NREL PV

Working With Industry

Shedding Light on the Matter

Advances in the field of photovoltaics rely on an intimate understanding of the interaction of light and matter. The more completely we understand the interaction—and apply that knowledge to improving PV technologies—the sooner citizens of the United States and the world can move into an era of clean, affordable energy generated directly from the sun.

At NREL, and within the universities and private-sector companies that partner with the Lab, the insights gained and the inroads made have been substantial. More than ever, PV devices are efficient, cost effective, and manufacturable. The scientific curiosity, ingenuity, and *just plain hard work* of hundreds of people within this partnership have made it so.

But much remains to be investigated. PV research at its most fundamental level is conducted within NREL's Basic Sciences Center, led by Satyen Deb—who is the editorialist for this issue.

Within his center, teams of scientists are using solid-state theory to predict the existence of new semiconductors, as well as solid-state spectroscopy to reveal the intricacies of defects in PV materials. They're using chemical sciences to synthesize quantum dots of a variety of PV materials, and examining the dramatic effects that are introduced when the crystals are "nanosized." The work of another team is expanding the science of crystal growth and devices, including developing methods to expand the supply of silicon to the PV industry.

So, too, are the Lab's university partners making their presence felt. They're lighting the way to future-generation PV technologies, as you'll read in the article that profiles the PV sessions held at the most recent meeting of the Electrochemical Society. These sessions were successful in bringing together experts in PV and related fields to discuss initiatives on innovative, high-risk, high-payoff research.

Features

Departments

Second Quarter, 1999

Photovoltaics R&D—More Exciting Technologies Await

An Editorial by Satyen Deb

David Parsons, NREL/PIX08093

Martha Krebs, Director of DOE's Office of Science, is pictured with NREL's Satyen Deb (center) and Miguel Contreras. As the Director of NREL's Basic Sciences Center, Deb is responsible for a staff of about 80. Photovoltaics R&D is high on their list of research priorities.

Photovoltaic technology is a subject that's near and dear to my heart. Since I came to NREL some 21 years ago, I have been involved—one way or another—with researching and developing this technology.

I firmly believe photovoltaics has a great future. In the course of the next few decades, it is bound to make a strong impact by displacing a significant percentage of the conventional energy supply—not only in this country but in the world at large.

It has been my good fortune to attract, and be associated with, a great number of NREL's very talented scientists. Over the years, they have pushed the frontiers of PV technology while continuing to provide it with a strong scientific foundation. They are innovators in every sense of the word, with their work leading to exciting new developments in several different areas of PV technology.

I am particularly proud of my long association with one of the most exciting PV technologies yet introduced—the high-efficiency GaInP/GaAs solar cell. This cell has not only achieved world-record efficiency (30.2%), but has also been an enormously fruitful area of cutting-edge, fundamental research that has enabled NREL to achieve worldwide recognition as a premier research institution. It is gratifying to see that this technology is now being exploited by several private companies, particularly for space applications. This was possible because of the strong support provided by the DOE Office of Energy Efficiency and Renewable Energy and the DOE Office of Science, Basic Energy Sciences. This is an outstanding example of a success story based on the integration of DOE's basic and applied research in the PV technology area.

One of my major responsibilities at NREL is to ensure that our PV-related basic research is strong. This is crucial for PV, because today's technology becomes obsolete tomorrow—particularly in the face of intense competition worldwide, notably from Europe and Japan, where *enormous* resources are being dedicated to basic R&D for photovoltaics. The sustenance of U.S. leadership in this area critically depends on our ability to maintain a long-range vision for PV technology.

As Jack Morton, Vice President of Research at Bell Laboratories, said many years ago, "An industry can be a dynasty spanning many generations—if it has the good fortune or good sense to seek repeated renewal... through repeated trips back to the 'fountain of youth' of basic science. It must consciously seek to translate basic science into new technology that is economically more powerful than the old."

I believe that this is particularly true for photovoltaics. When I said earlier that the GaInP/GaAs solar cell was one of the most exciting PV technologies *yet introduced*, I meant just that. There are many innovative PV technologies—*and, assuredly, ones that are even more exciting*—on the scientific horizon. With this thought planted firmly in mind, we must move forward with a strong basic research program for U.S. photovoltaics.

Contact Satyen Deb at 303-384-6405.

PV Web Sites

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

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

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

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

Solid State Spectroscopy.....*http://www.nrel.gov/sss*
Capabilities • Research Topics • Team Members

Solid State Theory.....*http://www.sst.nrel.gov*
Research Topics • Staff • Downloadable Data

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

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

NREL's Basic Sciences Center comprises nine teams devoted to fundamental research in renewable energy sciences. The PV-related research of four of those teams—Solid State Theory, Solid State Spectroscopy, Chemical Sciences, and Crystal Growth and Devices—is profiled in the following article.

Predicting Outcomes with Solid-State Theory

Alex Zunger and the Solid State Theory Team sometimes feel that they are in the midst of a revolution. The changes taking place in solid-state theory in the last 10–15 years are that dramatic—and what this signifies for PV technologies could be even more so.

Twenty years ago, theorists could only develop models of semiconductors that explained, after the fact, why an experiment achieved the results it did. Now they have the tools to *predict* results in certain areas. Before any experimentation takes place, they can predict some properties of semiconductors, including optical properties of quantum dots, effect of surface reconstruction on "spontaneous ordering," and the effect of defects on doping and on stability of copper indium diselenide (CIS). The predictions stem from quantum-mechanical computations based on the charge and mass of the electron and Planck's constant as the only input.

"We can narrow down a large number of possibilities theoretically, which provides experimentalists with strong candidate materials to test in the laboratory," says Zunger. Beyond this, theory contributes to finding solutions for existing semiconductor problems (e.g., finding the reason behind certain effects that limit the PV performance of amorphous silicon or nitride alloys).

