NREL PV

Working With Industry

New Looks

We've given a new look to this report on the National Renewable Energy Laboratory's photovoltaics staff working with industry. As we come to our tenth issue, many of you have let us know you appreciate this quarterly review of photovoltaic information. We hope that the content is enhanced by our effort to provide a more attractive format.

Another new look we have is our Solar Energy Research Facility—or SERF, as it is known on site. The new facility is complemented by improved equipment that extends our capabilities in serving industry's research activities. We devote this issue to describing some of the research labs to let you know what is available to you.

Finally, we have a familiar face to the photovoltaics community as NREL's new Director. We in NREL's PV program are especially pleased to have Charles F. Gay write the editorial for this issue because of his extensive experience and accomplishments in advancing PV. Although new looks are the theme of this issue, our basic goal remains that summarized in the title of Charlie's editorial—to work with industry to move PV forward.

Features

Departments

Summer 1995

Working with Industry to Move PV Forward

An Editorial by Charles F. Gay


Photo by Warren Gretz

Charles F. Gay, Director, National Renewable Energy Laboratory

Since its inception in 1977, NREL has worked hand in hand with members of the photovoltaic community to fulfill our legislative mandate to advance the progress of renewable energy technologies and to nurture the development of a competitive domestic industry base.

NREL's government-industry partnerships are yielding tremendous progress in photovoltaics (PV) technology. Progress is evident at every stage of the technology development process—from advances in fundamental materials science, to breakthroughs in device efficiencies, to more efficient module fabrication techniques, to the opening up of vast, new international markets for PV systems. Budget constraints and the evolution in the nation's view of the role of the federal government are modifying NREL's mandate to include establishing new kinds of partnerships and ventures with industry, tapping into new funding sources to finance NREL's programs, and working to ensure American industry fair access to serving the burgeoning overseas markets for renewable energy products and services.

As NREL moves forward to implement these new mandates, two elements at the core of NREL's culture will not change: our commitment to serving the nation as its center of excellence in renewable energy R&D, and our commitment to working with the PV industry to meet the nation's needs for a secure, reliable energy supply.

This issue of PVWWI highlights a cross-section of NREL's capabilities in photovoltaics R&D. As NREL's director, I invite you to join us in using these capabilities to advance PV technology, to assure international competitiveness of American PV goods and services, and to move toward meeting a significant portion of the world's needs for clean, reliable electricity with photovoltaics.

New Equipment Stays Busy Analyzing Surfaces and Interfaces

The Solar Energy Research Facility (SERF) is nestled into the south-facing hillside of South Table Mesa. Not visible to the eye is the fact that a 4,000-sq-ft basement exists and is about ready to open with several new labs. Some existing equipment, like the secondary ion mass spectrometer (SIMS), is being moved in from another building. But it will be met by a new, upgraded SIMS unit. These pieces of equipment, with the X-ray photoemission spectroscopy (XPS) and Auger electron spectroscopy (AES) units on the first floor, comprise an extraordinary array of surface- and interface-measuring equipment.

In SIMS, an ion beam impacts the surface of a sample and sputters the material. Some sputtered particles are secondary ions, which are focused into a mass spectrometer that analyzes the ions according to mass-to-charge ratio. Concentrations can be measured down to the parts-per-billion level, so extremely low doping or contamination concentrations can be measured. NREL researchers often use SIMS to generate depth profiles that cut across heterojunctions. "SIMS has become more important,"

