NREL PV

Working With Industry

Fourth Quarter, 1999

Knowledge Is PV Power

The axiom, "knowledge is power," has never seemed truer than by adding one word: Knowledge is PV power. The more than 70 universities participating in the PV Program attest to that. Fine minds, creative spirits, and dedication to research are just a few of the attributes that our university partners bring to the table.

University partners extend and enrich the capabilities of the national labs and the U.S. PV industry. As you'll see in the article beginning on page 3, they are working the entire development cycle of PV technologies, from research on PV ideas of the future to hands-on assistance with the manufacturing problems encountered today.

Of equal or greater importance, university partners are teaching and training the PV workforce of tomorrow. These students are earning high marks in the classroom while working side by side with professors and researchers in the laboratory on real-world PV projects. Students are even moving beyond the laboratory, traveling to PV workshops in the United States and to developing countries in Africa, where they install PV systems.

This issue of *NREL PV Working With Industry* focuses on the contribution of the PV Program's university subcontractors. But it's also important to note the participation of university students here at NREL—totaling in the hundreds in the last ten years alone—as visiting scholars, research assistants, and post-doctoral candidates. Many schools are represented here, including NREL's neighbors, the University of Colorado, the Colorado School of Mines, Colorado State University, and Denver University. And NREL scientists reciprocate by serving as adjunct professors at several schools in the area.

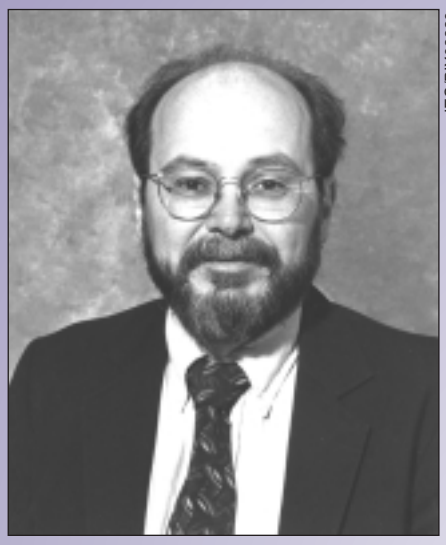
That NREL and the NCPV are richer for this university connection is undeniable. That for the U.S. PV industry to continue to grow and flourish, the universities must stay involved, is indisputable. That the fulfillment of this quest for knowledge will translate to more dynamic forms of PV power is, we hope, inevitable.

Features

Departments

Universities Provide the Foundation for PV Technologies

An Editorial by Robert Birkmire



IEC/PIX08826

Robert Birkmire is the director of the Institute of Energy Conversion, a DOE Center of Excellence for Photovoltaic Research and Education, and a Professor of Physics and Professor of Materials Science at the University of Delaware. His current research efforts are growth and characterization of thin-film semiconductors for PV and optoelectronic devices and the relationship of the growth process to film properties and device performance. He has authored more than 90 technical publications and is inventor on several U.S. patents.

Contact Robert Birkmire at 302-831-6220

In developing and commercializing PV technologies, universities have two important roles: (1) to help educate and train the workforce pool required by the emerging PV industry; and (2) to provide the scientific and engineering basis required to develop manufacturing facilities and commercial products. In addition to formally educating and training individuals at the undergraduate, graduate, post doctoral, and visiting scholar levels, universities also inform the general population and government of the advantages of PV as a renewable technology. Universities address a broad spectrum of science and engineering issues—from basic science on materials and device physics, to exploring and identifying promising new concepts, and ultimately, to technology transfer for manufacturing.

I have been fortunate to work at the University of Delaware's Institute of Energy Conversion (IEC) for the past 21 years, starting as a junior scientist and advancing to my present position as Director. The Institute holds the unique position in the university community of having had active research programs in thin-film photovoltaics for nearly 28 years. IEC is also one of the few laboratories in the world working simultaneously on thin-film solar cell technologies based on $CuInSe_2$, CdTe, and Si. One of the hallmarks of IEC throughout its history is its ability to forge working alliances with industry, government laboratories, and other universities worldwide. Since this issue of *NREL PV Working With Industry* focuses on how university-based research supports and strengthens the U.S. PV industry, I'll highlight several activities at IEC.

For nearly four years, IEC has been a member of a consortium sponsored by DARPA (Defense Advanced Research Projects Agency) to develop vapor-phase manufacturing technologies for PV using intelligent process control. Led by ITN Energy Systems, the consortium comprises six companies and IEC, and was organized so that IEC provided the technology base for developing flexible $CuInGaSe_2$ modules. This program led to the establishment of a new company, Global Solar Energy, and is an example of how DOE-sponsored research at universities can be transferred to industry. The same research effort has also provided the foundation for an Advanced Technology Program through the National Institute of Standards and Technology to develop the next generation of high-performance $CuInSe_2$-based modules, in which IEC is a university partner, again leveraging DOE-sponsored research.

IEC research also supports industrial activities in several other ways. For example, Unisun, a start-up company, has been developing a new particle-based technology to deposit $CuInSe_2$-based materials and has used IEC's well-established cell-fabrication and analysis capabilities to evaluate the $CuInSe_2$ materials. This has allowed Unisun's R&D efforts to focus on the $CuInSe_2$ materials development rather than simultaneously developing the complementary processes needed for cell fabrication and materials and device evaluation. We are also collaborating with BP Solarex by using our CdTe expertise (developed under our long-standing DOE-sponsored research program) to evaluate and improve their CdTe material and devices. In the area of Si, IEC is working with AstroPower on next-generation, thin-silicon solar cells and has established collaborative efforts with NREL and other university researchers. In addition, IEC is a strong supporter and active participant in the Thin Film PV Partnership, in which NREL, university, and industrial researchers team to collectively solve problems.

