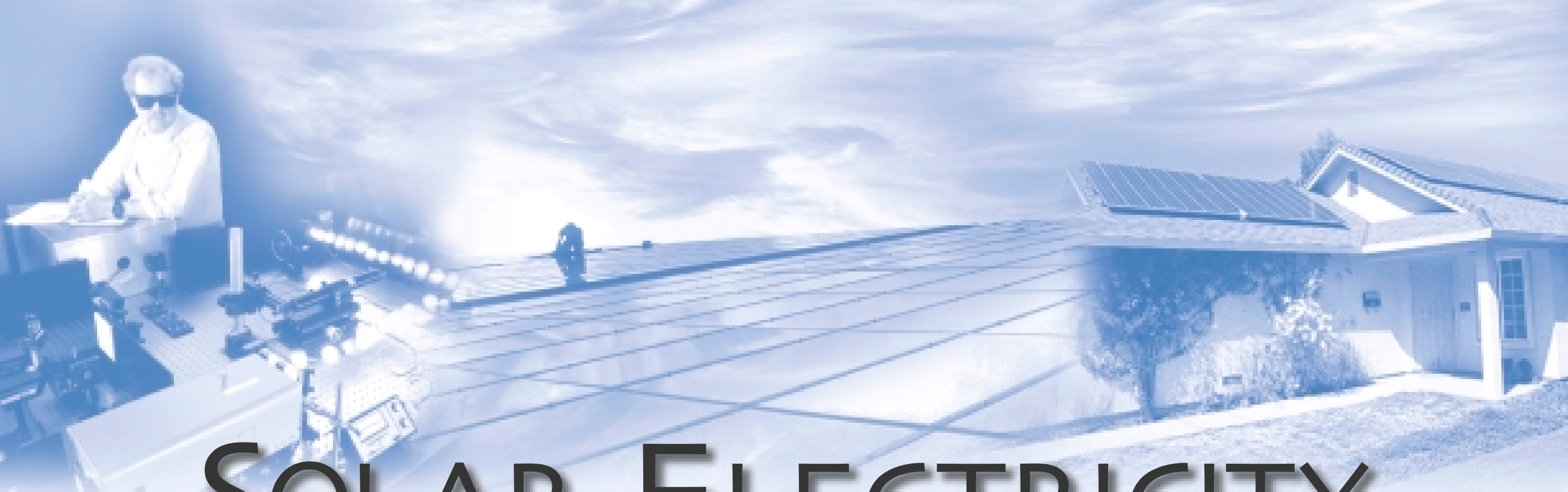


SOLAR ELECTRICITY

the power of choice

First Quarter, 2001

Features

Departments

National Center for Photovoltaics
Phone: 303-384-NCPV
www.nrel.gov/ncpv

Reporting on solar electricity research and related activities from the National Renewable Energy Laboratory and its partners within the National Center for Photovoltaics

Take a Closer Look

If you were expecting a copy of *NREL PV Working With Industry* this quarter, take a closer look. You're reading it!

The old name and design served us well for many years. Since *PV Working With Industry's* debut in December 1992, products that rely on photovoltaic technologies have grown into a multimillion-dollar worldwide industry. And, although the terms "photovoltaics" or "PV" are near and dear to *our* hearts, they're a bit arcane for popular usage. Hence the term "solar electricity."

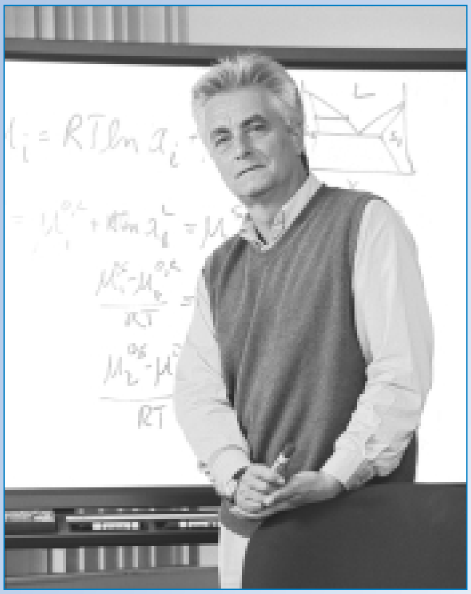
Nor was the National Center for Photovoltaics (NCPV) in existence in 1992. We hope the new design, with the NCPV featured on the cover, will focus attention on the important work that lies ahead for our organization: to continually increase efficiencies and decrease costs of solar electricity technologies.

This work starts in the national labs, as exemplified by the masthead photo above showing research at NREL, and culminates in solar electric systems on top of homes, businesses, and government buildings—two of which are also shown on the masthead. Most importantly, this work gives U.S. consumers "the power of choice."

Some things *haven't* changed. The research contributions of NCPV partners from government, academia, and industry will still be featured. The editorial voices celebrating independent viewpoints from this same constituency will still be heard. And our dedication to telling this significant story—*and to taking a closer look*—will never change.

University Research Plays an Essential Role in PV's Success

An Editorial by Tim Anderson


University of Florida/PIX09991

Tim Anderson is chairman and professor of the Department of Chemical Engineering at the University of Florida. His department's current research is largely devoted to the study of advanced electronics, photonics, and the processing of composite materials. Of particular interest is understanding the fundamentals of chemical vapor deposition of thin films.

Contact Tim Anderson at 352-392-0882

The university system in the United States has long been recognized as a critical component of our nation's research enterprise. Its impact on our economy is well documented, having been credited with such innovations as the Internet, lasers, and nanotubes. Integrating university research into technology development programs contributes toward technology commercialization in several ways.

In the case of solar energy, it's my contention that using this world-class university resource is essential to maintaining U.S. leadership in PV technology. A central role of the university is to provide a basic research component that fosters technology development. Specific to PV technology, we're creating a foundation for inventing and improving cell structures and their manufacturing processes.

Universities are able to devote extended time to in-depth studies and bring a wide variety of approaches, characterization tools, and expertise to bear on issues. And the cost of university research is relatively low. A recent comparison to research at a large chemical company suggests that fully costed industrial research is about five to eight times more expensive than at a university. This focus on fundamentals, access to a range of tools and expertise, and low cost make university laboratories well suited for exploratory research and the testing of new concepts.

The university research setting is a meeting place for the science and engineering disciplines, providing a fertile ground for innovation and for adapting advances in other fields. It's all about making connections. Amorphous silicon groups need to rub elbows with the silicon processing community, the space cell folks can learn much by interacting with optoelectronics researchers, and material growers should be working with process control experts. Such interactions, fostered by the university community, can't help but advance the technology.

Universities are also in the people business. We develop a skill set and knowledge foundation that prepares students for productive careers. The PV industry is technology based and must have a sufficiently large, qualified workforce to sustain current and anticipated growth. The industry, however, often finds itself at a disadvantage when competing with the core semiconductor industry for the best people. My experience indicates that graduate students coming out of PV research groups are more likely to take positions in a PV company because of their commitment and familiarity with the technology. Of course, they also contribute quickly.