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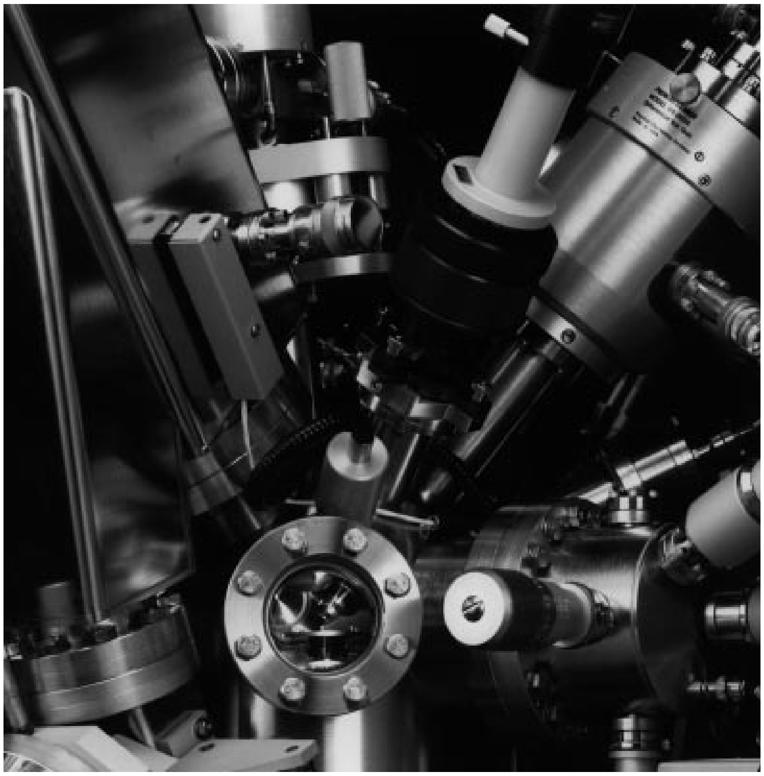
Photo by Jim Yost

The sample chamber (lower center) of the X-ray photoemission spectroscope can hold multiple samples for analysis.

New Equipment, *from page 2*

researcher Sally Asher explains, "as we see that low levels of elements in semiconductors are critical." Asher, who is in charge of SIMS analysis at NREL, says that helping in-house and outside researchers understand the importance of diffusion at CdS/CdTe interfaces by using this technique is just one example of its usefulness.

Although the newest equipment still works on the same principles as earlier generations, a better vacuum and a better-designed ion source enhance its capabilities. Also, improved electronics boost the system's versatility and sensitivity. Operating SIMS in a static mode with a time-of-flight (TOF) analyzer provides great lateral resolution, on the order of 0.1 microns—compared to about 10 microns for the earlier model. The TOF SIMS, to be available this fall, also provides molecular information and shallow depth-profiling capabilities.

David Niles is Asher's counterpart for XPS and AES analyses. The newest XPS system that Niles and his coworkers use has many improved capabilities. A monochromator filters out "satellites" from the aluminum X-ray source to optimize the excitation beam. Six or more samples can be mounted in the test chamber—a time-saving feature because the ultra-high-vacuum system does not have to be reestablished after each sample. The actual sample sizes accepted can vary tremendously, from 2 mm^2 to almost a full 3-inch wafer.

Compared to older XPS models, the new analyzer can collect a much larger fraction of electrons from a much smaller spot size on the sample. The resolution—once a 2- to 4-mm-diameter spot—now ranges from 800 down to 26 microns. At 26 microns, very small samples can be analyzed, or very specific parts of a sample can be examined. Furthermore, parallel line-scans can be combined

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The small spot size of the Auger electron spectroscope provides excellent analysis and mapping capabilities.

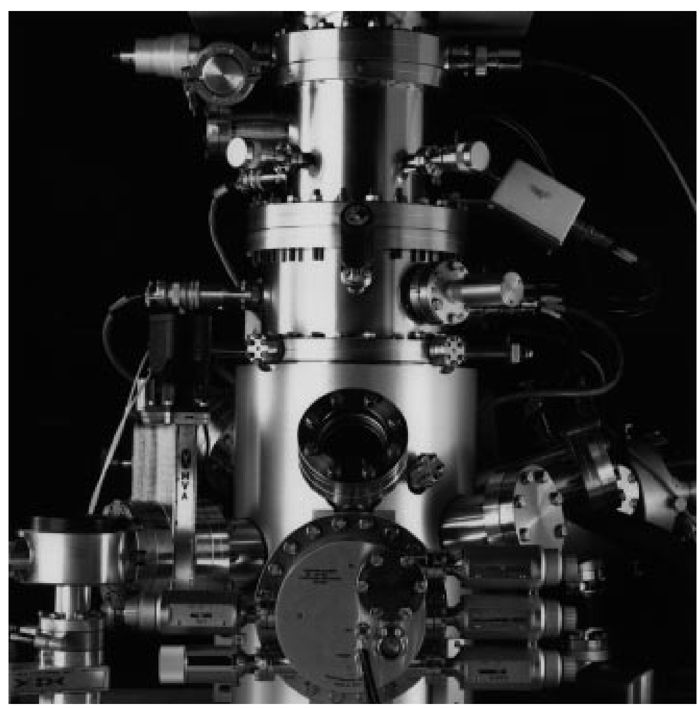
Photo by Jim Yost

Optical Techniques Give Characterization a Boost

Dick Ahrenkiel, head of NREL's Electro-Optical Characterization Lab in the PV Division, is in the midst of filing an invention report on his state-of-the-art technique to measure minority-carrier lifetimes in indirect- and low-bandgap semiconductors.