Continued on page 11

PV Web Sites

DOE PV Program ..... *www.eren.doe.gov/pv*
About Photovoltaics • News and Information • About Our Program

National Center for Photovoltaics ..... *www.nrel.gov/ncpv*
World Class R&D • Partnering and Growth • Information Resources

The Center for Basic Sciences .....*www.nrel.gov/basic_sciences*
Capabilities • Optoelectronics • Crystal Growth and Devices

Measurements and Characterization .....*www.nrel.gov/measurements*
Virtual Lab • Capabilities • Doing Business • Data Sharing

Million Solar Roofs .....*www.eren.doe.gov/millionroofs*
Initiative Goals • Scope • Solar Technologies • Solar Registry

Photovoltaic Manufacturing Technology .....*www.nrel.gov/pvmat*
Overview • Partners • Fact Sheets • News and Events • Contacts

PV Silicon Materials Research .....*www.nrel.gov/silicon*
Thin-Layer Si Growth • Research with Industry

Surviving Disaster with Renewables ..*www.nrel.gov/surviving_disaster*
Renewables to the Rescue • NREL's Work • Solar Recovery

Masters of Science
The University PV Connection

Universities are known for their expertise in research and pursuit of scientific excellence. What better way to broaden a research perspective and expand problem-solving creativity than to tap into this reservoir of knowledge?

That's exactly what project leaders at DOE and NREL realized years ago when they began to pool resources with universities involved in PV research. As a result, PV technology is strong and is quickly becoming the energy source on everyone's lips for the new millennium. However, as with all successful technologies, maintaining leadership means continued research and development. Today, more than 70 universities throughout the country have teamed up with NREL scientists to further enhance PV technology. This partnership continues to be a major source of NREL's scientific success.

Management of the university research subcontracts is provided by two lead laboratories in DOE's National Center for Photovoltaics—NREL and Sandia National Laboratories. Brookhaven National Laboratory spearheads the efforts in environmental, safety, and health research.

Teaming Up with the Best and Brightest

Only the best and brightest from universities are selected for the program, based on the impact their research will have on the PV industry—both today and tomorrow. Within NREL, the university research subcontracts are divided into five categories: Historically Black Colleges and Universities (HBCUs), Future Generation, Crystalline Silicon, the Thin Film PV Partnership, and the Photovoltaic Manufacturing Technology (PVMaT) project.

"The main reason we subcontract with universities is to plant seeds for the PV technologies of tomorrow," says Bob McConnell, the key contact for PV-related university research at NREL. "If we fund the best and brightest to work on nonconventional ideas, some will reach new horizons and discover new knowledge and technology."

With regard to HBCUs, a program begun to help undergraduate students participate in active research, seven projects were selected that range from atomic-level microscopy of PV materials and solar architecture to field projects installing PV systems in developing countries. For example, students from Howard University are raising awareness in their community by implementing a virtual PV laboratory and applying PV technology to practical uses at the university, such as security lighting and scoreboards.

As part of the University R&D for Future Generation PV Technologies solicitation, 18 university projects will receive $5 million over a 3-year period. Cornell University is using an elastic measuring technique to explore the order in thin-film silicon, with characterization done at NREL using IR absorption and X-ray diffraction. Northwestern University's focus is next-generation transparent conducting oxides for improved PV performance. Chemical-reaction modeling for encapsulants in PV modules is under study at Pennsylvania State University, with another group at the university applying novel spectroscopic probes to fabricate textured thin-silicon films. Cal Tech's novel process for growing thin-film silicon is profiled on page 6. Two universities are investigating amorphous silicon: the University of Illinois and the University of Minnesota are studying medium- and long-range order, respectively. Three universities—UC San Diego (see article on page 7), UC Santa Barbara, and North Carolina State—are researching the new III-V nitrides for a possible 40%-efficient cell. The University of Oregon conducts novel capacitance measurements in CIGS alloys. The University of Rochester seeks to create an efficient thin-film PV device using porous

Dr. Joshua Hill/PIX08510

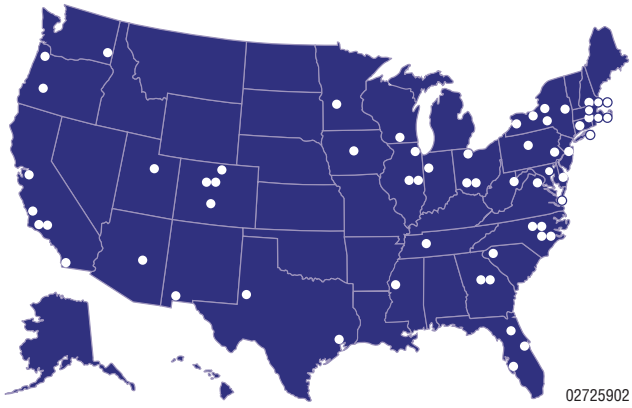
Texas Southern University (TSU) PV research associates Rahsaan Arscott and Oral LaFleur (from left to right) are shown working on a PV research project for TSU's School of Technology, Photovoltaic Research and Demonstration Laboratory. TSU is a partner in NREL's HBCU program.


Wayne Anderson/PIX08502

A "homemade" electron cyclotron resonance-chemical vapor deposition system for depositing thin-film silicon. The system is being discussed by research assistants Elena Guliants and Young Song of the State University of New York at Buffalo.

silicon technology. Quantum dots and multijunction solar cells are under study at West Virginia University, while Vanderbilt and UC Berkeley are exploring innovative solar cells based on quantum dots and polymers. Arizona State University is developing new test standards for future-generation PV technologies. Finally, SUNY Buffalo and Washington State University bring new techniques to the PV Program: synchrotron radiation for microstructure characterization and positron annihilation spectroscopy for analyzing defects.

Five universities received funding in the Crystalline-Silicon Research and Development Project, jointly managed by NREL and Sandia. At NREL, the emphasis is on crystal growth and material processing, whereas at Sandia, the focus is on device processing and development. NREL hopes to make defects and impurities in silicon material more benign. "The work of our university research partners is very complementary to our own research—we have an intimate collaboration with them," says Bhushan Sopori, the technical monitor for these subcontracts. Texas Tech is one such research partner, whose current research in fundamental theoretical work is described as "fantastic" by Sopori. The principal universities involved in the program are Georgia Tech, U.C. Berkeley, North Carolina State, Duke, and Cornell.



The NCPV's university partners span the continental United States.

NREL's university subcontractors involved in Future Generation and Crystalline Silicon research programs focus on basic research issues, whereas the universities involved in the Thin Film PV Partnership and PVMaT, about 24 in total, take on more of an applied research role that supports the further progress of existing PV technologies.