The politically neutral position and nonprofit status of universities impart objectivity and credibility on issues within the broader community. Faculty members help spread an understanding of PV technology and its vital application through their many interactions with students, colleagues, and the public. Universities also play a special role in technology diffusion on a global scale. We are inclined to collect and synthesize the literature to generate review articles, monographs, and textbooks. We promote the global exchange of information through presentations, scholar exchanges, consultancies, seminars, short courses, and sabbaticals. Clearly, the increased collection and exchange of information promotes faster development of the technology.

Perhaps the area where we can most improve is in our interactions with industry. The DOE Thin Film PV Partnership is a case in point, having demonstrated the value of bringing industry, government laboratory, and university researchers together to advance the technology. But more should be done to promote these productive relationships. Joint proposals, graduate student internships, sabbaticals among members of both groups, advisory boards, materials exchange, and workshops would all serve this purpose.

The university system in the United States is arguably the best in the world. Understanding its role and integrating its research potential into PV technology development—and particularly, in the U.S. PV industry's 20-year technology roadmap—is crucial to our energy future. The university community, however, depends largely on federal support. Therefore, reducing university research funding—a likely result of the budget proposed by the President for fiscal year 2002—would disperse the community and the progress it has made, much as it did in the mid-1980s. Let us hope that a long-term vision, along with adequate and continuous support, will prevail.

Solar Electricity Shines at National Western Stock Show

Rising energy prices made solar electricity a big hit at the 95th National Western Stock Show held in Denver, Colorado, January 6–21, 2001. Some 623,000 persons went through the gates of the Denver Coliseum to attend these annual rodeo, livestock demonstrations, and horse events. In talking to volunteers staffing an NREL exhibit at the show, farmers, ranchers, and city dwellers all expressed concern about the rising cost of natural gas and other fossil fuels used to produce electricity.

For 6 years now, NREL has displayed an educational booth about solar energy and other renewables in the Hall of Education at the Stock Show. NREL also offers free workshops on solar and wind power for the farm and ranch to demonstrate how electricity from photovoltaics and wind turbines provides an economical option for stock watering, electric fence charging, and irrigation. Usually, workshop attendees express great interest in solar energy for the home, both urban and remote, which is also discussed. The workshops, staffed by volunteers from NREL's National Center for Photovoltaics (John Thornton, Byron Stafford, Lorenzo Roybal, and Wendy Larsen) and from the National Wind Technology Center (Trudy Forsyth, Jim Green, and Sue Hock), offered demonstrations on PV-powered equipment and small wind turbines. The group also answered many questions from the audience. This year, a record number of people attended the workshops, and thousands dropped by the booth for some 9,000 pieces of literature on solar and wind power, and some biomass and geothermal information.

The huge interest in solar energy caught the attention of local news stations. Most news channels in Denver ran a story about solar and NREL at least three times a day for a week or longer. Local TV Channels 4 and 7 aired short segments containing interviews with NREL's Bob Noun, manager of Communications and Public Affairs, and John Thornton, team leader for PV Domestic Markets and Applications, and filmed the booth and parts of the workshop. A reporter and photographer from Associated Press attended the entire workshop and interviewed some of the attendees.

For more information, contact Wendy Larsen, 303-384-6497.

Wendy Larsen/PIX09895

Wendy Larsen/PIX09821

Wendy Larsen/PIX09820

Wendy Larsen/PIX09894

NREL's booth and PV workshops at this year's National Western Stock Show in Denver, CO, did a land office business. Photos: (a) Byron Stafford addresses a workshop audience about solar energy for the farm and ranch; (b) Dave Christensen talks to people interested in solar at the NREL educational booth; (c) people picking up literature about solar and wind power before the workshop; (d) John Thornton answers questions from the audience after the workshop.

Mapping the PV Industry's Future

Starting with a mere "skeleton" some 18 months ago, the *U.S. Photovoltaic Industry Roadmap* has been fleshed out over time and is now alive and kicking. The final 32-page document received an enthusiastic reception when it was presented at the Solar Energy Industries Association PV Division meeting on April 22 in Washington, D.C.

"Make no mistake," said Allen Barnett of AstroPower, "this *is* the industry roadmap, and it clearly shows that solar electricity *is now* and *will continue to be* significant." Barnett's sentiments were echoed by Harry Shimp of BP Solar, Chet Farris of Siemens Solar Industries, and Roger Little of Spire Corporation—all members of the Roadmap Steering Committee.

The steering committee, made up of the National Center for Photovoltaics (NCPV) Advisory Board, also included other representatives of major U.S. PV manufacturers and universities. The committee established the initial goals of the roadmap more than a year ago, and industry leaders have worked since then to refine the goals, discuss the means to reach them, and explore the hurdles they might encounter.

The Road to Washington, D.C.

In September 2000, at the 28th IEEE PV Specialists Conference in Anchorage, Alaska, industry partners came together to plan the roadmap and to offer input and guidance. The industry contributions to this meeting were invaluable. As NCPV Director Larry Kazmerski states, "The guidance received from industry for commercializing solar-electric power turned out to be the highlight of the roadmap."

This input was then taken to Dallas, Texas, in December 2000, where more than 40 members of industry, representing 36 companies, gathered to discuss the roadmap. Organized by Energetics Corporation, the workshop included discussion of PV markets and of intended audiences for the roadmap document itself.

The roadmap's finishing touches were applied on February 14 at the committee's final working meeting, which was also held in Washington, D.C. Here, the industry group hashed out details of the executive summary, the role of government, and specifics of the numerous goals. Energetics used this input to complete the final draft and publish the roadmap.

What is the Roadmap?

The roadmap describes PV's value to customers and the nation; the players involved; the industry's vision, goals, and targets; technical, market, and institutional barriers; and finally, how industry will reach its goals and ultimate target: bringing solar electric power into the mainstream marketplace.

Among the high-priority research and technology transfer areas identified in the roadmap are markets and applications, which focus on educating the public about PV and on challenges in the political arena. In the manufacturing area, the roadmap outlines the importance of increased collaboration between the PV industry and government to develop manufacturing partnerships. These partnerships will allow manufacturers and PV vendors to work together to develop the next generation of equipment. Also considered high priority is reducing the cost of PV through improved fabrication, installation, and servicing of PV systems in new-home and home-retrofit projects.

To keep the U.S. industry competitive in the international arena, and to further reduce the cost of PV, new technology development is also very important to the PV industry. Fundamental research outlined in the roadmap focuses on four broad categories:

- Evolutionary R&D, which seeks to reduce production costs by developing new materials and encapsulation processes
- Leapfrog R&D, which is research that will "leapfrog" over today's PV technologies to those of tomorrow by exploring unconventional ways of producing electricity using the sun
- Manufacturing Infrastructure and R&D, which is research designed to increase throughput and yield
- Institutional R&D, which strives to gain more support from government for exploratory research and development.

The map will help to guide U.S. photovoltaic research, technology, manufacturing, applications, markets, and policy through 2020. Its success will depend on the continued efforts of the "best and the brightest" among industry, the federal government, research organizations, and our educational institutions.

Mapping the Future

The U.S. industry is in the lead when it comes to PV technology and manufacturing, but staying there requires strategic planning for the long journey ahead—overcoming market barriers, increasing production, accelerating research and development of new technology, and bringing down costs.

