compile a list of PV-related projects in fundamental and exploratory research that are supported by OS at NREL, other national laboratories, and universities. The compilation shall contain abstracts of each project, principal investigator contact information, contract duration, and funding amounts.

Task 2: Compare development and manufacturing issues for concentrator and flat-plate technologies. Manufacturing analyses shall include processes, plant and equipment investment issues developed from experience in the PVMaT program.

Task 3: Work with NREL and DOE staff to support the PV technology road map and five-year program plan activities, including preparation of schedules, outlines, and drafts, including arrangements for workshops and other means for obtaining various stakeholder inputs and reviews.

Task 4: Subcontractor shall survey the United States PV industry to identify how much of their product in 1998 was sold for grid-connected applications in the US, remote systems in the US, consumer products, and overseas remote systems. Estimate the cumulative totals from the 1970s to today for each of these markets. Then evaluate and compare contrasting projections of future PV installed capacity completed recently by the Energy Information Administration, Royal Shell, and others. Recommend an analytical framework for estimates of future installed MWs, kWhrs produced, tons of carbon avoided, BTUs avoided, market sizes, etc., to more accurately quantify the value of photovoltaics in future energy scenarios that include other energy sources.

Approach/Background: These four tasks address program planning, data and analysis needs for the PV program. The first task is designed to characterize related basic research outside the program that may help improve sharing of scientific information and collaboration in key areas. Task 2 will update information on concentrator manufacturing and development issues which are of increased interest because of continuing advances in high-efficiency PV technology. The third task involved McNeil in assisting NREL in developing the PV 5 Year Plan and inputs to the industry road map, which had to be completed in time for a 1/1/2000 publication date. The fourth task expands on current collection of industry data and projections to try and resolve some of the lingering inconsistencies between data sets and explore the methods and assumptions behind different sources of information needed for program planning.

Status/Accomplishments: McNeil Technologies completed a report and database on Office of Science research projects relevant to the PV program. It is available to NREL personnel and other researchers interested in finding out about research projects funded by the Office of Science. Over 80 projects representing over $20 million in research projects with some relevance to PV development were found, categorized by the type of research: basic, directed basic, specific basic, materials/processes, applied, technology applications, or education testing. The data is easily sorted by performing organization and principal investigator to highlight centers of research activity and key contacts.

For the 5-Year Plan McNeil gathered photos from industry sources, obtained release forms to allow their use in the final publication, and explanations of the content. Sources included the HBCUs, individual manufacturers and installers, and university partners. Photos not used in the 5-Year Plan may be used for future publication projects, with proper releases. McNeil worked with James Rannels to develop his Director's message, and reviewed late versions of the final plan. For the roadmapping exercise McNeil Technologies reviewed different growth projections developed by NREL with industry input, critiqued the assumptions used to develop them, and compared the projections to other sources. The inputs eventually became part of the industry roadmap projections through NREL.

The objective of the PV concentrator study was to review the current status of concentrator technology and the industry and identify issues that will affect future development, including comparisons and lessons learned from flat-plate PV development. For this study McNeil reviewed available information on concentrator technology, manufacturing and products to characterize the state of technology and commercialization, particularly PVMaT research summaries and published literature on technology and markets for both concentrator and flat-plate PV. McNeil also interviewed concentrator manufacturers and development teams to update information on manufacturing issues, and solicit their views on R&D priorities and markets.

For the PV manufacturer and distributor survey McNeil developed a web based and written survey tool. McNeil e-mailed the instructions and link to the on-line survey to all U.S. manufacturers and distributors of PV and to all major manufacturers and distributors specializing in PV related products of whom we obtained electronic contact information. For those lacing e-mail, the survey was faxed and/or mailed to the participants. A telephone follow-up was completed on all of the domestic manufacturing parties in order to encourage their participation in the survey, confirm the data on their survey and to obtain anecdotal materials about their distribution systems, their effectiveness and lessons learned over the course of their growth. Most of the information gathered in the surveys and subsequent folow-up interviews is potentially commercially sensitive. Therefore, raw response data was not made available with the study.