"Our program is intensely goal-oriented, and we organize people very aggressively on our national research teams," says Ken Zweibel, manager of the Thin Film PV Partnership. These teams research copper indium diselenide (CIS), cadmium telluride, and amorphous-silicon alloys for use in solar cells. A fourth team, called the ES&H National Team, focuses on the environmental, safety, and health issues surrounding the real-world applications of thin-film materials. Each team consists of 40 to 60 scientists—a very large research collaboration. "The CIS team has become even more intense lately," says Zweibel. "About one year ago, we started a new program within CIS that requests team members to sign confidentiality agreements so they can work 'inside the fence' on industrial problems."

The university partners get involved when industry encounters a problem and then enlists their help. That way, the students get to work on industry-specific issues. The program is well-suited for graduate students because it offers them a chance to work on real technological problems, which are usually tailored to make good graduate thesis projects. The Partnership has no trouble keeping students for three years or longer. "Students want to do things that include characterization of samples," says Zweibel. "They like to know why things happen—not just how to make them better."

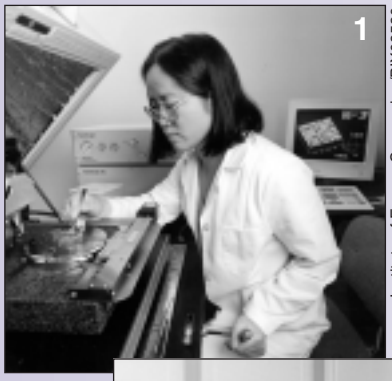
This year, about 20 universities are involved with the Thin Film PV Partnership. Projects range from work on cells, deposition processes, and devices to analytical techniques. In addition, the universities also perform their own thin-film research, as defined by their winning proposals in the 1997 Thin Film PV Partnership competition. Total funding of universities within the Partnership is about $13 million over the course of the resultant three-year contracts. About 80% of the university work funded is self-directed; the remainder is done in collaboration with the national research teams within the Thin Film PV Partnership.

One university in particular that is heavily involved with both NREL and industry is the University of Delaware through its Institute of Energy Conversion (IEC), which Zweibel calls a "mini NREL." The IEC is a multidisciplinary laboratory devoted to research and development of thin-film PV cells. Its research parameters, which include numerous PV manufacturers and government entities, allow undergraduate and graduate students to obtain degrees while working with professionals engaged in solar cell research. "The University of Delaware works with industry in a way NREL cannot—as a direct, private-to-private partner," Zweibel says.

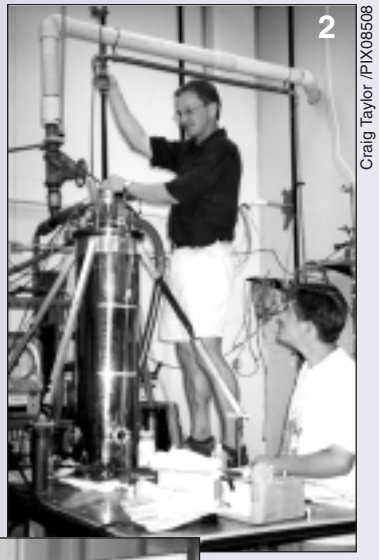
The IEC was designated a University Center of Excellence for Photovoltaic Research and Education in 1992, an award given by DOE to only two institutions in the United States. The second institution is the Georgia Institute of Technology's PV research center. Georgia Tech's PV research center mission is to improve the fundamental understanding of the science and technology of advanced crystalline-silicon PV devices, to fabricate high-efficiency solar cells, to provide training and enrich the educational experience of students in this field, and to give the United States a competitive edge by providing guidelines to industry and DOE for achieving cost-effective and high-efficiency PV devices. Georgia Tech works closely with both Sandia National Laboratories and NREL. At NREL, several research groups work with the institute as a research subcontractor, and NREL's director, Richard Truly, was director of the Georgia Tech Research Institute (from 1992 to mid-1997) before heading to NREL. Other university-related PV resources

that the NCPV draws on are two Regional Experiment Stations: the Florida Solar Energy Center, which is affiliated with the University of Florida, and the Southwest Technology Development Institute, associated with the University of New Mexico.

For the last category, PVMaT, universities are involved indirectly. PVMaT was initiated by DOE in 1990 to help the domestic PV industry extend its world leadership role. Since then, the U.S. PV industry has come a long way, helped along by this multi-phased, cost-shared project. Industry participants are selected for the program through competitive procurements. The solicitations are generally open to all companies that believe they can perform manufacturing R&D related to photovoltaics.



Institute of Energy Conversion/PIX08520



Craig Taylor /PIX08508

Dr. James Momoh/PIX08562

Ajeet Rohatgi/PIX08530

Although the PVMaT project doesn't contract with universities directly, about half the companies it works with have university research partners that aid them in addressing specific manufacturing issues. "We stimulate some interaction with universities because we believe it will be beneficial to industry, but we don't want to tell companies what to do," says Richard Mitchell, PVMaT's contract manager for module manufacturing. ASE Americas, Inc., has worked with Harvard University in the past to increase light-trapping on cell surfaces, with New Hampshire University to increase laser cutting rates for its wafers, and with Georgia Tech on high-speed processing of wafers. Both First Solar and BP Solarex have worked with the University of Texas at Arlington. The university's Automation and Robotics Research Institute (ARRI) conducted research for First Solar on high-speed illumination processes to design module components and for BP Solarex on production line and process improvements. "ARRI's primary interest is robotics research, so it is a useful university research institute for industry," says Mitchell. "But we're not trying to create centers of excellence, we just want to help companies."

Photo captions: (1) Scanning probe microscope at the Institute of Energy Conversion, University of Delaware, for microstructural characterization of materials used in fabricating thin-film solar cells. Juliette Zhu is mounting a sample for measurement. (2) University of Utah student, Russell Nagle, is inserting an amorphous-silicon sample into a superconducting magnet in preparation for measuring stability of amorphous silicon films at low temperatures, while Niko Schultz looks on. (3) Blending theoretical and practical understanding of PV systems, Dr. Momoh, Center for Energy Systems and Control, Howard University, takes his research team step by step through PV systems analysis. (4) In a research lab at the University Center of Excellence for Photovoltaic Research and Education at Georgia Institute of Technology, this graduate student is testing the evaporation of antireflection coating for Si solar cells.

Synergy for the Future

By expanding its research efforts through collaboration with universities, NREL has progressed further scientifically than it could ever have done on its own. But NREL isn't the only one who benefits from this research group effort. The Lab's university partners are also a plus for industry. "Each university subcontract supports graduate students who represent a future talent pool for industry," says McConnell. These students develop problem-solving skills that are very useful to industry and they can adapt to new problems well, unlike some basic researchers who sometimes become too specialized, he says.