The U.S. photovoltaics industry deliberately set ambitious goals for itself in the document. Plotting a course for the industry, the roadmap outlines numerous goals, including a 25% yearly manufacturing growth rate over the next 20 years, and system costs to the end user approaching $3 to $4 per watt AC in 2010.

The executive summary stresses an important concept for the PV industry: "Photovoltaic solar power will be a significant part of our electrical energy economy in the future. How significant it is—and who owns it—depends on setting our sights in the right direction—on the right road—today."

For more information, view the PV Industry Roadmap online at ***www.nrel.gov/ncpv/pdfs/30150.pdf***

Siemens Solar Reaches 200-Megawatt Milestone

In November 2000, Siemens Solar Industries celebrated an unprecedented achievement—a cumulative total of 200 megawatts (MW) of solar cells and solar modules produced. The event came just 4 years after its 100-MW milestone, doubling the installment of Siemens Solar panels worldwide since 1996.

Hundreds of attendees marked the accomplishment by gathering at Siemens Solar in Camarillo, California, on November 15, 2000. The celebration included a tour of Siemens' manufacturing facility. Guest speakers such as John Paul DeJoria, president of Paul Mitchell Systems, and television actor Larry Hagman, brought star power to the event. Chief operating officer of Siemens Solar, Chet Farris, welcomed guests and presented speakers and other members of the solar community with commemorative modules.

Siemens Solar modules are used worldwide. Installations include the Mont Soleil project in Switzerland and the Kerman project in California, each with an output of 500 kilowatts, and the 1-MW system at the new Munich Trade Fair Center. With a module surface area of about 7,800 square meters, the system in Munich is the largest rooftop solar installation in the world.

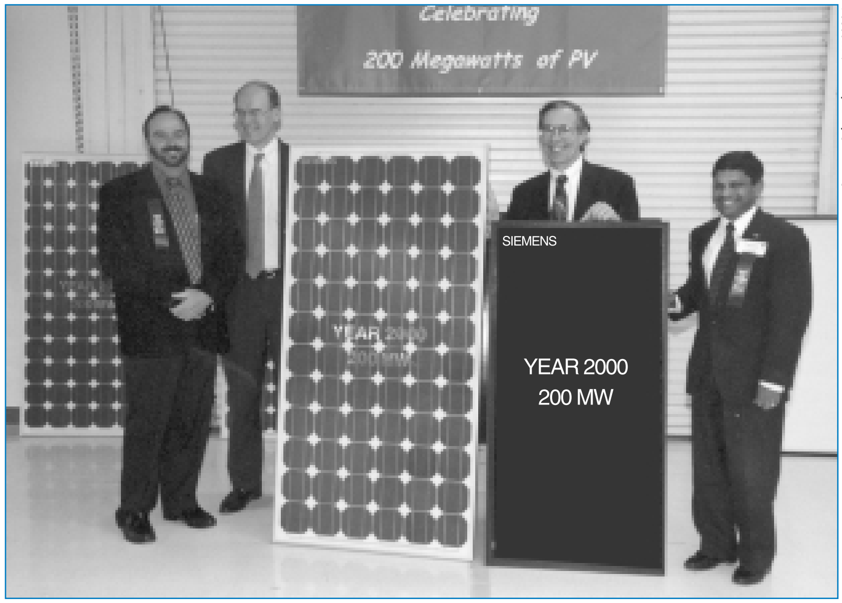
It took Siemens Solar more than 20 years to reach the 200-MW world record. In this period. "We have seen module efficiency and performance improve manyfold, and we have seen the cost come down by a factor of 1000," Farris said. But significant work remains to be done because of continued manufacturing growth, he added.

In Japan and Germany, in particular, incentive schemes for renewable energies are accelerating growth in the photovoltaics sector. The current development of the world market is also prompting Siemens Solar to invest large sums in expanding its existing production facilities. Compared to last year, Siemens Solar has increased monthly production by about 50%, to some 3 MW currently. If the market continues to grow at its current pace, production will have to double every 3 or 4 years to enable market participants to retain their shares.

"People have become more and more concerned about the cost and availability of energy," said Farris. "They demand to know where it comes from, how it was made, and what are the long-term implications of its use."

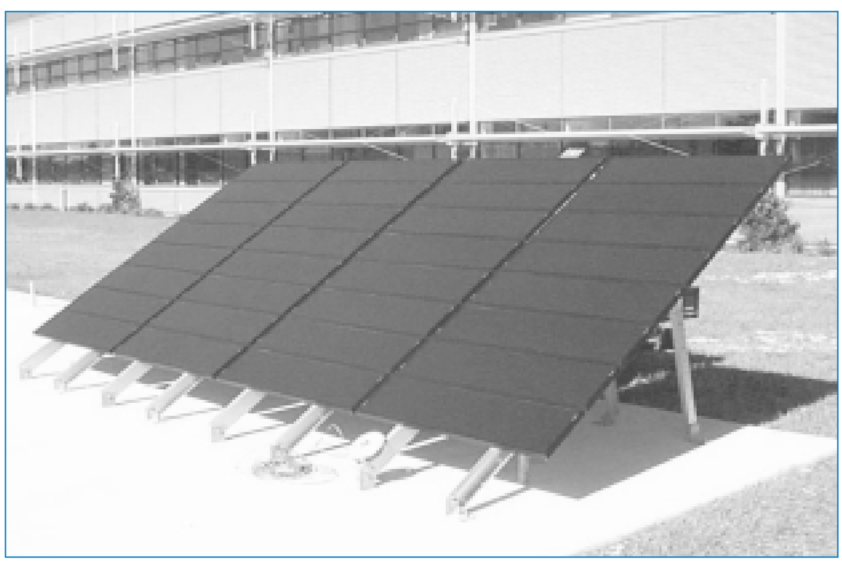
Farris closed the celebration by stating that Siemens Solar aims to build on its strength in crystalline silicon technology to lead the manufacturing transition from this technology to a lower-cost, thin-film semiconductor material—CIS technology. Based on a compound semiconductor made of copper, indium, and selenium, CIS technology reduces the consumption of semiconductor material by a factor of 100, thereby enabling a necessary and much-anticipated cost reduction. At the same time, unlike conventional thin-film technologies, CIS already approaches the efficiencies enjoyed by silicon technology.

For more information, contact Harin Ullal at 303-384-6486.



Siemens Solar Industries/PIX09824

Siemens Solar Industries celebrated its cumulative production of 200 megawatts of PV in November 2000. (Left to right) Chester "Chet"" Farris, COO, Siemens Solar Industries; Jim Rannels, director, DOE's Office of Solar Energy Technologies; Larry Kazmerski, director, NCPV; and Harin Ullal, representing NREL's Thin-Film PV Partnership Program.