Using 1998 as a baseline, McNeil compared and contrasted the survey findings and projections with those of the EIA and Photovoltaic Energy Systems, Inc. The data offers historical trends in the various PV end-use applications. The report and data project the yearly quantity of PV that will be manufactured in kWs and the cumulative amount of PV that will be installed with a detailed breakdown of shipments based upon their various end-use applications. McNeil added an analytical tool to determine the amount of particulate matter, sulfur dioxide, carbon monoxide, nitrogen dioxide, lead, ozone, carbon dioxide, methane, nitrous oxide, halocarbons and other related compounds that will be displaced by PV systems.

Major Reports Published in FY 2000:
K. DeGroat, and S. McAllister, (July, 2000), "Development and Manufacturing Issues for Concentrator PV Systems," 18 pp. NREL/AXE-9-29605-01, Golden, CO: National Renewable Energy Laboratory.

K. DeGroat, and S. McAllister, (May, 2000), "Survey of Grid Connected Applications In U.S. and Remote Systems Overseas," 42 pp. NREL/AXE-9-29605-01, Golden, CO: National Renewable Energy Laboratory.

Major Articles Published in FY 2000: none

Program Management

National Center for Photovoltaics and NREL PV Program Communications

Contract#: DE-AC36-99GO10337	**Contract Period:** 10/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Boulevard Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Don Gwinner **Phone:** 303-384-6570 **Fax:** 303-384-6430 **E-mail:** don_gwinner@nrel.gov	
Technical Monitor: Thomas Surek Phone: 303-384-6471 Fax: 303-384-6481 E-mail: tom_surek@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** none
	DOE Funding Allocation: 2000: $400,000	**Cost Share Funding:**

Project Objective: We seek to understand the needs and interests of stakeholders in the PV community, reach out to those who need to know about PV or about us, and provide pertinent information about various aspects of PV and our programs to numerous groups and individuals. Specifically, we do the following: (1) Support the National PV Program, especially by producing communications products that highlight past accomplishments, current activities, and future directions in PV, by maintaining the DOE PV Web site, and publishing a quarterly newsletter of NREL's PV work with industry and universities. Work for DOE specifically involves the Five-Year National PV Program Plan, PV Program Overview, and other communications such as brochures and CD-ROMs for the Office of Solar Energy Technologies. (2) Help the NCPV to fulfill one of its strategic goals of coordinating information and outreach—to be a forum and information source for the PV community—especially by providing support for the NCPV Advisory Board and the PV industry roadmapping project, and by developing products such as the NCPV Web site, a traveling NCPV exhibit, R&D 100 nomination packets, and NCPV Review Meeting proceedings.

Approach/Background: The national laboratories' primary product is information, and we must make sure that the right people get this information in a form that is understandable and useful to them. Communications is essential in this whole pursuit. We need a good understanding of the various audiences in the PV community and what their needs are; we develop the proper types of material for them, at the proper level of understanding and usefulness, and in the right form, whether paper or electronic, textual or graphical. We must not only produce good material, but must ensure that the proper people receive this material. And we must better solicit feedback on our materials so that we can determine how effective we are at meeting our goals. The response will help us to modify our program in the future. Communications activities in this project are primarily carried out by three writers/editors, two graphic artists, and one administrative specialist at NREL (all of whom are part of NREL's Communications and Public Affairs Office). The NREL team works closely with other C&PA writers, editors, graphic artists, photographers, and experts in electronic media. Outside contractors are occasionally used, either for a particular expertise or to help meet a specific deadline.

Status/Accomplishments:
- Published *National PV Program Five-Year Plan: 2000-2004*; *PV Energy Program Overview, FY 1999*; *PV Program Contract Summary, FY 1999*; and four issues of *NREL PV Working With Industry* newsletter.
- Maintained DOE PV Program and NCPV Web sites.
- Developed *Solar Energy Showcase* CD-ROM with 120 solar technology photos.
- Produced new NCPV exhibit (Photovoltaics: Energy for the New Millennium) for conferences and expositions.
- Supported several Solar Office communications activities (e.g., *Something New Under the Sun*).