Furthermore, funding these university research projects can have a dramatic impact on PV technology and the industry as a whole. "We are not competing against the U.S. PV industry," McConnell says. "On the contrary. It's better to have the technology discovered and developed here than to have it discovered and developed in foreign countries. That would be the worst thing for the U.S. PV industry."

NREL designed its research alliance with universities to maintain the U.S. PV industry's lead through technology advancement and to keep the economy strong by staying in step with international competition.

For more information, contact Bob McConnell at 303-384-6419.

Progress in PV Research
Two Universities Capturing the Future

Although there are many key players among NREL's university partners involved in "Future Generation" PV research, one of its oldest partners, the California Institute of Technology, and its newest partner, the University of California at San Diego, are both taking hold of PV's future with their own unique brand of research. Research in future-generation PV is important to the United States because PV is one of the technologies that will help power the 21st century as nonrenewable sources of energy are depleted further.

Cal Tech—Exploring Novel Processes

Cal Tech attracted NREL's attention in 1994, when Professor of Applied Physics Harry A. Atwater, Jr., began research in low-temperature growth of compound semiconductor solar cells on low-cost substrates.

Originally, the idea was to develop a novel solid-phase crystallization process for obtaining large-grained crystalline-germanium films on low-cost amorphous substrates, such as glass. These films could later serve as templates for gallium-arsenide thin-film solar cells. But in order to be compatible with glass, which softens at 550°C, growth of very large grain semiconductor thin films must be done at low temperatures. Achieving this may solve one of the most important challenges facing the PV community—the reduction of the cost-per-watt of solar power generating capacity.

"I realized that absent from the list of thin-film approaches were the III-V compound materials," says Atwater. "We decided to investigate further to see if breakthroughs were possible." The general trend is that efficiency increases with grain size in polycrystalline films. Polycrystalline material generally has small grain sizes, one of the primary problems limiting its use in thin films.

Atwater's idea attracted NREL's attention because it generated large templates at low cost. He used glass substrates to generate arrays of grains that are 100 times larger in size than the norm. However, by the time the Cal Tech team members could grow 50-micron grains, they realized it still wasn't large enough. "We humbly realized that for this material to work, we needed to achieve grain sizes of millimeters or even centimeters." Unfortunately, they had already reached the greatest size possible without exceeding the desired low temperature.

Cal Tech/PIX08735

Student Gang He and Professor Harry Atwater of Cal Tech discuss details of an epitaxial growth process.

In the meantime, Atwater saw an opportunity to use his process for the growth of crystalline silicon using a thin-film technology. Making the switch to this "new" material was logical. Silicon solar cells are known for their high efficiencies, they are more stable than traditional amorphous silicon thin films, and decades of research already exist for this material—scientists know more about crystalline silicon than any other solar cell material. And an existing crystalline-silicon PV industry infrastructure is already in place.

Yet as widespread as silicon technology is today, traditional silicon growth methods are expensive and produce substrates of limited size. Also, improvements in thin-film technologies strongly suggest that a significant part of the future of photovoltaics will be defined by thin films.

Consequently, about nine months ago, Cal Tech, among others, switched research directions and began to explore an analogous approach for silicon called "thin-layer silicon technology," in which the silicon absorber layer is supported on a low-cost substrate, such as glass. A deposition technique similar to that used to produce amorphous silicon (a-Si) is being used by the Cal Tech team to create this thin-layer silicon. The process involves template formation by selective nucleation and solid-phase epitaxy, which allows precise control of crystallization and growth of a-Si thin films and produces very large (10–50 micron) grains of silicon on glass. In addition, his researchers are exploring hot-wire chemical vapor deposition (HWCVD) to produce high-quality, thin poly-Si layers on large areas of glass. The HWCVD research may lead to improvements in the a-Si industry as well, expanding the research benefits to other applications.

But developing this technology requires further research by the Cal Tech team. For now, their focus is on improving silicon material to increase grain size and lower defect density, improving silicon film growth rates at low temperatures, and developing a surface with enhanced optical absorption.

"Partnering with NREL gives us a sharp focus," says Atwater. "It brings the problems faced by manufacturers today to our attention." Having NREL as their "center of gravity" also allows an effective use of PV research resources and encourages research collaboration. At NREL, Atwater was invited to attend several of Bhushan Sopori's annual crystalline-silicon workshops. He also participated in the Basic Energy Sciences' team activity on thin-film silicon led by Satyen Deb,

who directs NREL's Center for Basic Science. During one of those meetings, Atwater met Professor Kelvin Lynn, Washington State University's Materials Science Director. Washington State, another NREL-university research partner involved in Future Generation research, uses positron annihilation spectroscopy to analyze silicon defects. Since Atwater's meeting with Lynn, Cal Tech and Washington State have collaborated in research.

Because scientists at NREL and Cal Tech are both working on different approaches to thin-layer silicon growth for PV, they worked together, along with other university researchers, on a publication entitled "Research Opportunities in Crystalline Silicon Photovoltaics for the 21st Century." The paper, prepared under Atwater's leadership, serves as a "white paper" to guide further research funding in this field. It appeared in the Electrochemical Society Proceedings entitled *Photovoltaics for the 21st Century*.

Cal Tech's overall research objective is to overcome the obstacles that retard the development of highly efficient, thin-layer crystalline-silicon solar cells on low-cost substrates. But the ultimate measure of Cal Tech's success in its collaborative research efforts will be an increased interest in thin-film silicon technology by the PV industry.

Harry Atwater and Charles Tu, whose research is highlighted in the following section, both participate in the Center of Excellence for Synthesis and Processing of Advanced Materials. Atwater is active in the Thin-Film Team and Tu in the Next-Generation PV Team. The Center is funded by DOE's Office of Science, Basic Energy Sciences. Center Director Satyen Deb often refers to this as "glue funding," because it binds together universities and national labs in collaborations involving both basic and applied research.

For more information, contact Harry Atwater at 626-395-2197.