Siemens Solar Industries/PIX09100

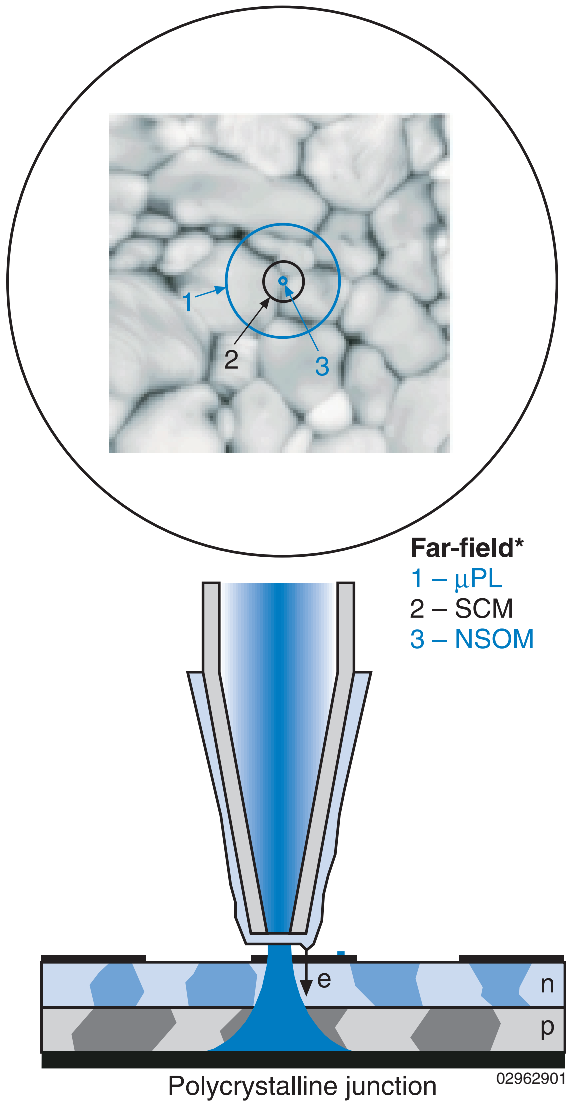
This CIS array from Siemens Solar Industries is being tested at the Florida Solar Energy Center, Cocoa, FL.

The PV Race Is On...

Twenty years ago, thin-film solar cells were no more than a gleam in a scientist's eye. Today, serious investing in this technology is taking place to help thin films catch up with silicon solar cells in pursuit of the marketplace. Investment in thin-film technology results from exploratory research funded decades ago. But thin-film and silicon solar cell materials are not the only competitors.

“In a way, PV technology is a horse race with lots of different horses and jockeys,” says NREL's Bob McConnell, who heads the NCPV's “PV Beyond the Horizon” research initiative. “Right now, crystalline silicon is way ahead in the field because it's the oldest and most established technology,” he says. “It has good jockeys, so to speak, because of the good R&D community that surrounds it. But another horse with a good jockey could catch up fast, too.”

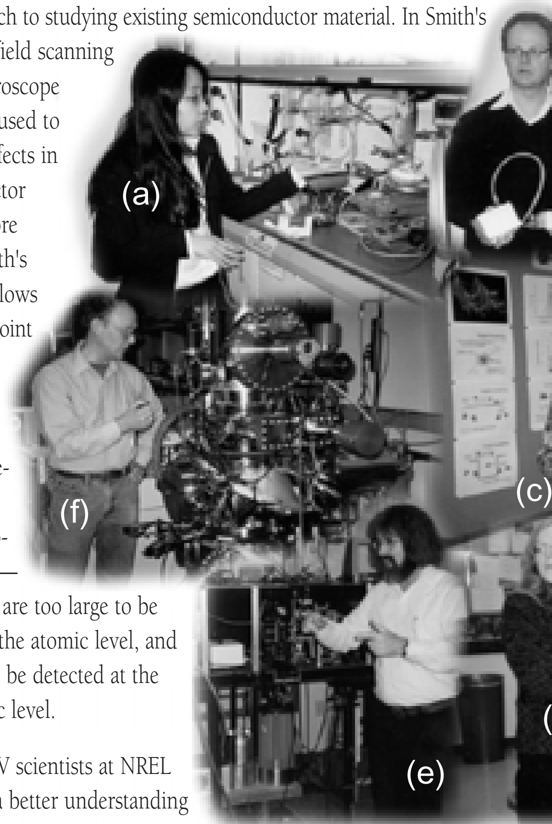
One program that is helping new technology “catch up” in the PV race is the “PV Beyond the Horizon” initiative funded by DOE. The initiative recently selected 11 universities and 5 companies for funding of high-tech research into nonconventional photovoltaic technologies, involving research with the potential to create a breakthrough in dramatically reducing the cost of solar electricity in the future. Initiative awards range from $160,000 to $500,000 for 3-year periods. Universities in Arizona, California, Illinois, Iowa, Maryland, Michigan, New Jersey, and Ohio were selected, as were companies in California, Colorado, Delaware, and Michigan. Some larger companies, such as DuPont, will share the cost of the research. The awards are pending the outcome of budget deliberations for the next fiscal year.



AFM image courtesy of Helio Moutinho, NCPV/NREL

*The basic concept of the near-field scanning optical microscope (NSOM) is a single-mode optical fiber drawn to a fine point and coated with aluminum. This forms a nanometer-sized light source that can then illuminate a submicron area of a sample to perform highly localized spectroscopy. *1 is photoluminescence, 2 is scanning confocal microscopy, and 3 is defined above.*

If the future of PV is indeed a horse race, then one of the newcomers out of the gate is NREL's Steve Smith. Smith, and his collaborators in the solid-state spectroscopy lab, attracted the attention of the “PV Beyond the Horizon” awards committee because their proposal dealt with a new approach to studying existing semiconductor material. In Smith's lab, a near-field scanning optical microscope (NSOM) is used to examine defects in semiconductor material more closely. Smith's approach allows him to pinpoint the actual location of defects that hinder material quality at the microscopic level—defects that are too large to be detected at the atomic level, and too small to be detected at the macroscopic level.



While NCPV scientists at NREL try to gain a better understanding of existing semiconductor material used to make solar cells, other researchers entering the race come from universities and the PV industry. These NCPV partners are investigating new solar cell materials and devices based on organic chemistry.

One “PV Beyond the Horizon” awardee is the University of Arizona, where scientists are exploring the development of new solar electric devices based on liquid-crystalline materials. Neal Armstrong and his research group at the University in Tucson proposed using self-assembled organic molecules, with high charge mobility, in PV technologies. These materials can be wet-processed into large-area panels. And like polymers, the thin films can be “self-repairing,” thereby minimizing defect sites and recombination centers. They also exhibit the high charge mobility seen in organic single crystals. Armstrong's group hopes their work will advance the understanding of charge injection and charge transport in organic materials and leapfrog other emerging organic technologies.

Other universities were selected for their research in organic semiconductors. For example, until recently, electronic devices such as transistors, color displays, and lasers have been based on silicon technology. But within the past few years, plastic semiconductors were found to be a competitive alternative. Flexible, easy to manufacture, and inexpensive, organic semiconductors might be used to make a whole series of new and improved electro-optical devices, something that could possibly ignite a second semiconductor revolution. However, several major challenges need to be overcome for polymer PV to be an effective renewable energy alternative. Among them are obtaining a sufficient energy conversion efficiency and achieving low-cost manufacturing that results in both long lifetimes and high reliability.