The technique—radiofrequency photoconductive decay (rf PCD)—is not a new idea. "The basic idea has been around for awhile, it just hasn't worked well," comments Ahrenkiel, "and we needed to make some improvements to make it work great!" These improvements have not gone unnoticed by industry, especially the silicon industry. As a result, Ahrenkiel and his coworkers have been busy working on a variety of materials for groups like AstroPower, Solarex, Siemens, ASE Americas, Texas Instruments, and the Georgia Institute of Technology.

The beauty of this technique is that it is contactless and can be done on very small samples. For example, Texas Instruments' (TI) Spheral Silicon technology comprises silicon spheres, 500-600 microns in diameter, embedded in an aluminum-foil sandwich. Electrical contacts could not be attached to these tiny spheres, but ultra-high-frequency (UHF) PCD allows the contactless measurement of lifetimes on individual spheres. Prior to terminating its activities, TI planned to incorporate this technique for in-line production characterization.

Another great advantage of this new system is its sensitivity. A new sensing circuit and a high-quality bridge circuit for amplification have increased the sensitivity by 2-3 orders of magnitude.


Photo by Jim Yost

Resolution of lifetime measurements is greatly enhanced by using the femtosecond laser.

This technique stemmed from initial work conducted under a $20,000 in-house grant some 4 years ago to study recombination lifetimes in materials such as silicon and indium gallium arsenide. Standard rf PCD could measure only lightly doped silicon, not heavily doped photovoltaic material. Inductively coupling the sample to an rf coil was retained, but the configuration and circuitry were redesigned. And the contactless feature of the conventional microwave reflection technique was retained. UHF waves of 430 megahertz penetrate heavily doped silicon well and resolve lifetimes down to nanoseconds, rather than the previous microseconds.

The Electro-Optical lab also features other laser diagnostics. A yttrium-aluminum-garnet (YAG) laser can send out a pulse of coherent light in 100×10^{-15} second—that is, 100 femtoseconds. The length of the pulse is what limits lifetime measurements, and so, the shorter the pulse, the better the resolution. This high resolution is especially useful in studying polycrystalline materials with high defect levels.

Two accessories to the femtosecond laser are the optical parametric amplifier and the white-light continuum generator. In the first, the laser can be "tuned" to the material anywhere on the spectrum from ultraviolet to infrared. The purpose of tuning is to tailor the wavelength so that the light is distributed as evenly as possible throughout the material. The white-light continuum generator is used for pump-probe experiments and uses two light sources: a white light and a laser. The white light illuminates the sample, which is then pulsed with a laser. Spectral analysis—done at the femtosecond timescale—can then help determine such things as whether certain optical transitions may have been bleached out.

For further information, contact Dick Ahrenkiel (303/384-6670).

One of three close-spaced sublimation reactors used to deposit the active layer in CdTe devices.

Process Control Leads to Improved Reproducibility in CdTe

"Here is what we brought with us when we moved to the Solar Energy Research Facility—virtually nothing!" So says Pete Sheldon, principal investigator of NREL's cadmium telluride (CdTe) team, while pointing to a small deposition reactor and control unit. "We've built the rest of this lab from scratch in the SERF."

Sheldon and his coworkers now have a well-equipped lab for fabricating CdTe devices. And as Sheldon explains, "There just is no vendor we could go to in order to get what we need." As a result, NREL researchers have designed their own close-spaced sublimation (CSS) systems to deposit CdTe thin films. With the help of NREL's machine shop, the custom equipment was—and continues to be—assembled in house.

Of the more than 10 different techniques for producing high-quality CdTe cells, NREL has concentrated mostly on the CSS method. A variant of CSS is used by Solar Cells, Inc. (SCI) of Toledo, OH, to produce state-of-the-art modules. The process begins with a tin-oxide-coated glass substrate obtained commercially. A chemical vapor deposition system—to be delivered in November 1995—will provide an in-house tin-oxide deposition capability. A CdS layer is then deposited in a chemical bath to a thickness of 600–1200 angstroms.