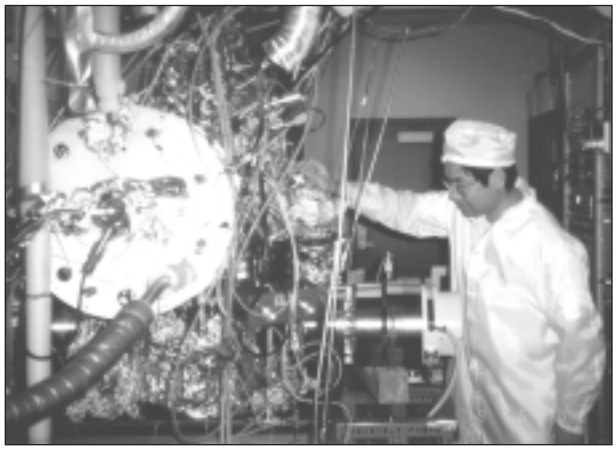
UCSD—Investigating Novel Materials

Few people know more about gas-source molecular beam epitaxy (MBE) than Professor Charles Tu at the University of California at San Diego—one of NREL's newest research partners. Tu, a former lecturer in the Yale University Physics Department and technical staff member at AT&T Bell Laboratories in New Jersey, is conducting research into III-V compound structures grown by gas-source MBE for electronic and optoelectronic applications. Tu arrived at UCSD in 1988 and set up the first two gas-source MBE systems to be used in U.S. universities.

But the systems are not what got NREL's attention. Gas-source MBE has been around for a long time, but the material Tu is researching for use in semiconductors is new. Tu is working with a novel class of nitrogen-containing III-V compounds, such as gallium indium nitrogen arsenide (GaInNAs). The material can be lattice-matched to GaAs and has a lower bandgap.

"I discovered that incorporating a small amount of nitrogen into the compound structure has a large effect on the properties of compound semiconductors," says Tu. Originally, Tu used this material for fiber optics applications, but soon explored using it for multijunction solar cells. He realized, however, that certain problems needed to be overcome, such as the decrease in photoluminescence intensity and photocurrent collection efficiency that occurs when nitrogen content is increased in the material.

When it comes to problem-solving, working with NREL as a research partner has already paid off. "Quite active collaborations are going on right now due to the NREL partnership," says Tu. "You get to know people and their partners." Not only is Tu working with Yong Zhang and Angelo Mascarenhas at NREL, but through them, he was introduced to the work of Professor Venky Narayanamurti at Harvard University, a subtier contractor to UC Santa Barbara, after Mascarenhas discovered that the research being conducted by the two universities was complementary.



Huoping/PIX06245

Henry Huoping, a UCSD graduate student working with Charles Tu, uses a modified Varian Gen-II gas-source MBE system to study GaInNAs structures.

"I provide the new material and they use different characterization techniques to look at it," says Tu, summarizing the partnership. "Only a handful of people in the United States are working on this right now."

NREL and Harvard University are doing characterization research on Tu's new material to learn more about its optical properties. At NREL, Yong Zhang, a senior scientist on the Solid State Spectroscopy Team, uses reflection/absorption spectroscopy to study the material, which is grown and ther-

Continued on page 10

NREL PV researchers and managers interact with industry on several levels. Although we freely share our research results and the nonproprietary results of our subcontractors, many of our interactions involve the exchange of confidential information, including the results of certain measurements. The following are some notable recent interactions.

A valuable space-industry solar cell set a world-record efficiency under terrestrial conditions. **NREL's** GaInP/GaAs solar cell, invented by **Jerry Olson**, was recognized as valuable for the space industry when it achieved almost a 30% efficiency. In July 1998, an active Ge junction was added to the multijunction cell by **Spectrolab** to increase its efficiency without increasing manufacturing costs. Last October, GaInP/GaAs/Ge cells became well positioned for use on Earth when Spectrolab and NREL's III-V, Cleanroom, and Measurements Teams achieved a world-record conversion efficiency of 32.3% at 47 suns for a triple-junction $GaInP_2$/GaAs/Ge concentrator solar cell for terrestrial applications. The two-terminal, high-voltage (2.8 V) nature of this cell makes it ideal for use in terrestrial concentrator systems. **Contact: Sarah Kurtz, 303-384-6475**

NREL's Thin Film PV Partnership has supported **Siemens Solar Industries** (SSI) for the past several years in developing thin-film CIS-based products. NREL, the **California Energy Commission**, and SSI were joint winners of an R&D 100 Award for the development of these CIS-based products. SSI recently received a letter of approval for Underwriters Laboratories (UL) listing for its thin-film CIS-based commercial products. Currently, there are four products available in the market: 5, 10, 20, and 40 W. The UL listing should be of significant help to SSI as these CIS-based products gain acceptance in the marketplace. Contact: **Harin Ullal, 303-384-6486**

In September 1999, **Toshiaki Sasaki** of **Fuji Electric** visited **NREL** and brought two dual-junction amorphous-silicon submodules manufactured on polyimide using the "SCAF" interconnection scheme. In this scheme, cells are connected in parallel and series through small holes punched into the polyimide foil, with patterned conductors and insulators deposited by vacuum deposition to accomplish the interconnects. Fuji indicated that this scheme presently causes a 7% area loss. Thanks to the collaboration of the NREL module performance group, the modules were measured while Sasaki was at NREL. The modules had been light-soaked for 1000 hours at Fuji, and NREL inferred aperture-area efficiencies of about 8.4% for these 750-cm^2 submodules. Contact: **Bolko von Roedern, 303-384-6480**

More changes are brewing for the PV portion of the National Electrical Code (NEC). A forum of industry participants, including **BP Solarex, Siemens Solar Industries, Advanced Energy Systems, Salt River Project, PVUSA, Southwest Technology Development Institute** (SWTDI)**, NREL,** and **Sandia National Laboratories** met in October to discuss changes to the 2002 version. The NEC describes the requirements in the United States for safe installations of PV systems. The technical group reviewed more than 20 proposed changes to the NEC. Some of the most significant changes to the code involved diversion charge controllers, ground-fault protection, array disconnects, and marking and safety of batteries in PV systems. The proposed changes will be submitted to CMP-3 for approval in January 2000. If approved, the changes will help improve PV installations and should lead to better long-term system performance and reliability. Contact: **Ben Kroposki, 303-384-6170**