One recent "PV Beyond the Horizon" contract designee trying to overcome these challenges is Professor Sue Carter at the University of California at Santa Cruz. Carter and other researchers at U. of C. Santa Cruz are experimenting with polymer-hybrid photovoltaic materials and devices to develop a reliable polymer-hybrid PV device that retains high efficiencies while keeping manufacturing costs to a minimum. Carter visited NREL several years ago and presented a seminar on her work. During her visit, she also learned about issues associated with NREL's PV technologies.

As a result of her visit, Carter proposed to synthesize a class of soluble, conjugated copolymers, based on poly-phenylenevinylene and polythiophene backbones, with bandgaps close to 1.6 eV, designed specifically for PV applications. The group's PV device design differs from traditional ones in that it makes the transparent electrode the electron-accepting contact. If developed, this nonconventional solar electric technology would be compatible with liquid-based plastic processing, and devices based on this technology could be assembled onto plastic substrates under atmospheric conditions using standard printing technologies such as reel-to-reel and screen printing. A breakthrough here could lead to significant cost reductions for PV.

(Continued on page 11, column 1)

PV Beyond the Horizon

Proposals Selected for Award

- University of Arizona — Liquid Crystal-Based PV Technologies
- University of California, Santa Cruz — Polymer Hybrid PV
- California Institute of Technology — (1) Efficiency Improvements of Dye-Sensitized Nanocrystalline TiO_2 Solar Cells and (2) Layer Transfer Fabrication of High Efficiency Solar Cells
- UNISUN — Non-Vacuum Processing of CIGS Solar Cells
- United Innovations, Inc. — Broad-Band Rugate Filters for High Performance Solar Electric Concentrators
- ITN Energy Systems, Inc. — Optical Rectenna Solar Cell
- DuPont Central Research and Development — Development of a Solid-State Electrolyte for Dye-Sensitized Solar Cells
- University of Illinois — Low-Temperature Processing for CIGS Solar Cells
- Iowa State University — (1) Novel Group IV Materials for PV Devices and (2) Nanoscale Design of Thin-Film Heterogeneous Silicon Solar Cell Materials
- Johns Hopkins University — Solar Energy Conversion with Ordered Molecular, Light Harvesting Arrays
- University of Michigan — Synthesis and Nanometer-Scale Characterization of GaInNAs for High Efficiency Solar Cells
- United Solar Systems Corporation — Microcrystalline Silicon Solar Cells
- Princeton University — Double Heterostructure and Tandem Devices
- Ohio State University — GeSi Buffer Layers on Si Substrates for III-V Solar Cells

Photo montage: (a) student/professor demonstrating latest nanocrystal composite (University of California-Berkeley); (b) positron annihilation spectroscopy (PAS) to determine void fraction in a-Si; (c) explaining PAS theory; (d) femtosecond spectroscopy to characterize ultra-fast carrier dynamics in a-Si (b, c, d Washington State University); (e, f) novel capacitance techniques to study new CIGS deposition method (University of Oregon).

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.

BP Solar has installed its first 10-kW thin-film Apollo CdTe PV array at the **Western Area Power Administration** (WAPA), Folsom, CA, about 60 miles from Sacramento. State-of-the-art, large-area, power modules (0.94 m^2) were used in this installation, which includes a remote data acquisition system via modem. The energy generated will be used internally in the WAPA building. The array, installed on a south-facing metallic roof, consists of 144 thin-film Apollo CdTe modules with a flying-lead connector system and specially designed aluminum mounting brackets. A 10-kW Trace inverter is used as the power conditioner. Twelve thin-film Apollo CdTe modules, fabricated by the potentially low-cost electrodeposition method, are wired in series to form 12 subarrays. These subarrays are then wired in parallel in a combiner box adjacent to the inverter. The inverter is located underneath the roof in the attic, with the Campbell Scientific data acquisition system. **NREL** has supported the R&D activities in this project, the largest thin-film CdTe PV array deployed by BP Solar. BP Solar is currently ramping up production to 10 MW annually at its plant in Fairfield, CA. Contact: **Harin Ullal, 303-384-6486**

Global Solar Energy (GSE), along with its lower-tier subcontractor **ITN Energy Systems** (ITN/ES), has fabricated a large-area, thin-film, lightweight, flexible CIGS power module with an output of 36.5 W. This is the highest power output for any such CIGS module in the world. GSE and ITN/ES have interacted extensively with **NREL** in-house scientists to understand the growth of CIGS films and also to characterize the films, as part of the National CIS R&D Team activities. The CIGS film is grown by physical vapor deposition, whereas the CdS, ITO, and Mo films are deposited by sputtering. Typical module structure is ITO/CdS/CIGS/Mo/stainless steel. GSE and ITN/ES also interact with the **Institute of Energy Conversion at the University of Delaware**, Newark, DE. The module's output has been independently verified by NREL staff at the **Outdoor Test Facility**, and, most recently, yields in excess of 80% have been achieved on the large-area continuous web. Several such power packs have been supplied to the **U.S. Army** for various applications. GSE expects to exceed 1 MW of power module production this year, and has signed a Memorandum of Understanding with an international company to expand its CIGS activities. Contact: **Harin Ullal, 303-384 6486**

The **NREL System Performance and Engineering Task** established a relationship with **Trace Engineering** to install a Sun Tie 2500 inverter in the **Outdoor Test Facility's** Flexible Testbed (FTB). Trace wanted this inverter to be tested with a crystalline-silicon array in a cold, sunny climate such as found at NREL in Golden, CO. NREL will monitor the solar insolation and the output current, voltage, and power of the inverter. The System Performance and Engineering Task is going to expand the FTB to include arrays of different PV technologies: triple-junction a-Si, CdTe, and CIGSS. Giving PV balance-of-systems manufacturers access to these NREL facilities will lead to better-engineered PV systems. Contact: **Peter McNutt, 303-384-6767**

A collaborative effort between **NREL's Amorphous Silicon Team** and **United Solar Systems Corporation** (USSC) has produced an 11.66%-efficient amorphous silicon tandem solar cell. NREL deposited the bottom midgap cell's active layer at the high rate of 10 Å/s, and the tandem stabilized at 9.62% during 1000 hours of light-soaking. These efficiencies (active-area values measured at USSC) demonstrate that high-efficiency amorphous silicon solar cells can incorporate midgap cells that are fabricated at high deposition rates, an important result for low-cost production of PV modules. The tandem solar cell was deposited on a USSC stainless-steel substrate with a textured Ag/ZnO back-reflector designed to scatter light and enhance red quantum efficiency. At 10 Å/s, the a-SiGe:H bottom cell is deposited about ten times faster than commercial bottom cells, but USSC grows the top cell at the normal rate of about 1 Å/s. The new cell loses only about 18% of its efficiency during degradation. This is remarkably little degradation for a device containing a 10 Å/s i-layer, but still worse than tandem cells deposited entirely at 1 Å/s. The stabilized, active-area efficiency of 9.6% is a result of two changes in NREL's high-rate a-SiGe:H device. First, the a-SiGe:H is deposited from hydrogen-diluted silane and germane precursor gases. Second, researchers graded the a-SiGe:H active-layer bandgap by varying the Ge content from 0 to 16 atomic percent. The results will be presented in a joint paper at the **Materials Research Society's** Spring Meeting in San Francisco in April 2001. Contact: **Qi Wang, 303-384-6681**