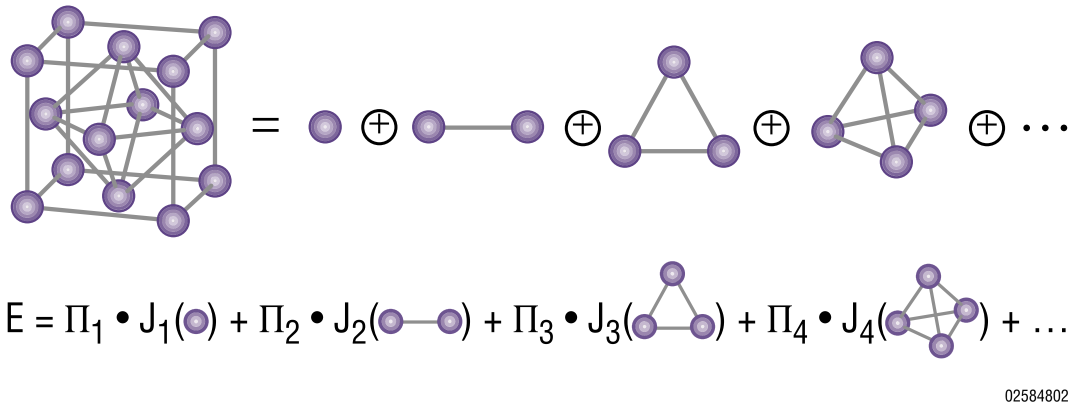
Theorists are also applying their expertise to a search for new semiconductor materials. It is highly unlikely that the ten or so existing basic semiconductors (all belonging to the same crystal type!) represent an exhaustive list. But an approach was needed to search the universe of possibilities.

Rising to the challenge, theoretical physicists at NREL have developed strategies that take advantage of fast computers and concepts from quantum mechanics to search for the "winning combination" of atoms producing novel, stable crystal structures. The method they invented—Linear Expansion in Geometric Objects (LEGO)—is based on the recognition that even complex crystal structures can be viewed as a collection of simple geometric objects, such as pairs of atoms (dumbbells), triangles of atoms, and so on. By assigning a quantum-mechanical energy value to each geometric object, physicists can rapidly scan hundreds of thousands of candidate structures (obtained by different assemblies of the geometric objects), looking for the one with the lowest overall energy.

Using the LEGO approach, NREL physicists have predicted a number of hitherto unsuspected structures, including intermetallics such as Cu_7Pt, Pd_3Pt, RhPt, and Rh_3Pt. In oxide physics, Chris Wolverton and Zunger used LEGO to predict that the partially "de-lithiated" $Li_{0.5}CoO_2$ battery material will have the unexpected $LiCo_2O_4$ spinel structure. This was later experimentally confirmed.
(See Wolverton and Zunger, "Prediction of Li Intercalation and Battery Voltages in Layered vs. Cubic Li_xCoO_2," *Electrochemical and Solid-State Letters*, July 1998.)

Proving a theory with experimentation was also rewarding in another case—that of CIS materials. Other PV materials, such as silicon or gallium arsenide, demand tender loving care... they must be grown perfectly with few or no defects in order to perform optimally. CIS, on the other hand, can have major defects and still perform well. NREL's solid-state theorists explained this mystery using first-

Linear Expansion in Geometric Objects (LEGO)



In the search for new semiconductors, NREL physicists use LEGO to break crystal structures into geometric figures whose energy can be written as a linear combination of the energies of its constituent figures. J's are obtained from quantum-mechanical calculations and Π's are structure-dependent weights of each geometric object.

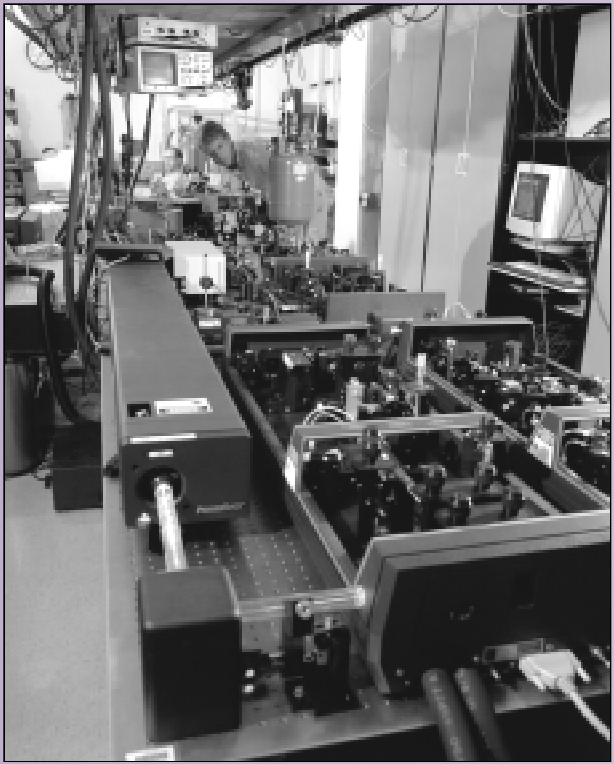
principles calculations. The process for preparing CIS unwittingly involves "abusing" it: removing Cu from the lattice, which creates Cu vacancies (designated as V_{Cu}), and placing In on the Cu site (In_{Cu}). Working together, NREL theorists and PV researchers confirmed that V_{Cu} and In_{Cu}, both of which are defects, actually attract and compensate for each other. The combination becomes a self-healing mechanism. (See Zhang, Wei, and Zunger, "Stabilization of Ternary Compounds via Ordered Arrays of Defect Pairs," *Physical Review Letters*, May 26, 1997.)

Contact Alex Zunger at 303-384-6672.

Freezing Electron Motion in the Solid-State Spectroscopy Lab

In NREL's Solid State Spectroscopy lab, Angelo Mascarenhas and his team are taking a microscopic look at PV materials and processes. "The quality of our research has been greatly enhanced since we installed the ultrafast laser system and the near-field scanning optical microscope," he says. (To see exactly what he means, check out the animations on the Spectroscopy Web site at *http://www.nrel.gov/sss/spectrum.html*)

The system took 3 years to build and has been in operation for one-and-a-half years. Researchers are now looking at light pulses one ten-trillionth of a second in duration, observing materials and sequential changes. "It used to be that solar cell material was studied macroscopically," says Mascarenhas. "It was almost alchemy. A change was made and the material improved, but often we did not know why. Now we're studying material on the submicron level to pinpoint where the problems are actually located."



Warren Gretz, NREL/PIX06342

The Solid State Spectroscopy Team uses the ultrafast laser paired with the near-field scanning optical microscope to better understand the fundamental mechanisms that limit the performance of PV materials.

In effect, the laser becomes a controlled sun. By adjusting the laser's wavelength, researchers can create electrons and holes where they want them, and follow what happens within the material as a train of events. It's as though they're controlling the shutter of a camera that freezes motion on an ultrafast time scale. To put this in perspective, light only travels 30 microns in the length of time they can freeze.