In early November, a new AC module from **Ascension Technology** was installed at **NREL's Outdoor Test Facility**. The unit consists of one 285-watt module from **ASE Americas** and one 325-watt inverter from Ascension. The AC module is a prototype developed under a **Photovoltaic Manufacturing Technology** (PVMaT) 5A subcontract. The packaged AC module is a new version of the SunSine™, which has been under test at the OTF since 1998. The AC modules will be monitored for long-term performance. This testing will help Ascension understand the performance and reliability of the new AC module package and help them make changes for a final commercial product. Temperature data collected from the inverter will help in predicting inverter lifetime. Contact: **Ben Kroposki, 303-384-6170**

The **NREL Amorphous Silicon Team** has fabricated 8.7%-efficient hydrogenated amorphous silicon (a-Si:H) n-i-p solar cells with all-doped and undoped Si layers made in-house by hot-wire chemical vapor deposition (HWCVD). The a-Si:H i-layer is deposited at 18 Å/s and the doped layers are at 11 Å/s for n-type and 5 Å/s for p-type, much greater than the usual 1–2 Å/s used in industrial PV production by plasma-enhanced (PE) CVD. In the hot-wire technique, silane is thermally decomposed onto a substrate by a 2050°C tungsten filament. NREL researches HWCVD a-Si:H because of the demonstrated high stability of film properties at high deposition rate. Previously, NREL collaborated with **United Solar Systems Corp.** to fabricate a 9.8% hybrid HW/PE CVD device, but that cell had PECVD-doped and i-p interface layers deposited at low rates by United Solar using proprietary techniques. Due to improved

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Publications

Dissemination of research results is an important aspect of technology transfer. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings, as exemplified by the recent publications listed below. PV program and subcontractor reports are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161. For further information, contact Ann Hansen (303-384-6492).

Coutts, T.J. *Overview of Thermophotovoltaic Generation of Electricity.* 6 pp.; 1999; CP-520-26904.

Emery, K. "Rating of Photovoltaic Performance." *IEEE Transactions on Electron Devices.* Vol. 46(10), October 1999; pp. 1928–1931; JA-520-26034.

Gao, W.; Lee, S.H.; Bullock, J.; et al. "First a-SiC:H Photovoltaic-Powered Monolithic Tandem Electrochromic Smart Window Device." *Solar Energy Materials and Solar Cells.* Vol. 59(3), October 1999; pp. 243–254; JA-520-24430.

Ginley, D.S. *Nanoparticle Derived Contacts for Photovoltaic Cells.* 7 pp.; 1999; CP-520-26685.

Jorgensen, G.; Brunold, S.; Kohl, M.; et al. *Durability Testing of Antireflection Coatings for Solar Applications.* 14 pp.; 1999; CP-520-26843.

Kapur, V.K.; McConnell, R.D.; Carlson, D.; et al., eds. (1999). *Photovoltaics for the 21st Century, Proceedings of the International Symposium*, The Electrochemical Society, Pennington, NJ, Vol. 99-11.

McMahon, W.E.; Olson, J.M. "Atomic-Resolution STM Study of a Structural Phase Transition of Steps on Vicinal As/Ge(100)." *Physical Review. B, Condensed Matter.* Vol. 60(23), 15 December 1999-I; pp. 15,999–16,005; JA-520-26819.

Mid-Atlantic Region Consumer's Guide to Buying a Solar Electric System. 27 pp.; 1999; BR-520-27166.

Rockett, A.; Granath, K.; Asher, S.; et al. "Na Incorporation in Mo and $CuInSe_2$ from Production Processes." *Solar Energy Materials and Solar Cells.* Vol. 59(3), October 1999; pp. 255–264; JA-520-27802.

Sopori, B. *Impurities and Defects in Photovoltaic Si Devices: A Review.* 16 pp.; 1999; CP-520-27524.

Weichman, J.; Hayter, S.; Gwinner, D. *Photovoltaic and Solar-Thermal Technologies in Residential Building Codes: Tackling Building Code Requirements to Overcome the Impediments to Applying New Technologies.* 86 pp.; 1999; TP-550-26579.

Witt, C.E.; Mitchell, R.L.; Symko-Davies, M.; et al. *Current Status and Future Prospects for the PVMaT Project.* 7 pp.; 1999; CP-520-26922.

News at Press Time

NCPV Advisory Board Meets in Denver

The NCPV Advisory Board met at NREL, February 1–2, to review recent NCPV activities and to explore strategies for continued progress and leadership in R&D, partnering, and dissemination of information. Two new Board members were welcomed: Harry B. Shimp, President and CEO, BP Solarex; and J. Michael Davis, President and CEO, Kyocera Solar, Inc. All the existing Board members attended, including Allen Barnett of AstroPower, Chester Farris of Siemens Solar Industries, Roger Little of Spire Corporation, Lionel Kimerling of Massachusetts Institute of Technology, William Roppenecker of Trace Engineering, and Richard Schwartz of Purdue University. They reviewed the R&D portfolio of the NCPV and the U.S. Photovoltaics Program, revisited the PV Industry Roadmap and DOE PV Program Five-Year Plan, and investigated strategies for the U.S. PV Program—with emphasis on investments that will be needed in the coming few years. While in Denver, board members met with NCPV senior staff, executive management from Sandia and NREL, and with James Rannels, Director of DOE's Office of Solar Technologies. In its capacity, the Board provides guidance regarding NCPV priorities, evaluates the needs and directions of programs, and assists in the strategic planning processes with the NCPV and DOE for a national vision, mission, strategy, and metrics for photovoltaics. Contact: **Larry Kazmerski, 303-384-6600**

PV Expo a Hot Ticket at Stock Show

The National Western Stock Show is a famous event in Denver. Each year, for two weeks in January, Stock Show activities capture the attention of the public and the media in Colorado and neighboring states. This year was no exception, with more than 600,000 visitors crowding the turnstiles. Farmers and ranchers from far and near came to show and sell their prize livestock and learn the latest farming and ranching techniques. For the fifth year, NREL volunteers staffed a booth to display and distribute information on renewable energy. In addition, they presented three free "Workshops on Solar and Wind Power for the Farm and Ranch." Workshop audiences, which totaled more than 400 people, learned how electricity from PV and wind turbines provides an economical option for stock watering, electric fence charging, and irrigation. Contact: **Wendy Larsen, 303-384-6497**