The silicon ingot lifetime testing equipment that **NREL** designed and custom-built for **Siemens Solar Industries** (SSI) several years ago is playing an increasingly important role at SSI's Vancouver, WA, crystal growth facility as a key in-line quality control tool. At the request of SSI and in the spirit of assisting U.S. silicon PV companies, **Tihu Wang** traveled to SSI's plant in March 2001 to train their newly hired technician to use the instrument. This equipment identifies potential problems before any wafering and cell processing is done on the ingots. With the speedy operation and rugged construction of the instrument, one worker-shift is capable of checking all Si ingots produced by the 30-MW plant running round the clock. This is made possible by a unique probe-head design with integral light source, conceived by NREL's **Ted Ciszek**, implemented by Tihu Wang, and transformed into an industrially functional testing machine by **Marc Landry**. The new instrument eliminates the problem of imperceptibly small photoconductive decay (PCD) signals usually encountered when using the ASTM testing method on large, heavily doped silicon ingots. The NREL researchers obtained a comprehensive understanding of the relationship between measured effective lifetime and true bulk lifetime of minority carriers in silicon ingots by this localized PCD method via a full three-dimensional and transient finite-element analysis. Contact: **Ted Ciszek, 303-384-6569**

Subcontracted research with universities and industry, often cost-shared, is an important part of NREL's PV Program. From October 2000 to March 2001, we awarded more than $17 million to 123 new and existing subcontracts. Examples are listed below.

ASE Americas, Inc., Billerica, MA
Cost Reductions in High-Volume EFG PV Module Manufacturing Line

Colorado State University, Fort Collins, CO
Device Physics of Thin-Film Polycrystalline Solar Cells

ENTECH, Inc., Keller, TX
Near-Term Integration of III-V Cells, Operating at 440X, into ENTECH's Field-Proven Concentrator Module

ITN Energy, Littleton, CO
Atmospheric-Pressure Chemical Vapor Deposition of CdTe for High-Efficiency Thin-Film PV Devices

Siemens Solar Industries, Camarillo, CA
Specific R&D Problems in Product Manufacturing

Spire Corporation, Bedford, MA
Post-Lamination Manufacturing Process Automation for Photovoltaic Modules

United Solar Systems Corporation, Troy, MI
High-Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology

University of Delaware, Newark, DE
Thin Film Multijunction Solar Cells: Development of a High-Bandgap Cell

University of South Florida, Tampa, FL
Advanced Processing of Technology for CdTe and High Bandgap CIGS Solar Cells

University of Toledo, Toledo, OH
Polycrystalline Thin-Film Tandem Photovoltaic Cells

University of Utah, Salt Lake City, UT
Characterization of Amorphous Silicon Thin Films and PV Devices

Research papers, technical reports, and patents are one of NREL's most valuable contributions to the PV community. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings. Listed below are a few examples (see ***www.nrel.gov/publications*** *for more). When possible, publications relate to articles in the issue.*

R.K. Ahrenkiel et al. "Transport Properties of $GaAs_{1-x}N_x$ Thin Films Grown by Metalorganic Chemical Vapor Deposition," *Appl Phys Lett*, 77(23), 4 Dec 2000, 3794–3796.

C. Ballif et al. "Cross-Sectional Atomic Force Microscopy Imaging of Polycrystalline Thin Films," *Ultramicroscopy*, 85, 2000, 61–71.

B. Bathey et al. *PVMaT Cost Reductions in the EFG High-Volume PV Manufacturing Line: Annual Report*, Aug 1998–Dec 2000, 24 pp., Report SR-520-29626.

R.W. Birkmire. "Compound Polycrystalline Solar Cells: Recent Progress and Y2K Perspective," *Sol Energ Mat Sol C*, 65, 2001, 17–28.

J. Britt et al. *Process Development for CIGS-Based Thin Film Photovoltaic Modules: Phase II Technical Report*, 2000, 50 pp., Report SR-520-29227.

T.J. Coutts et al. "Search for Improved Transparent Conducting Oxides: An Investigation of CdO, Cd_2SnO_4, and Zn_2SnO_4," *J Vac Sci Technol A*,18(6), Nov/Dec 2000, 2646–2660.

S.K. Deb, B. Sopori. "Chapter 11: Recent Advances in Thin Film Solar Cells." M.H. Francombe et al., eds. *Handbook of Thin Film Devices, Semiconductor Optical and Electro-Optical Devices*, 2, 2000, 311–362. Academic Press, San Diego, CA.

M.A. Green et al. "Solar Cell Efficiency Tables (Version 16)," *Prog Photovoltaics*, 8, 2000, 377–383.

F.H. Karg. "Development and Manufacturing of CIS Thin Film Solar Modules," *Sol Energ Mat Sol C*, 66, 2001, 645–653.

B. Kroposki et al. *Comparison of Module Performance Characterization Methods for Energy Production*, 2000, 62 pp., Report TP-520-29245.

A.H. Mahan et al. "Explanation for the Low-Temperature H Evolution Peak in Hydrogenated Amorphous Silicon Films Deposited 'On the Edge of Crystallinity,' " *Phil Mag Lett*, 80(9), 2000, 647–652.

P. McNutt et al. *Validation Testing of Procedures for Determining the Performance of Stand-Alone Photovoltaic Systems*, 2000, 69 pp., Report TP-520-29185.

C.R. Osterwald, K.A. Emery. "Spectroradiometric Sun Photometry," *J Atmos Ocean Tech*, 17, Sept 2000, 1171–1188.

N.G. Park et al. "Comparison of Dye-Sensitized Rutile- and Anatase-Based TiO_2 Solar Cells," *J Phys Chem B*, 104(38), 2000, 8989–8994.

J. Thiesen et al. "Explanation of the Limiting Thickness Observed in Low-Temperature Silicon Epitaxy," *Appl Phys Lett*, 77(22), 27 Nov 2000, 3589–3591.

C.E. Witt et al. *Ten Years of Manufacturing R&D in PVMaT—Technical Accomplishments, Return on Investment, and Where We Go Next*, 2001, 6 pp., Report CP-520-28973.

X. Wu, P. Sheldon. *Process for Fabricating Polycrystalline Semiconductor Thin-Film Solar Cells, and Cells Produced Thereby*, U.S. Patent No. 6,137,048, (2000), 14 pp., Report 29284.