Planned FY 2001 Activities:
- Revise *National PV Program Five-Year Plan: 2002-2006* by January 2002.
- Compile the *PV Program Contract Summary, FY 2000* by February 2001.
- Complete *PV Energy Program Overview, FY 2000* by March 2001.
- Produce 4 issues of *NREL PV Working With Industry* newsletter—December, March, June, September.
- Redesign the DOE PV Program and NCPV Web sites.
- Complete the CD-ROM of solar applications from all 50 states by July 2001.

Contract#: DE-AC36-99GO10337

- Complete an outreach brochure for the Solar Office.
- Participate in the Solar Outreach Team with others at DOE, NREL, Sandia, RSOs, and others.

Major Reports Published in FY 2000:

Photovoltaics: Energy for the New Millennium, The National Photovoltaics Program Plan, 2000-2004, DOE/GO-10099-940 (January 2000).

U.S. Department of Energy Photovoltaic Energy Program Contract Summary, FY 1999, DOE/GO-102000-0976 (February 2000).

U.S. Department of Energy Photovoltaic Energy Program Overview, FY 1999, DOE/GO-102000-0963 (March 2000).

NREL PV Working With Industry—4Q99, "Knowledge is PV Power," NREL/BR-27259; 1Q00, "Pulling Out All the Stops," NREL/BR-27989; 2Q00, "Our Shared PV Future," NREL/BR-27990; 3Q00, "Ready for the PV Challenge?," NREL/BR-28491.

National Center for Photovoltaics and NREL PV Program Management

Contract#: DE-AC36-99GO10337	**Contract Period:** 10/1/99–9/30/00

<table>
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<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
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<tr><td rowspan="2">Technical Monitor:
N/A</td><td>B&R Code: EB22</td><td>Cost Share Information: none</td></tr>
<tr><td>DOE Funding Allocation:
1998: $1,761,000 2000: $1,835,855
1999: $2,215,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objectives are to provide the program management, planning, analysis, coordination, integration, and reporting necessary to conduct an efficient and effective DOE PV Program. The National Center for Photovoltaics (NCPV), headquartered at NREL, serves as the focal point for the DOE PV Program. The NCPV performs world-class R&D, promotes partnering and growth opportunities, and serves as a forum and information source for the PV community. The NREL PV Program objectives include management support to coordinate and integrate the activities of NREL in-house and subcontracted research activities. This project also ensures that in-house PV facilities are maintained as resources for, and open to, the U.S. PV research and development community.

Approach/Background: The NCPV provides overall coordination of the DOE PV Program's Annual Operating Plan at the request of DOE. NREL and Sandia National Laboratories (SNL), partners in the NCPV, provide the management oversight for the respective projects in their laboratories, as well as management support for the NCPV. This project consists of program management, planning, analysis, administration, budget control, reporting, and integration, as well as staff, equipment and facilities oversight to provide the foundation for consistent program progress. Staff members respond to new research developments, changing resource requirements and availability, and to overall PV program needs, including environmental safety and health (ES&H). The project also oversees communications activities such as developing and maintaining the DOE/NCPV/ NREL/SNL web sites, periodic news releases, and various program overviews, brochures, and publications. Major activities in FY 2000 included publishing the new DOE PV Program five-year plan and facilitating development of a PV Technology Roadmap by industry.

Status/Accomplishments:
- Published the new five-year plan for the DOE PV Program.
- Published proceedings of the U.S. PV industry roadmapping workshop and continued to facilitate development of the roadmap.
- Held two meetings of the NCPV Advisory Board.
- Submitted a five-year capital equipment plan for the NCPV, including an implementation plan and funding recommendations.
- Submitted a plan for the new Science and Technology Facility (STF).
- Facilitated implementation of two new program initiatives for award in FY 2001: the High-Performance (Hiper) PV initiative and the Beyond-the-Horizon PV initiative.
- Managed PV program resources to achieve minimal carryover of funds into FY 2001.

Planned FY 2001 Activities:
- Facilitate completion of the U.S. PV Industry PV Technology Roadmap (01/02).
- Revise DOE PV Program five-year plan for publication in early CY 2002.

Major Reports Published in FY 2000:
“Photovoltaics: Energy for the New Millennium, The National Photovoltaics Program Plan, 2000-2004”, DOE/GO-10099-940 (January 2000).

Proceedings of the *“U.S. Photovoltaics Industry PV Technology Roadmap Workshop”*, June 22-25,1999, prepared by Energetics, Inc. (September 1999).