"Must Read" PV Documents

Three documents important to the PV Program are either available now—or soon will be. The *National Photovoltaics Program Plan for 2000-2004* (also called the Five-Year Plan) has arrived, and it's must reading for anyone looking to understand the thrust of the PV Program. Titled "Photovoltaics: Energy for the New Millennium," the document is downloadable from the NCPV Web site (*http://www.nrel.gov/ncpv/pdfs/25847X.pdf*). Coming early in March is the *Photovoltaic Energy Program Overview, Fiscal Year 1999*, which highlights a year's worth of accomplishments in Research and Development, Technology Development, and Systems Engineering and Applications. Also in March comes the *Photovoltaic Energy Program Contract Summary, Fiscal Year 1999*, which includes a two-page status report from each Program subcontractor. Contact: **Don Gwinner, 303-384-6570**

University Corner

When the **University of Colorado at Boulder's** chemistry department appointed **NREL's Art Nozik** Professor Adjoint, he naturally turned to the science and technology of renewable energy for his graduate course material. His expertise is solar photochemistry, but he wanted to give students a broader background in renewables. Rather than cover all the topics himself, he decided to round up 13 expert guest lecturers from NREL, including **Dan DuBois**, also recently appointed Professor Adjoint in chemistry at CU; **Larry Kazmerski, Brian Keyes, Ken Zweibel, Mike Seibert, Brian Gregg, Howard Branz, Helena Chum, John Turner, Mike Heben, Bill Adney, Ron Judkoff,** and **Bob Thresher**. This way, he could expose students to experts in the different fields of renewable energy such as photovoltaics, photobiology, photosynthesis, photoconversion, catalysis and carbon dioxide chemistry, fuel cells, biotechnology, biofuels, wind energy, hydrogen, and solar thermal conversion. The program, given over the course of the past entire fall semester, was very popular with students. Contact: **Art Nozik, 303-384-6603**

The IEEE SCC21 Small Systems Testing PAR Working Group met in October 1999, at **Arizona State University** to discuss "IEEE PAR 1526—Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems." The group reviewed the **NREL** document, "Procedures for Determining the Performance of Stand-Alone PV Systems" (NREL/TP-520-27031), which is the basis for developing the IEEE standard. The NREL test procedure was recently revised after being validated at four sites: NREL, **Florida Solar Energy Center, Southwest Technology Development Institute, and PVUSA**. The group reviewed the revised NREL test procedures and offered suggestions so that the test procedure can be developed into an IEEE standard. This standard will be used by testing agencies to determine stand-alone PV system performance. Contact: **Peter McNutt, 303-384-6767**

Preparations have begun for the **10th Workshop on Crystalline Silicon Solar Cell Materials and Processing**. The Program Committee, which includes representatives from three U.S. universities and one each from Germany and Japan, met at the **NREL Visitor Center** in January to discuss planning issues. Members of the committee are: **Ron Sinton, Sinton Consulting; Dick Swanson, SunPower; Teh Tan, Duke University; Juris Kalejs, ASE Americas; Eicke Weber, University of California, Berkeley; Juergen Werner, University of Stuttgart; Tadashi Saitoh, Tokyo Agriculture University; Michael Stavola, Lehigh University; James Gee, Sandia;** and **Bhushan Sopori**, NREL.

The 10th Workshop will be held on August 13–16, 2000, at Copper Mountain, CO. A review meeting for the **Silicon Team of the Center of Excellence** for Advanced Material Processing will be held in conjunction with the Workshop, on Sunday, August 13. The theme of the 10th Workshop will be "Si Photovoltaics: 10 Years of Progress and Opportunities for the Future." Two special sessions will address current bottlenecks and approaches that can circumvent the current limitations in Si-PV to meet the PV Industry Roadmap goals. In addition, a new session, "Metallization and Interconnections," will cover recent advances in epoxy interconnections and printed contacts in the microelectronics industry. This area of technology is very important to the Si-PV industry to address new metallization schemes for low-cost cell interconnections. Contact: **Bhushan Sopori, 303-384-6683**

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mally annealed at various temperatures. "We did contactless electroreflectance measurements for a set of GaInNAs samples and observed—with increasing annealing temperature—a slight increase of the bandgap energy. We also saw an improvement in the sample uniformity—or put another way, a reduction in the alloy fluctuation," says Zhang.

"We also confirmed a finding of theirs using our technique, which is that the annealing changes the conductivity type from n-type (in the as-grown sample) to p-type.

Meanwhile, Narayanamurti's team at Harvard is using ballistic electron emission microscopy (BEEM) to study the physics of electron and hole transport in Tu's material. Unlike more traditional methods of microscopy, BEEM allows the study of local transport with nanometer resolution. Depending on the carrier mean free path, interfaces buried deep in the semiconductor can be probed.

By working in a collaborative environment with NREL and other university research partners, Tu hopes that his GaInNAs structures grown by MBE will someday be used for solar cells with very high efficiencies that reach 40%.

For more information, contact Charles Tu at 858-534-4687.

Industry Update, Continued from p. 8

light-trapping, NREL's earlier n-i-p solar cell recipes yielded more than a 2% improvement in efficiency when transferred to textured Ag/ZnO-coated stainless steel supplied by United Solar. Contact: **Qi Wang, 303-384-6681**

Solar power generation in the Northwest was the hot topic at the second Northwest Solar Summit held in Winthrop, Washington, in November 1999. The summit was attended by **NREL** and members from 16 utilities (15 rural electric cooperatives [RECs] and **Bonneville Power Administration** [BPA]), the PV industry (**Siemens Solar, AstroPower, BP Solarex, Spire, Trace Engineering**), universities, state and city agency staff, and the **Environmental Protection Agency**. The overall theme of the meeting was distributed generation, particularly solar for the Northwest. NREL's participation in the first summit involved the presentation of the Okanogan feeder study, which showed it was less expensive to use distributed resources (gas generators, efficiency, and PV) than to upgrade a feeder in northeast Washington, even with electricity at $0.05/kWh. This year's presentation from NREL focused on coupling or merging value propositions for distributed generation. The summit had much greater utility and state and local agency participation than in past years. BPA has volunteered to work with NREL for outreach of NREL's products to its 140 REC customers. As usual, value analysis and documentation were of major concern to the REC community. Contact: **Christy Herig, 303-384-6546**