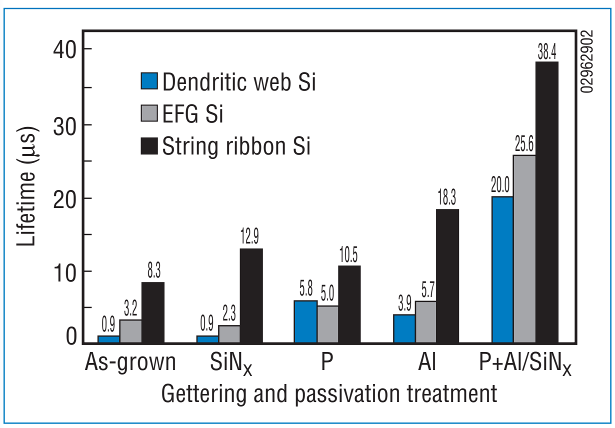
X. Wu et al. *Photovoltaic Devices Comprising Zinc Stannate Buffer Layer and Method for Making*, U.S. Patent No. 6,169,246 B1, (2001), 13 pp., Report 29826.

D. L. Young et al. "Direct Measurement of Density-of-States Effective Mass and Scattering Parameter in Transparent Conducting Oxides Using Second-Order Transport Phenomena," *J Vac Sci Technol A*, 18(6), Nov/Dec 2000, 2978–2985.

Georgia Tech Improves Solar Cell Processing

The goal of the University Center of Excellence in Photovoltaics (UCEP) at the Georgia Institute of Technology is to improve the technology, physical understanding, and cost-effectiveness of photovoltaics. Particular emphasis is placed on technologies involving silicon substrates used by the PV industry. In addition, UCEP aims to increase the awareness and understanding of PV systems through education and hands-on training. The Center was established in 1992 and was renewed by DOE in July 2000, based on its successes that include several world records for solar cell conversion efficiencies. UCEP has also expanded, with Dr. Christiana Honsberg from the University of New South Wales in Sydney, Australia, having joined the Center in January 2001.

One research area is the development of low-cost, rapid-process technologies for industrial production of high-efficiency silicon solar cells. For industry, rapid thermal processing (RTP) offers a key advantage because processing time can be dramatically reduced by a factor of five or more. The research program at UCEP is investigating the impact of RTP on device performance, particularly regarding emitter saturation current, back-surface passivation, contact resistance, and, for multicrystalline material, the effect of RTP on gettering and hydrogenation.



Bar chart showing improved lifetime values of three different silicon materials following gettering and passivation treatments at the University Center of Excellence for Photovoltaics at Georgia Tech.

For several types of processes, RTP improves the performance of conventional furnace processing. Recent results have shown that RTP has advantages for multicrystalline-silicon (mc-Si) wafers. For example, results on mc-Si wafers indicate that rapid cooling after hydrogenation enhances cell performance. Results on single-crystalline wafers show that the saturation current from RTP emitters is consistent with efficiencies greater than 20%. Solar cells processed by RTP on planar float-zone silicon wafers with photolithographic contacts produced a record efficiency of 19.3%. Similar results were achieved with Czochralski (CZ) and magnetic-field-applied CZ silicon, which produced efficiencies of 18.5% to 19%. Overall, the combination of low emitter saturation currents and improved performance from RTP shows that RTP can produce high efficiencies in mc-Si material while lowering processing costs.

Although RTP may have cost and efficiency benefits that can be exploited with novel processing techniques and device structures, research at UCEP also focuses on developing low-cost processes using belt-line processing and screen-printed contacts. Improved understanding of the hydrogenation and gettering processes have resulted in optimized processing procedures that produce experimental efficiencies approaching 15% in a wide range of mc-Si materials, including edge-defined film-fed growth, string-ribbon, and dendritic-web material, and wafers cast by the heat-exchanger method. In addition, recent results show that minority-carrier lifetime improvements of an order of magnitude or more can be achieved in different types of multicrystalline material. These results show that efficiencies above 16% can be achieved even if the starting lifetime is low.

For more information, contact Georgia Tech's UCEP Director Ajeet Rohatgi, 404-894-7692.

IEC Advances Semiconductor Deposition Systems

At the Institute of Energy Conversion (IEC), University of Delaware, a DOE University Center of Excellence in Thin Films, semiconductors made from both copper indium gallium diselenide ($CuInGaSe_2$) and cadmium telluride (CdTe) are being deposited on continuously moving substrates. Deposition of semiconductors onto moving substrates is not new to IEC. In the late 1970s and early 1980s, under the direction of Professor Fraser Russell and with support from Chevron Corporation, IEC was the first group to deposit a thin-film semiconductor, cadmium sulfide (CdS), on a flexible web, for which a patent was awarded. The design of evaporation sources used in the system was based on quantitative models developed at IEC. This forward-looking approach has been employed for a-Si and is currently being developed by several companies for both $CuInSe_2$- and CdTe-based solar cell technologies.

Two years ago, with financial assistance from Global Solar Energy, ITN Energy Systems, NREL, and the State of Delaware, IEC obtained an in-line deposition system to deposit $CuInGaSe_2$ on a moving substrate. The heart of the system is a set of thermal effusion sources, the design of which is based in part on the early CdS work and in part on models developed at IEC under a Defense Advanced Research Projects Agency program. The in-line evaporation system, which was designed for a 12-inch-wide web at translation speeds up to 20 inches per minute, is presently configured for 6-inch-wide substrates. Each elemental effusion source has two nozzles, and the sources are positioned in the sequence Cu-Ga-In, although the source sequence can be changed as needed. The Se is supplied into the deposition zone through a system of manifolds connected to a single thermal source. The Cu, In, and Ga effusion rates are controlled by ATOMICAS™ atomic absorption spectroscopy systems, whereas the Se rate is controlled by temperature. A model-based process control system currently under development will allow precise control of the growth of $Cu(In,Ga)Se_2$ films for long run times in which there is depletion of material in the sources. Solar cells composed of $CdS/Cu(In,Ga)Se_2$ and having efficiencies greater than 14% have been made from materials deposited in the system.

To expand its research effort on CdTe, IEC embarked on designing a system that would be similar to close-spaced vapor transport (CSVT), but one that would eliminate the need to have a source comparable in size to the substrate. A team organized to design such a system developed a new source that can transport Cd and Te vapors to the surface of a moving substrate at rates similar to that of CSVT. The source operates by saturating a carrier gas, flowing over CdTe maintained at an appropriate temperature, with Cd and Te vapors. The saturated gas is then directed onto the cooler substrate surface, where vapor supersaturation leads to the condensation of CdTe. This is analogous to what is being used by First Solar in its manufacturing line. Deposition rate is controlled by a combination of source temperature, carrier-gas flow rate, total pressure, and substrate translational speed. Substrate position and translation are computer-controlled to allow preheating, deposition, and cooling steps to be set independently. MVSystems, using IEC's design and its own expertise in thin-film deposition system engineering, built the system.

With the addition of these continuous deposition systems, the research effort at IEC took a giant step closer to manufacturing reality. The systems will provide an effective means to investigate and modify laboratory-scale processes in order to develop commercial-scale in-line production systems. Furthermore, these in-line systems will also provide a platform to develop in-situ diagnostics and model-based process-control schemes required for the operation of commercial-scale systems. As a result, the science and engineering base needed to transfer the technology from laboratory to manufacturing can effectively be developed.

For more information, contact IEC Director Robert Birkmire at 302-831-6220.