By pairing the ultrafast laser with the near-field scanning optical microscope, the Spectroscopy Lab now has unique capabilities for characterizing PV materials. In the important emerging class of polycrystalline PV materials, grain-to-grain variations are found in chemical composition, doping, and optoelectronic properties. With this project, NREL researchers have developed an ultramodern technique for examining optoelectronic properties on the nanoscale and correlating those properties to the material's submicron topography.

Recently, they studied a sample of cadmium telluride that had just one grain boundary (as opposed to the multiple boundaries contained in most samples). This presented an ideal opportunity to test the capabilities of their apparatus. They observed that, indeed, it was possible to actually see how the photogenerated carriers were being captured in the proximity of the grain boundary, and then, how this defect would degrade the PV performance.

Contact Angelo Mascarenhas at 303-384-6608.

Better Photovoltaics Through Chemistry

Arthur Nozik and NREL's Chemical Sciences Team are thinking small these days. Nanostructures play a role in four areas of this team's work: the dye-sensitized solar cell, hot carriers, quantum dots, and thin-film precursors.

The scientific principles underlying the dye-sensitized solar cell have been known for about 30 years: titanium dioxide (TiO_2) converts the ultraviolet portion of sunlight to electricity; dyes make TiO_2 sensitive to the rest of the solar spectrum. Researchers have long been tantalized by the cell's promise of low cost (TiO_2 is plentiful and cheap), inherent simplicity (no semiconductor junctions required), and versatility (the cells can by painted on in any color, even for application as power-producing transparent windows). Recent breakthrough research in Switzerland showed that making dye cells with nanosize TiO_2 particles can produce efficiencies as high as 12%. Research at NREL is under way to increase the efficiency to at least 15%. Another major challenge is how to replace the *liquid* electrolyte that's currently required with a *solid* one. Finding the answer will help in the quest to improve the cell's stability.

"The dye cell takes advantage of a *geometrical* effect of nanosizing, but the changes produced by the *quantum-mechanical* effect of nanosizing are more profound," says Nozik. This includes dramatic changes to the optical and electronic properties of the semiconductor as the size of the semiconductor structure changes. This quantum-mechanical effect applies to the Chemical Sciences Team's work with quantum dots, which is related to its work with hot carriers.

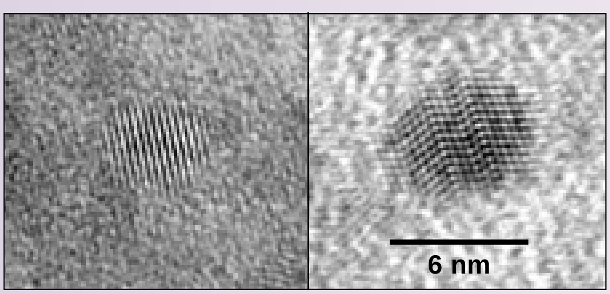
Semiconductor nanocrystals (known as quantum dots) represent a novel class of materials that lie between the molecular and solid-state forms of matter. Quantum dots are large enough to maintain the bulk crystal structure, but small enough to produce discrete electronic energy levels rather than the quasi-continuous levels present in bulk semiconductors. This produces many interesting effects in semiconductors and allows the tuning of critical properties simply by controlling size.

The team synthesized an important group of III-V semiconductors (InP, GaAs, GaP, and $GaInP_2$) as quantum dots with diameters ranging from 2.5 to 8 nanometers. They then investigated their fundamental optical and electrical properties. Among the findings were anti-Stokes photoluminescence (light emission with energy greater than the light absorbed) and two-color photoluminescence blinking.
(See Nozik and Mićić, "Colloidal Quantum Dots of III-V Semiconductors," *MRS Bulletin*, Feb. 1998)

Another phenomenon of the quantum regime plays a role in the team's research on hot carriers. When particles are in this regime, the natural cooling of electrons can be slowed. "The cooling represents wasted energy," says Nozik. "If we could keep this from happening, we could, in principle, convert more of the solar energy to electricity and theoretically double the device efficiency." This is a difficult problem to solve, however, because the electrons cool in much less than a nanosecond. "We've shown we can slow the cooling, but we haven't made the device." Still, the hot-carrier work is an area that Nozik feels is well worth pursuing.

Nanoscale size is having a large impact in yet another area—preparing novel precursors for PV thin films. The use of quantum-dot precursors for thin-film spray deposition offers several potential advantages over conventional deposition. For example, a lower melting point is a property of quantum dots, and the resulting decreased growth temperatures may allow the use of low-cost substrates such as soda-lime glass. Also, the improved packing during deposition, which is inherent with the small particle diameter, can produce smooth, dense films. This could yield films similar in quality to those obtained by vacuum techniques, but without the expense and complexity. NREL researchers are working with cadmium telluride and CIGS (copper indium gallium diselenide) with the goal of exploiting these advantages.
(See D.L. Schulz, C.J. Curtis et al., "Cu-In-Ga-Se Nanoparticle Colloids as Spray Deposition Precursors for $Cu(InGa)Se_2$ Solar Cell Materials," *J. Electron. Mater.*, May 1998.)

Contact Arthur Nozik at 303-384-6603.

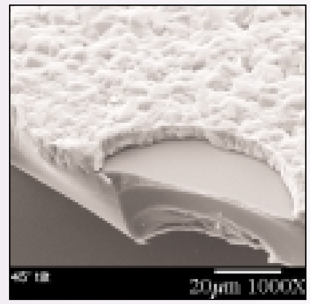


NREL researchers are investigating quantum dots (in the case shown, of indium phosphide) and their applicability to PV technologies. The right-hand view shows an InP quantum dot with a stacking fault.

Breaking a Thin-Layer-Silicon Barrier

"Our biggest focus is thin-layer crystalline silicon growth," says Ted Ciszek, leader of the Crystal Growth and Devices Team. "I think of it as the next logical step in silicon PV. First there was single-crystal technology, followed by cast silicon, and then came various sheet-growth methods."

The challenge is to produce an active silicon layer of sufficient electronic quality, with a thickness on the order of 10 micrometers (µm), and at a fast deposition rate of about 1 µm per minute on a low-cost substrate such as glass. The principal requirement regarding electronic quality is a long minority-carrier diffusion length (and, therefore, a large grain size) that is at least equal to the layer thickness—and larger values are even better. Efforts around the world have thus far only resulted in partial solutions.