The highest-efficiency ZnO/CdS/CIGS thin-film solar cell reported by **NREL's CIS Team** (18.8%, world record) was fabricated on Mo-coated glass substrates provided by one of NREL's industrial partners, **Lockheed Martin Astronautics** (LMA). However, a great deal of variation in the substrates obtained from LMA caused problems for researchers, who also found it difficult to fabricate high-efficiency devices consistently on the substrates fabricated in-house. To solve the problem, NREL's CIS Team, with the help of the Measurements and Characterization Division of the NCPV, undertook a systematic study of glass preparation, Mo sputter conditions, morphology, and microstructure effects using a comprehensive matrix of experimental conditions (**Jeff Alleman, Falah Hasoon**). The important aspects of growing high-efficiency CIGS films (**Miguel Contreras**) were incorporated, and resulted in fewer growth defects in the absorber (Falah Hasoon, **Kim Jones**). This work has resulted in many devices with efficiencies greater than 18%, with the best ones at 18.5%. The researchers are also looking at the repeatability of the process. Over a period of a month, they have produced 18%-efficienct cells on different batches of Mo. Contact: **Kannan Ramanathan, 303-384-6454**

PPG Industries, Inc., a major U.S. glassmaker, is considering possible entry into the thin-film PV marketplace through a strategic alliance with an existing PV company. **NREL's Ken Zweibel** visited PPG, Pittsburgh, PA, on November 11–12, 1999, at the invitation of senior management who are members of the PPG business development team. Zweibel met with **Chuck Greenberg**, **Peter Foller**, and others (including two vice presidents) who are members of the development team, and **David Schiferl, Los Alamos National Laboratory**, who is DOE's representative at PPG. Subsequent to the visit, Greenberg wrote: "I am putting together a position paper for **Gerry Gruber**, our VP of Science and Technology." This indicates progress toward a potential position in PV for PPG. Contact: **Ken Zweibel, 303-384-6441**

ITN/Energy Systems (ITN/ES), a spin-off of **Martin Marietta** (now **Lockheed Martin**), is about to get bigger. In December 1999, **UniSource Energy** (UE, parent company of **Tucson Electric Power**), Tucson, AZ, announced an investment of $14 million in **Global Solar Energy** (GSE), Tucson, AZ, to expand the manufacturing capacity of thin-film-based CIS flexible products to 10 MW in the next few years. GSE is a joint venture of UE (67%) and ITN/ES (37%) of Wheat Ridge, CO. ITN/ES is a spin-off of Martin Marietta from the mid-1990s. **DOE/NREL** was instrumental in starting the CIS project at Martin Marietta, Denver, CO, in the early 1990s. GSE is currently being supported by two NREL projects in the Thin Film PV Partnership program and PVMaT. This new investment should help GSE expand its flexible thin-film CIS-based manufacturing capacity to 10 MW in the next few years. Contact: **Harin Ullal, 303-384-6486**

Editorial, Continued from p. 2

It's clear that university research activities and education programs are providing—and will continue to provide—the foundations for the emerging PV industry. Further, the effective transfer of laboratory technology to a manufacturing facility requires a fundamental science and engineering underpinning that can most effectively be developed at the university level. The key issue, however, that the U.S. PV program faces is *not* the collaboration and coordination of the industrial, national laboratories, and university research efforts—that is already well established. Rather, the issue is whether federal support will be adequate to sustain the U.S. leadership in a globally developing PV industry—but this is a topic for another editorial!

PV Calendar

April 10–14, 2000, *The International Conference on Metallurgical Coatings and Thin Films*. Sponsor: American Vacuum Society. Location: San Diego, CA. Phone: 212-248-0200. Web site: *www.vacuum.org*

April 16–19, 2000, *16th NCPV Photovoltaics Program Review*. Sponsors: NREL, Sandia. Location: Adams Mark Hotel, Denver, CO. Contact: Camilla Course. Phone: 303-275-4321. Web site: *www.nrel.gov/ncpv_prm/*

April 19–22, 2000, *SOLTECH 2000: The Annual Solar Energy Conference*. Sponsor: Solar Energy Industries Association. Location: Washington, DC. Web site: *www.seia.org/main.htm*

April 24–28, 2000, *Materials Research Society Spring 2000 Meeting*. Sponsor: MRS. Location: San Francisco, CA. Web site: *www.mrs.org/meetings/spring00*

May 1–5, 2000, *16th European Photovoltaic Solar Energy Conference and Exhibition*. Location: Glasgow, Scotland, UK. Contact: Jenniy Gregory, Secretary General, The British PV Association. Phone: +44.118.932.4418. E-mail: PVUK@itpower.co.uk. Web site: *www.wip.tnet.de/pv00.htm*

June 10–15, 2000, *FEMA 2000: Technology Partnership for Emergency Management Workshop and Exhibition*. Sponsor: NREL. Location: Colorado Springs, CO. Contact: Wendy Larsen, NREL. Phone: 303-384-6497. E-mail: wendy_larsen@nrel.gov.

June 16–21, 2000, *SOLAR 2000: Solar Powers Life—Share the Energy*. Sponsor: American Solar Energy Society. Location: Madison, WI. Contact: ASES. Phone: 303-443-3130. Web site: *www.ases.org/conference/solar2000.htm*

July 1–7, 2000, World Renewable Energy Congress 2000. Sponsor: WREN. Location: Brighton, United Kingdom. Web site: *www.wrenuk.co.uk/menu.html*

August 13-16, 2000, *10th Workshop on Crystalline Silicon Solar Cell Materials and Processing.* Sponsor: NREL. Location: Copper Mountain, CO. Contact: Bhushan Sopori. Phone: 303-384-6683.

September 17–22, 2000, *28th IEEE PV Specialists Conference*. Location: Anchorage Hilton, Anchorage, AK. Contacts: Ajeet Rohatgi. Phone: 404-894-7692. Or John Benner. Phone: 303-384-6496. Web site: *http://ieeepvsc.nrel.gov/pvsc28home.html*

This quarterly report encourages cooperative R&D by providing the U.S. PV industry with information on activities and capabilities of the laboratories and researchers at NREL.

Robert McConnell 303-384-6419
PV Program Communications

Tom Surek 303-384-6471
Technology Manager, Photovoltaics

Lauren Poole 303-384-6624
Writer

Susan Moon.....303-384-6631
Editor

Jim Miller.....303-384-6595
Graphic Designer

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PV Program
1617 Cole Blvd. Golden, CO 80401-3393

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