The PV Race Is On, Continued from p. 7

At Iowa State University, Professor Vikram Dalal and his colleagues are exploring a new material system for solar electric devices based on crystalline germanium and carbon alloy films from the Group IV elements of the periodic table. The basic thrust will to develop high-absorption materials in the 1.3–1.6-eV bandgap region, while maintaining the superior optical properties of the alloy system. His group prepares the material using remote, reactive plasma deposition with an electron cyclotron resonance source. Preliminary experimental results show promising optical absorption and bandgaps for this new material system that are substantially better than those of silicon.

Also noteworthy is Princeton University's work with a new semiconductor material for a novel light-trapping molecular organic solar cell. Professor Stephen Forrest and his research group are building on the dramatic technological progress of the past decade in the field of organic light-emitting devices used in commercially available emissive flat-panel displays. Research done to date suggests that at least a threefold improvement can be expected by simply improving the thin-film growth control. Further efficiency improvements can be obtained through growth of multilayer structures, incorporation of phosphorescent dopants, and integration of optical collectors onto the cell substrate to trap solar radiation. Forrest anticipates a research outcome that yields organic PV cell conversion efficiencies in excess of 6% at AM1.5 (1-sun) illumination and with operational lifetimes exceeding 105 hours by the end of the 3-year program period.

Researchers at Johns Hopkins University are looking to create molecular solar cells by using linear chromophore rods that will be assembled into ordered, molecular, light-harvesting arrays on electrode surfaces. Professor Gerald Meyer, along with Professor Jonathan Lindsey at North Carolina State University, is using a new approach to solar cell material, but one that borrows from lessons learned in dye-sensitized and "organic" chemistry that allow the construction of linear chromophore arrays. The arrays provide strong light absorption such that a monolayer on a flat surface will capture significant fractions of the incident light energy. In addition, these arrays provide for energy migration and charge migration in opposite directions. Thus, the chomophore arrays absorb light and may exhibit an intrinsic molecular level rectification in the flow of excited-state energy and ground-state holes.

Among the companies identified for subcontract awards under the "PV Beyond the Horizon" initiative is United Innovations of San Marcos, California. United Innovation's project involves broadband rugate filters for high-performance, solar electric concentrators. This project will include developing a dish concentrator system consisting of a first-stage parabolic concentrator with circular heliostat facets, a second-stage non-imaging concentrator, and a spherical cavity that will collect the light and convert it to electricity using multiple III-V solar cells lining the interior surface of the cavity. The multiple III-V solar cells have different energy gaps; each cell will be covered by a rugate filter with selective transmission/reflective characteristics permitting transmission of only the portion of the solar spectrum that matches the spectral response of the cell underneath. Ultimate projected cell and system-level efficiencies for this concentrator concept are 50% and 38%, respectively.

These are but some of the exciting projects scheduled for investigation in future-generation PV research through the "PV Beyond the Horizon" initiative. All have the potential to outpace their particular area of PV research into the forefront of the PV race for future development. The efforts of these researchers could lead to significant cost reductions in solar cell manufacturing, as well as increase the efficiencies and lengthen the lifetimes of solar cell devices.

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

PV Calendar

June 11–15, 2001, *12th International Photovoltaic Science and Engineering Conference*. Sponsors: The Korean Ministry of Commerce, Industry and Energy/Korea Institute of Energy Research. Location: Cheju Island, Korea. Contact: *http://solarpv.or.kr/pvsec-12*

July 16–20, 2001, *Fourth International Conference on Nitride Semiconductors*. Sponsors: Materials Research Society, IEEE, and Electron Devices Society. Location: Denver, CO. Contact: *www.mrs.org/meetings/icns-4*

August 19–22, 2001, *11th Workshop on Crystalline Silicon Solar Cell Materials and Processes*. Sponsor: NREL. Location: Estes Park, CO. Contact: Bhushan Sopori, 303-384-6683 or bhushan_sopori@nrel.gov

September 30–October 5, 2001, *UPEx'01: The Photovoltaic Experience Conference and Exhibition*. Sponsor: Solar Electric Power Association (formerly UPVG). Location: Sacramento, CA. Contact: Julia Judd, 202-857-0898 or Web site: *www.SolarElectricPower.org*

October 14–17, 2001, *NCPV Program Review Meeting*. Sponsor: NREL. Location: Lakewood, CO. Contact: Kannan Ramanathan, 303-384-6454 or kannan_ramanathan@nrel.gov

October 22–26, 2001, *17th European Photovoltaic Solar Energy Conference and Exhibition*. Sponsor: WIP - Renewable Energies, Germany. Location: Munich, Germany. Contact: *www.wip.tnet.de/pv01.htm*

October 29-31, 2001, *First International Conference on Solar Electric Concentrators*. Sponsors: Universidad Politecnica de Madrid, NREL. Location: Marbella, Spain. Contact: Robert McConnell, 303-384-6419 or robert_mcconnell @nrel.gov or Web site:*www.nrel.gov/icsec*

November 4–8, 2001, *World Conference on Technology Advances for Sustainable Development*. Sponsors: Ministry of Water Resources and Irrigation, Ministry of Military Production. Location: Cairo, Egypt. Contact: *www.aast.edu/mceet*

November 25–December 2, 2001, *ISES Solar World Congress*. Sponsor: International Solar Energy Society. Location: Adelaide, Australia. Contact: "Events" at *www.ises.org*

This quarterly report covers solar electricity research and related activities from NREL, Sandia National Laboratories, and their partners within the National Center for Photovoltaics (NCPV). These partners include the DOE University Centers of Excellence for Photovoltaics at the Georgia Institute of Technology and the University of Delaware's Institute of Energy Conversion and Regional Experiment Stations at the Florida Solar Energy Center and the Southwest Technology Development Institute.

Robert McConnell 303-384-6419
NREL PV Program Communications

Tom Surek 303-384-6471
NREL Technology Manager, Photovoltaics

Lauren Poole 303-384-7466
Writer, Editor

Kristin Schnelten 303-384-6624
Writer, Editor

Susan Moon 303-384-6631
Editor

Jim Miller 303-384-6595
Graphic Designer

NCPV-Related 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

Sandia National Laboratories PV *www.sandia.gov/pv/main2.html*
Engineering • Balance of Systems • Crystalline Silicon • Performance

Georgia Institute of Technology PV . . . . . . *www.ece.gatech.edu/research/ucep*
Technologies • Hands-On Training • Modeling and Analysis Capabilities

Institute of Energy Conversion, Univ. of Delaware . . . . . . *www.udel.edu/iec*
PV Power Generation • Thin Film Solar Cell Technology

Florida Solar Energy Center . . . . *www.fsec.ucf.edu*
PV Education and Training • Houses and Buildings

Southwest Technology Development Institute . . . . *www.nmsu.edu/~tdi*
PV Testing • Performance Monitoring • Codes and Standards

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

NREL Report No. BR-520-29629.
NREL is a national laboratory operated for the U.S. Department of Energy under Contract No. DE-AC36-99-GO10337.

If you are not on the mailing list for this publication and would like to receive it, please send your name, affiliation, and address to: PV Program, NREL, 1617 Cole Blvd., Golden, CO 80401-3393.

Printed with a renewable source ink on paper containing at least 50 percent wastepaper, including 20 percent postconsumer waste