This scanning electron microscopy image shows a thin layer of silicon on glass, produced by a novel method developed at NREL.

"We're excited, because we've found a way to directly deposit silicon on glass and still get the large grain size," Ciszek says. The method takes advantage of a gas-phase growth technique in which iodine vapor reacts with source silicon in the hot part of the reactor, carries it to the cold part of the reactor, and then repeats the cycle continually. Thus far, it has produced continuous silicon layers of 5–20-µm thickness with 5–10-µm grain size on high-temperature glass at a growth rate of 1–10 µm/minute. An effective minority-carrier lifetime of about 5 microseconds was measured, implying a diffusion length far exceeding the layer thickness. The team is now working to characterize this material, further improve its properties, and investigate its PV performance. This is a novel method, and Ciszek's team has just applied for a patent.

Feeding Industry's Needs

The Crystal Growth and Devices Team is also investigating a problem of great substance to the PV community: how to produce enough silicon feedstock to meet the rapidly growing demands of the market. Pure, semiconductor-grade silicon, as it's now produced, is too expensive to be practical. Other sources, such as reject or "off-spec" material, can't keep pace with the demand. Therefore, alternative ways of making PV silicon feedstock must be developed.

Ciszek's team is exploring two methods for purifying metallurgical-grade (MG) silicon to levels adequate for PV use. One is recrystallization of silicon from multicomponent MG silicon/metal solutions at the lowest possible melting point. This approach uses the partitioning of impurities that is characteristic of such systems to purify MG silicon. The second approach uses the high density of gettering sites on a porous-silicon-etched surface to trap impurities. MG silicon is etched to create the sites and then is heated to allow impurities to diffuse to the surface. A thin surface layer is etched away, and

Continued on page 11

Focusing on PV's Future at the ECS Meeting

When Ted Turner first proposed his idea for a 24-hour news channel called CNN, everyone thought he was crazy. As it happened, Turner's "crazy" idea revolutionized the communications industry. In a similar vein, scientists from all over the world traveled to Seattle in May, packing not only raincoats and umbrellas, but scores of unconventional ideas that might someday revolutionize the PV industry.

The venue was the 195th Meeting of the Electrochemical Society (ECS). The pertinent sessions—"Symposium on Photovoltaics for the 21st Century" and "Workshop on Basic Research Opportunities in Photovoltaics"—were cosponsored by DOE, NREL, and ECS. The Energy Technology Division of ECS, recognizing the growing interaction of PV and electrochemistry, felt these topics would appeal to attendees. This assumption proved correct as about 50 people crowded into a small room, bringing together experts in PV and related fields to discuss initiatives on high-risk, high-payoff research programs.

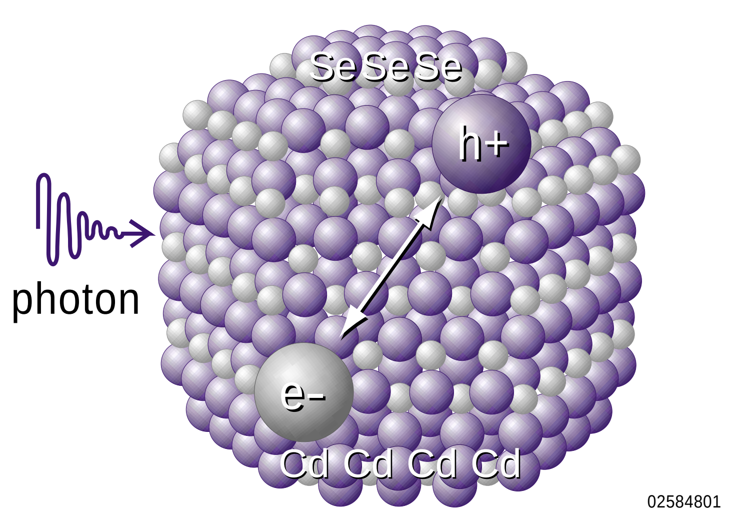
About ECS

The Electrochemical Society is an international nonprofit electrochemical and solid-state science organization with members in more than 75 countries worldwide in the scientific, engineering, and business community. Its meetings typically have 1,500 or more attendees. ECS will host the sequel to "Symposium on PV in the 21st Century" at its meeting in Washington, DC, in March of 2001. See the ECS Web site at: *http://www.electrochem.org*

Bringing New Technology to Light

A fundamental principle guiding DOE's National Photovoltaics Program has always been to provide some support for technologies that require long-term research, development, and innovation. Many PV technologies considered conventional today were exploratory research projects 20 or 30 years ago. Recognizing this research trend, NREL invited 120 researchers from nine countries to Denver two years ago to attend the "First Conference on Future Generation Photovoltaic Technologies." A "leaping frog" symbolized that conference, representing technologies with the potential to spring ahead to the next stage of PV development. The PV Symposium at the Seattle ECS Meeting was a follow-up to that initiative.

Using an innovative concept called "biomimetics," Vanderbilt University is developing a future-generation PV technology that mimics natural photosynthesis. This model is a "snapshot" of the natural separation of an electron-hole pair in a semiconducting nanocrystal after absorption of a photon.



Expanding PV Knowledge

"A major goal of the symposium was to expand PV knowledge," says Bob McConnell, from NREL's Center for Basic Sciences. "We believe innovation in PV is far from over. We examined each technology based on the potential it may have in the next century."

But keeping the door open to unconventional research ideas is difficult for scientists compelled by manufacturers to explore only those theories with short-term commercialization potential, he adds. The symposium encouraged ideas that—if supported by long-term research—could lead to major scientific breakthroughs toward more efficient, less expensive PV devices.

The symposium expanded PV knowledge by providing a receptive environment for bringing new technologies to light. This was achieved primarily through collaboration with U.S. universities. "Universities aren't required to generate a profit, making them a valuable source for finding inspired scientists with proposed long-term research projects," McConnell says. In fact, NREL's 1998 solicitation, "University R&D for Future Generation PV Technologies," drew a large and enthusiastic response. From among the 71 proposals received, 18 universities were awarded research funding, including 14 new universities not previously funded in photovoltaics. Many of those awardees participated in the ECS Meeting, attending the symposium, the workshop, or both. "Funding innovative research ideas shows our support for the scientists themselves," McConnell said. "We support good people doing good research."

Not all the unconventional research ideas came from academia. Scientists from small companies or small departments in large companies also brought their ideas, because their research was considered too exploratory for the U.S. PV industry to risk funding.