Program Management

Sandia PV Program Management

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/99 - 9/30/00

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<tr><td rowspan="2">Technical Monitor:
N/A</td><td>B&R Code: EB22</td><td>Cost Share Information: none</td></tr>
<tr><td>DOE Funding Allocation:
1998: $400,000
1999: $440,000
2000: $440,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objectives are to provide the program management, analysis, coordination, integration, and reporting necessary to conduct an efficient and effective DOE PV Program. The objectives include management support to coordinate and integrate the activities of Sandia in-house and subcontracted research activities. This project also ensures that in-house PV facilities are maintained as resources for, and open to, the U.S. PV research and development community. The objective of the National Center for Photovoltaics (NCPV), in which Sandia is a partner, is to serve as a focal point for the Program, to strengthen communications, and further unify national PV interests.

Approach/Background: Sandia participates in the NCPV, which provides overall coordination of the DOE PV Program's Annual Operating Plan at the request of DOE. Sandia and NREL (NCPV partners) provide the management oversight for the respective projects in their laboratories, as well as management support for the NCPV. This project consists of program management, analysis, administration, budget control, reporting, and integration, as well as staff, equipment and facilities oversight to provide the foundation for consistent program progress. The management and operation of the NCPV are also supported by this project. Staff members respond to new research developments, changing resource requirements and availability, and to overall PV program needs, including environmental safety and health (ES&H). The project also supports communications activities such as developing and maintaining the Sandia PV web site, periodic releases of interest to the PV industry, publication of technical and general interest documents about the program, and developing various program overviews and brochures. A major activity in FY 1999 included facilitating development of a PV Technology Roadmap by industry.

Status/Accomplishments:
- Assisted in publishing new five-year plan for the DOE PV Program.
- Published proceedings of the U.S. PV industry roadmapping workshop and continued to facilitate development of the roadmap.
- Held two meetings of the NCPV Advisory Board.
- Managed PV program resources to achieve minimal carryover of funds into FY 2001.

Planned FY 2001 Activities:
- Facilitate completion of the U.S. PV Industry PV Technology Roadmap (01/02).
- Help revise DOE PV Program five-year plan for publication in early CY 2002.

Major Reports Published in FY 2000:
Proceedings of the “U.S. Photovoltaics Industry PV Technology Roadmap Workshop”, June 22-25,1999, prepared by Energetics, Inc. (September 1999).

Appendices

PERFORMING ORGANIZATIONS BY NAME

[ ] DENOTES THE ORGANIZATION TYPE

PERFORMING ORGANIZATIONS BY STATE

[ ] DENOTES THE ORGANIZATION TYPE

PERFORMING ORGANIZATIONS BY TECHNOLOGY AREA

Applications and Market Development, Outreach, and Program Management

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International Applications and Market Development

Program Planning, Analysis, Outreach, and Management

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13. ABSTRACT *(Maximum 200 words)*
This report summarizes the in-house and subcontracted research and development (R&D) activities under the National Center for Photovoltaics (NCPV) and U.S. Department of Energy (DOE) National Photovoltaics Program from October 1, 1999, through September 30, 2000 (FY 2000). The mission of the DOE National Photovoltaics Program is to make PV a significant part of the domestic economy—as an industry and an energy resource. The two primary goals of the national program are to (1) maintain the U.S. industry's world leadership in research and technology development and (2) help the U.S. industry remain a major, profitable force in the world market. The NCPV is part of the National PV Program and provides leadership and support to the national program toward achieving its mission and goals.

14. SUBJECT TERMS
photovoltaics ; National Center for Photovoltaics ; NCPV ; crystalline silicon ; high-efficiency materials and devices ; amorphous silicon ; cadmium telluride ; copper indium diselenide ; gallium arsenide ; III-V materials ; balance of systems ; measurements and characterization ; exploratory materials and devices ; Historically Black Colleges and Universities ; HBCU ; thin films ; Photovoltaic Manufacturing Technology ; PVMaT ; modules ; systems ; applications ; market development

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Useful Web Sites
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NCPV: *www.nrel.gov/ncpv*
Sandia: *www.sandia.gov/pv*

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