As a complement to the PV Symposium, the PV Workshop examined the research potential of ideas that had been presented there. Satyen Deb, Director of NREL's Center for Basic Sciences and John Benner, Manager of the National Center for Photovoltaics' Electronic Materials and Devices Division, cochaired the PV Workshop with McConnell. They divided the attendees into eight teams: amorphous silicon, cadmium telluride, characterization, copper indium diselenide, crystalline silicon, novel materials, nanostructure and dye cells, semiconducting oxides, and III-V materials.

Each team held individual workshops to discuss the proposed research for their area and then selected the top three to six research ideas to support with funding.

Future-Generation PV

Among the many original ideas presented at the PV Workshop was a particularly intriguing one. The workshop team dedicated to *nanostructure and dye cells* proposed further research on dye-sensitized solar cells using a theory based on the principles of photography. Both photography and photoelectrochemistry rely on photoinduced charge separation. The silver halides used in photography have bandgaps on the order of 2.7 to 3.2 eV, and are therefore insensitive to much of the visible spectrum, just as is the TiO_2 used in dye-sensitized solar cells. The realization that the same dyes can function in both materials dates back to the 1960s. Later, the idea developed that the dye could function most efficiently if "chemisorbed" on the surface of semiconductor particles to provide a sufficient interface area. Recent developments have led to dyes that absorb across the visible spectrum, leading to higher efficiencies. This technology holds great potential for further cost reduction and simplification of the manufacturing of solar cells. Right now, 12% efficiency has been measured; if the goal of 20% efficiency can be reached, the technology would quickly become very significant. The largest research effort in the world for this type of technological research is in Switzerland, but the second strongest team in the world is being lead by Arthur Nozik at NREL (see page 4 of this issue).

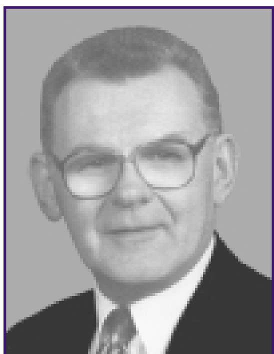
A unique *novel materials* proposal, presented by a research team from Vanderbilt University, was for further research into "biomimetic" PV. In this technology, charge separation occurs via extremely rapid injection of an electron across a semiconducting nanocrystal interface into a charge-transport medium surrounding the nanocrystal. The process "mimics" aspects of natural photosynthesis, which is both a fast and highly efficient solar energy converter.

Other new PV theories presented at the meeting dealt with extremely *high-efficiency concepts*. Scientists concerned with this PV research area want to convert as much as one-third or more of solar radiation into electricity. They believe that even 40% conversion is possible. These high-efficiency cells are excellent candidates for use with concentrator technologies, an area being seriously considered by several companies in Japan, Europe, Australia, and the United States.

Moving PV Into the Next Century

NREL and DOE hope that funding more research on these new ideas will not only expand scientific knowledge, but will also help the domestic PV industry seize opportunities in the 21st century. True, U.S.-based PV manufacturers still hold the major share of the PV market and generated about half a billion dollars worth of shipments during 1998. But funding for PV R&D in the United States has, for the last few years, fallen far short of the amount invested by Europe and Japan on maturing their PV technologies. This has resulted in an innovation deficit for the U.S. PV Program. To remedy this, DOE is now focusing increasing attention on the basic research issues that must be addressed to identify the new technologies needed for the U.S. PV community to be competitive in the future. Right now, support for these new initiatives is being sought in Congress. "NREL hopes to get as much as $9.3 million in government funding for research in high-efficiency and future-generation PV—to take us beyond the horizon of our present knowledge. We are awaiting results of Congressional deliberations, taking place as we speak," said McConnell.

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



Czanderna Receives Research Award

Since 1992, the Energy Technology Division (ETD) of The Electrochemical Society has honored only three scientists with awards for outstanding research. This year, the ETD selected Al Czanderna, a scientist at NREL, for its Fourth Research Award, in recognition of his outstanding solar research. During his 21-year career at NREL, Czanderna's work has focused on researching and developing solar technologies, including multilayer PV modules, electrochromic or "smart" windows, and solar reflectors used in concentrating solar power systems. Czanderna, a research fellow and internationally recognized surface scientist, is the author or coauthor of more than 250 technical publications. He received a $1,500 award, a scroll, and the honor of delivering the ETD keynote lecture. Further detail is available in the "full story" at *http://windows.lbl.gov/doeeci/whats-new.htm*

Contact Al Czanderna at 303-384-6460.

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.

Siemens Solar Industries (SSI), Camarillo, CA, **NREL**, and the **California Energy Commission**, Sacramento, CA, are the joint winners of an R&D 100 Award presented for the development of thin-film CIS-based PV modules. **DOE**/NREL has supported SSI for several years in developing this promising thin-film PV technology. At the last **SOLTECH** meeting in Kansas City last April, **Chet Farris**, Executive Vice President and Chief Operating Officer of SSI, acknowledged NREL's contribution toward the development of the thin-film, CIS-based PV technology. Farris presented a world-record, 12.1% thin-film CIS module to DOE Assistant Secretary **Dan Reicher**. Also, CIS modules were presented to **Jim Rannels**, Acting Director, Photovoltaics and Wind Technologies, and **Admiral Richard Truly**, Director, NREL. The R&D 100 Award recognizes SSI's and NREL's outstanding contribution to thin-film PV module development, and its potential for future low-cost PV technology. Contact: **Harin Ullal, 303-384-6486**

PV industry leaders, working with the **NCPV**, are finalizing major components of a **"PV Industry Roadmap"** to guide the industry's research, technology, manufacturing, applications, markets, and policy through 2020. The NCPV is facilitating the development of this important planning document to ensure a thriving, U.S.-based, solar-electric power industry that provides competitive and environmentally friendly energy products and services for domestic energy consumers. The guide will focus on four technology development areas: (1) Markets and Applications; (2) PV Components, Systems, and Integration; (3) Manufacturing, Equipment, and Processes; and (4) Fundamental and Applied Research. A "Roadmap Workshop" was held in Chicago June 23–25 and involved some 40 representatives of the PV industry and selected stakeholders. This workshop further developed the roadmap to provide near-, mid-, and long-term goals in the four technology development areas. Participants included: **Allen Barnett, AstroPower Inc.; Larry Crowley, Idaho Power; Chester Farris, Siemens Solar; Harvey Forest, Solarex; Roger Little, Spire Corporation; William Roppenecker, Trace Industries; Richard Schwartz, Purdue University; Scott Sklar, SEIA; Robert Gay, Siemens Solar; James Rannels, DOE; Chris Cameron** and **James Gee, SNL;** and **Roland Hulstrom, John Benner, Tom Surek,** and **Larry Kazmerski,** all of **NREL.** The Workshop proceedings are being compiled now and will be issued in September. The formal roadmap will be issued in January 2000. Contact: **Larry Kazmerski, 303-384-6600**

NREL and **Spectrolab** have signed an agreement giving Spectrolab rights to manufacture the GaInP/GaAs tandem cell for space applications. Included as part of the agreement is a plan for Spectrolab to pay NREL for additional research to push the technology farther. The GaInP/GaAs cell, invented by NREL's **Jerry Olson** in 1985, has achieved terrestrial efficiencies of 30% and is in production at both **TECSTAR** and Spectrolab for commercial telecommunications satellites. NREL played a key role in the invention, development, and transfer to industry of this technology. TECSTAR licensed this technology from NREL about a year ago. Spectrolab is interested in using the GaInP/GaAs cells in concentrator systems on Earth; however, the performance and reliability of these cells for this application are not yet known. A closer working relationship between Spectrolab and NREL will speed the development and deployment of such systems. Contact: **Jerry Olson, 303-384-6488, or Sarah Kurtz, 303-384-6475**

Two PV-powered area lighting systems were moved from **NREL's Outdoor Test Facility** (OTF) array field to the parking lot just west of the OTF. The first system, from **Solar Outdoor Lighting**, was refurbished and installed at the southwest corner of the parking lot and consists of three **Siemens** M75 modules, two 75-Ah valve-regulated lead-acid (VRLA) batteries, and a 24-W compact fluorescent lamp. The second system, provided through the **PV Manufacturing Technology** project, was moved to the southeast corner, where it will remain as part of a long-term reliability study. This system, known as the Modular Autonomous Photovoltaic Power Supply (MAPPS), consists of four Siemens M55 modules, four **Deka** 98-Ah VRLA batteries, a **Specialty Concepts, Inc.**, charge controller, and an 18-W, low-pressure sodium lamp. Besides providing light over the parking lot and steps leading to the adjoining **Thermal Test Facility**, these systems will also provide PV systems engineers with valuable long-term, real-world experience operating small, stand-alone PV systems. Contact: **Peter McNutt, 303-384-6767**

A 22-kW **AstroPower** crystalline-silicon array was installed on five Delta Trackers at Cherry Creek Reservoir State Park to provide ac power to an adjacent motor-home campground through five Omnion 2400 inverters. **NREL** and **Public Service Company of Colorado** (PSCo) personnel visited and repaired the data acquisition system (DAS) that monitors system performance. The DAS data-backup battery was replaced, and the DAS was initialized for proper operation. **Ascension Technology, Inc.**, personnel uploaded the data collection program, and the DAS resumed proper operation. The repair of the DAS will

Continued on page 11

Subcontracts Publications

Subcontracted research with universities and industry, often cost-shared, constitutes an important and effective means of technology transfer in NREL's PV Program. From October 1998 through June 1999, we awarded 54 new subcontracts (examples listed below) and awarded more than $23 million to new and existing subcontracts. For further information, contact Ann Hansen (303-384-6492).

Arizona State University (5/99–5/02)
Standards for Future Generation PV Technologies
$240,000

Cornell University (6/99–8/02)
Elastic Properties of Thin-Film Silicon
$280,000

Hampton University (8/99–8/02)
The Floating Theater
$119,000

Howard University (4/99–4/01)
Electronically Controlled PV Power Using Artificial Neural Network
$120,000

McNeil Technologies, Inc. (4/99–9/99)
Photovoltaics Program Technical Support
$139,900

Pennsylvania State University (5/99–7/02)
Chemical Reaction Modeling for Encapsulants in PV Modules
$260,000

Sentech, Inc. (5/99–9/99)
PV Program Technical Support
$73,400

University of California (7/99–9/02)
PV Devices Based on New Nanocrystal Composites
$290,900

University of Rochester (5/99–7/02)
Porous Polycrystalline Silicon Thin Film Solar Cells
$300,000

West Virginia University (5/99–7/02)
Nanostructure Arrays for Multijunction Solar Cells
$300,000

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).

Ginley, D. S., et al. "Nanoparticle Precursors for Electronic Materials," *Microcrystalline and Nanocrystalline Semiconductors—1998: Proceedings of the Materials Research Society Symposium, 30 Nov.–3 Dec.1998, Boston, MA*. Pub. by Materials Research Society, Warrendale, PA, 1999, Vol. 536., pp. 237–244.

Hanoka, J. I. *Advanced Polymer PV System: PVMaT 4A1 Final Report, Sept. 1995–Dec. 1997*. June 1999, 35 pp., NREL/SR-520-24911. Work performed by Evergreen Solar, Inc., Waltham, MA.

Herdt, G.C.; King, D.E.; Czanderna, A.W. "Penetration of Deposited Au, Cu, and Ag Overlayers Through Alkanethiol Self-Assembled Monolayers on Gold or Silver," *Metalized Plastics 5 & 6: Fundamental and Applied Aspects*. Netherlands: VSP BV, 1998, pp. 169–201. NREL/TP-412-21491.

Jester, T. L. *Photovoltaic Cz Silicon Module Improvements: Final Subcontract Report, 9 November 1995–8 November 1998*. June 1999, 60 pp., NREL/SR-520-26663. Work performed by Siemens Solar Industries, Camarillo, CA.

Kroposki, B.; Hansen, R. "Performance and Modeling of Amorphous Silicon Photovoltaics for Building-Integrated Applications." March 1999, 7 pp. NREL/CP-520-25851. Prepared for *Solar 99: Growing the Market*, 12–17 June 1999, Portland, ME.

Norman, A.G., et al. "Ge-Related Faceting and Segregation during the Growth of Metastable $(GaAs)_{1-x}(Ge_2)_x$ Alloy Layers by Metal-Organic Vapor-Phase Epitaxy." *Applied Physics Letters*. March 1999, 74(10), pp. 1382–1384. NREL/JA-520-25806.

Schulz, D.L., et al. "Nanoparticle-Based Contacts to CdTe," *Microcrystalline and Nanocrystalline Semiconductors—1998: Proceedings of the Materials Research Society Symposium, 30 Nov.–3 Dec. 1998, Boston, MA*. Pub. by Materials Research Society, Warrendale, PA, 1999, Vol. 536., pp. 407–411.

Sites, J.R. *Device Physics of Thin-Film Polycrystalline Cells and Modules: Dec. 6, 1993–March 31, 1998*. April 1999, 59 pp. NREL/SR-520-26315. Work performed by Colorado State University, Fort Collins, CO.

Webb, J.D. "Anisotropy in Hydrogenated Amorphous Silicon Films as Observed Using Polarized FTIR-ATR Spectroscopy." May 1999, 9 pp. NREL/CP-520-26355. Presented at the *Materials Research Society's 1999 Spring Meeting, 5–9 April 1999, San Francisco, CA*.

Wohlgemuth, J. *Cast Polycrystalline Silicon Photovoltaic Module Manufacturing Technology Improvements: Final Subcontract Report, 8 Dec. 1993–30 April 1998*. June 1999, 38 pp. NREL/SR-520- 26071. Work performed by Solarex, a business unit of Amoco/Enron Solar, Frederick, MD.

University Corner

- The nation's largest solar car race, **"Sunrayce 99,"** began on June 20th at the U.S. Capitol in Washington, D.C., and traversed five states—Virginia, North Carolina, South Carolina, Georgia, and Florida—under consistently cloudy and often rainy skies. As the first solar cars crossed the finish line at Epcot® in Walt Disney World, jubilant students cheered and members of the media, including CNN and ESPN, followed the cars with their cameras. The **University of Missouri-Rolla** took first place, with an overall winning race time of 56 hours, 16 minutes,and 44 seconds (56:16:44) and an average speed of 25.30 mph for the 10-day, 1,425-mile race. The route terrain and inclement weather conditions made this fifth biennial solar car race one of the most difficult so far. But it was an impressive race, even in the rain.

  Sunrayce is sponsored by **DOE**, **General Motors**, and **Electronic Data Systems** to provide a unique and valuable learning opportunity for some 1,000 competing university students. "Sunrayce provides students the challenge of taking an idea from the paper to the pavement as they design, build, and race a vehicle that is powered exclusively by energy from the sun," said U.S. Secretary of Energy **Bill Richardson**. "The event showcases the talents of some of the country's brightest young minds while helping to promote the growth of a renewable energy technology." These students are the future engineers at leading technology companies throughout the United States, and they will use their Sunrayce experience in future products and services. During the race, **NREL** helped students by purchasing a PV-hybrid system from **Sunwize** that was taken to each overnight finish site to provide clean, quiet power for students to use while fixing or modifying their vehicles. But students weren't the only benefactors. NREL's **Lorenzo Roybal** showcased PV system applications and their benefits at each overnight stop for the general public, too, and attracted considerable interest. Complete results are at the Sunrayce homepage: *www.sunrayce.com/sunrayce* Contact: **Byron Stafford, 303-384-6426**

- A new system for exposing modules to ultraviolet fluorescent light, designed and constructed by the **Photovoltaic Testing Lab** at **Arizona State University** (ASU), has been installed in the **Outdoor Test Facility** at **NREL**. It is now being used as part of a long-term comparison of different methods of UV exposure on commercial modules. Previously, UV-fluorescent exposure testing at NREL required the tubes to be operated inside a large environmental-cycling chamber, which precluded use of the chamber for other standard module qualification tests such as temperature and humidity/freeze cycling. The new ASU system does not need an expensive environmental chamber, thus reducing maintenance and downtime costs. Contact: **Carl Osterwald, 303-384-6764**

- A **DOE/NREL Renewable Energy Academic Partnership** (REAP) Conference, hosted by **Southern University and A&M College**, was held in Baton Rouge, LA, on August 8–13, 1999. This was the first REAP Conference to review progress on the DOE/NREL-funded projects at the eight **Historically Black Colleges and Universities** (HBCUs). Advisors and students of the HBCU Photovoltaic Research Associates Program gave comprehensive presentations about their projects. Both **Central State University** and **Texas Southern University** (TSU) have performed outstanding research projects and have extended their work to PV demonstrations in developing countries. The Central State team has projects in Senegal and the TSU team just returned from South Africa.

  The review meeting also included workshops given by professionals and experts in the field of renewable energy. One workshop taught by NREL's **Cecile Warner** covered renewable energy technology challenges and opportunities in the coming millennium. Another focused on the role of renewable energy technology in the global community. In this session, photovoltaics, biomass, biotechnology, and global climate change were discussed. On the last day, participants visited the **Agrilectric Power Corporation**, where agricultural waste from rice farms is being converted to energy for residents in Lake Charles, LA.

  The conference was a great way to bring the HBCU PV Program Associates together. It provided a tremendous opportunity for undergraduates, advisors, and experts to gather and discuss their research, future opportunities in the field of renewable energy, and the role that it will play nationally and globally in the future. Proceedings will be prepared and should be ready to distribute within the next two months.

  Participants included professors and undergraduate students from the following HBCUs: Central State University in Wilberforce, OH; **Clark Atlanta University** in Atlanta, GA; **Hampton University** in Hampton, VA; **Howard University** in Washington, D.C.; **Mississippi Valley State University** in Itta Bena, MS; **North Carolina Central University** in Durham, NC; **Southern University and A&M College** in Baton Rouge, LA; and Texas Southern University in Houston, TX. Contact: **Bob McConnell, 303-384-6419**

News at Press Time

PV Program 5-Year Plan and Industry PV Roadmap Are Well Under Way

With a planned publication date of December 1999, a draft of the National PV Program Plan 2000–2004 is currently being reviewed by NREL, Sandia, DOE, and members of the PV community. The first section of the document points out that photovoltaic technologies promise great things for our nation's energy supply, economy, environment, and overall future… that the PV Program works with the nation's PV community to build strong leadership in this valuable technology… and that the Program coordinates these efforts through its policies, organization, strategies, and funding. The second part of the document scopes out the direction of the Program within Research and Development, Technology Development, and Systems Engineering and Applications. Specific goals are highlighted by a 5-year milestone chart.

The 5-Year Plan fits within the context of the Photovoltaic Industry Roadmap, which is a U.S. industry-led effort to help guide domestic PV research, technology, manufacturing, applications, markets, and policy. The document, which is also in progress and covers the period of 2000–2020, will represent the direction of the PV industry and its critical partners—including the U.S. government programs. A shorter framework for the full document is on NCPV's Web site at *http://www.nrel.gov/ncpv/roadmap.html*

Contact: Larry Kazmerski , 303-384-6600

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enable all interested parties, which includes NREL, Ascension Technology, Inc., PSCo, **Utility PV Group**, **PV for Utility-Scale Applications**, and **Southwest Technology Development Institute**, to gather system data to determine the performance of this grid-intertied PV system. The system data can be accessed through the UPVG Web site at *www.upvg.com* Contact: **Peter McNutt, 303-384-6767**

PowerLight Corporation, with help from **DOE** and the **California Energy Commission**, is evaluating two products developed under DOE's **PV:BONUS2** program. The two products incorporate solar thermal improvements that originate from its PowerGuard® PV roofing tile. The first product, HeatGuard, incorporates coatings to improve the insulating value of the roofing product, and the second one, PowerTherm, incorporates a thermal absorber system. Early calculations indicate that HeatGuard can reduce the heat transfer from the roof into the building to 1%, and the benefits of the thermal barrier are significant, doubling the value on a $/ft^2 basis over the PowerGuard® product alone. For the PowerTherm product, a mechanical attachment between the absorber and the PV laminate is being investigated, and the team has consulted **Al Czanderna** at **NREL** to gain a better understanding of potential materials and bondings between the absorber and the laminate. Performance and reliability for both products will be thoroughly evaluated through accelerated testing. PowerLight Corporation is a **PV Manufacturing Technology** project partner. Contact: **Holly Thomas, 303-384-6400**

NREL's Cadmium Telluride Team developed a novel manufacturing process for fabricating CdS/CdTe polycrystalline thin-film solar cells that yielded a CdS/CdTe device with an NREL-confirmed efficiency of 14%. The process addresses undesirable manufacturing issues such as time-consuming and expensive heat-up and cool-down processes and generation of large amounts of liquid waste. In this new process, the first three layers (i.e., transparent conducting oxide layer, buffer layer, and window layer) of the CdS/CdTe superstrate device structure were prepared by the same deposition technique at room temperature. The new process has only one heat-up segment and, therefore, can significantly reduce operation time and thermal budgets, increase throughput, and eliminate wet-chemical processes, thereby reducing manufacturing costs. Preliminary device results have demonstrated that CdS/CdTe cells with efficiencies of 13%–14% can be fabricated with good run-to-run reproducibility. A patent application was filed at the end of 1998. NREL's CdTe Team and division manager John Benner visited **First Solar** in April to demonstrate this process. Contact: **Xuanzhi Wu, 303-384-6552**

A collaboration of **United Solar Systems Corp.**, **Colorado School of Mines** (CSM), and **NREL** has discovered a new method to probe the ordering in hydrogenated amorphous silicon. The team found that infrared absorption provides a rapid and simple technique for identifying hydrogenated amorphous silicon (a-Si:H) with enhanced medium-range ordering. United Solar uses a-Si:H deposited on the "edge" of crystallinity, because enhanced ordering improves the stability of their PV modules. This innovation has led to United Solar's recent record efficiencies for its a-Si:H solar cell. This work was presented at the Amorphous and Heterogeneous Silicon Symposium of the Materials Research Society Spring Meeting in April. NREL collaborates with United Solar and CSM via the **Thin Film PV Partnership** program. Contact: **Harv Mahan, 303-384-6697**

After 9 months of outdoor exposure, the 1-kW CIGSS array from **Siemens Solar Industries** (SSI) is still performing well, with no sign of degradation. During the test period, the average operating temperature was 48°C, the average operating efficiency was 9.3%, and the average normalized dc power was 954 W. When corrected to Standard Test Conditions of 1000 W/m^2 and 25°C, the average operating efficiency was 10.2%, with a power of 1028 W. System performance and reliability will be monitored for a period of several years by **NREL's PV System Performance and Standards Task Team** and **Thin Film PV Partnership** program members. The testing done at NREL will help SSI validate the performance of its CIGSS modules and help to promote the commercialization of this technology. Contact: **Ben Kroposki, 303-384-6170**

Feeding Industry's Needs, Continued from p. 5

the process is repeated. The team has demonstrated that many impurities, including the particularly bothersome boron, are drawn to the surface by this treatment. They are now working to determine the number of treatment cycles required and whether the method is economically practical.

This and other work of the team is described in a new Web site (http://www.nrel.gov/silicon/) called PV Silicon Materials Research. This site also details four R&D projects the team conducted recently with industry partners.

Contact Ted Ciszek at 303-384-6569.

PV Calendar

October 4–6, 1999, *Utility Photovoltaic Experience Conference (UPEx '99): Opening Doors in the Solar Marketplace*. Sponsor: Utility Photo-Voltaic Group. Location: Tucson, AZ. Contact: Tina Schneider. Phone: 202-857-0898. Web site: *www.ttcorp.com/upvg/upex99.htm*

October 18–21, 1999, *PV Performance Reliability and Standards Workshop*. Sponsor: NREL. Location: Vail, CO. Contact: Tom Basso. Phone: 303-384-6765. Or Peter McNutt. Phone: 303-384-6767.

October 25–29, 1999, *American Vacuum Society, 46th International Symposium: Vacuum, Thin Films, Surfaces/Interfaces and Processing*. Sponsor: AVS. Location: Washington State Convention Center, Seattle, WA. Phone: 212-248-0200. Web site: *www.vacuum.org/call/cfp.html*

November 29–December 3, 1999, *Materials Research Society 1999 Fall Meeting*. Sponsor: MRS. Location: Boston, MA. Contact: MRS Headquarters. Phone: 724-779-3003. Web site: *www.mrs.org/meetings/fall99*

April 16–20, 2000, *16th NCPV Photovoltaics Program Review*. Sponsors: NREL, SNL. Location: Adams Mark Hotel, Denver, CO. Contact: Camilla Course. Phone: 303-275-4321.

May 1–5, 2000, *16th European Photovoltaic Solar Energy Conference and Exhibition*. Location: Glasgow, Scotland, U.K. 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 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*

June 19–22, 2000, *EUROSUN 2000, 3rd International Solar Energy Society's European Solar Congress*. Sponsor: ISES. Location: Copenhagen, Denmark. Contact: ISES-Europe. Phone: +45.73.423100.

September 17–22, 2000, *28th IEEE PV Specialists Conference*. Location: Anchorage Hilton, Anchorage, AK. Contact: 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.

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