Next, the substrate is mounted in the CSS system—a horizontally oriented reactor that is evacuated to a relatively low vacuum. Depositions are typically done in a helium/oxygen ambient, where graphite susceptors are heated to above 600°C by infrared lamps. As a CdTe source is heated to about 640°–660°C, a CdTe layer is deposited on the substrate at a rate of about 1–2 microns per minute—depending on deposition ambient. This produces dense films with large grains—favorable for manufacturing processes. A programmable controller automatically regulates the partial pressure of process gases, temperature of substrate and source, and total system pressure.

When removed from the reactor, the film undergoes a cadmium chloride treatment, annealing, and etching, before an ohmic back-contact is applied. The completed CdTe device is about 5–10 microns thick.

One of the CdTe team's current focus areas is developing reproducible processes for high-efficiency CdS/CdTe devices. Before scaling up device areas, the team wants to understand the fundamentals and establish a reliable baseline process. As Sheldon points out, "We would rather have a reproducible process that will allow us to explore alternative processes and novel device structures—ultimately leading to a better understanding—than produce one cell with a very high efficiency but not be able to reproduce it—or worse yet, not know why." This philosophy is reflected in one of the project's milestones: to demonstrate a 10% baseline process. In June, this milestone was met by demonstrating a >11% baseline process with a standard deviation of 0.6%.

NREL's CdTe team participates—along with industry and university researchers—in projects of the national Thin-Film Partnership Program. And in a cooperative research and development agreement with SCI, NREL is developing a photoluminescence-based quality-control monitor that can be used in an in-line manufacturing process.

For further information, contact Pete Sheldon (303/384-6533).

CIGS Team Takes Aim at Manufacturability

When asked about an ultimate goal for copper-indium-gallium diselenide (CIGS) work, Rommel Noufi replies, "To take low-quality, low-cost precursor material, modify it in a 'blackbox,' and be left with a high-efficiency, high-quality device—all done at high speed and low cost!"

Noufi, who heads up NREL's team that has been studying CIGS for more than 13 years, admits they haven't reached this goal yet. But much progress is being made. "Efficiencies are high enough now," he continues, "to confirm the importance of CIGS technology. While we continue to work toward higher conversion efficiencies, we are also developing prototype fabrication processes that will lend themselves to flexible and robust manufacturing."

The team recently produced a CIGS cell with total-area efficiency of 17.1%—another world-record effort. Fabricating and characterizing such a cell takes place in three separate labs at NREL's Solar Energy Research Facility. In the "high tech" lab, researchers use physical vapor deposition reactors to lay down the basic materials of cells by a variety of pathways. Within the high-vacuum confines of the reactor chamber, elemental sources of Cu, In, Ga, and Se are deposited either simultaneously, sequentially, or in combination, to produce homogenous cells or a variety of graded-profile cells. Deposition is done on a Mo-coated glass substrate—which may first be overlain with a layer of $CuGaSe_2$, as in the world-record cell.

In a second lab, a CdS layer is deposited by chemical bath atop the CIGS active layer before sputtering a coat of ZnO and finishing the device with Ni/Al grids and an anti-reflection coating. The third lab allows researchers to measure the device characteristics by determining current-voltage curves, spectral response, and capacitance.

The CIGS deposition lab in particular is filled with sophisticated equipment, but the steady incremental improvements in cell efficiency are more related to process improvements than to large gains in equipment capabilities. One possible exception is the relatively new rf sputtering system that deposits a bilayer of high-quality zinc oxide at a vastly improved deposition rate. And better control of the process leads to much better reproducibility—an essential aspect of any process. The new equipment also allows the processing of substrates up to 1 ft^2 and the sputtering of a Mo coating on glass substrates.

A multitarget/multichamber deposition system will soon grace a corner of the lab. The system, currently being constructed by a firm in Colorado, was designed at NREL. Using this apparatus, researchers will be able to compare various cell-fabrication approaches and verify which ones hold potential for scale-up.

This work is being fostered by NREL's participation in Thin-Film Partnership Program research teams and by two cooperative research and development agreements (CRADAs) with industry partners. One CRADA, with Lockheed Martin of Littleton, CO, builds on NREL's state-of-the-art processes and efficiencies. And another, with Energy Photovoltaics (EPV) of Princeton, NJ, explores fabrication pathways based on NREL-developed processes with a view to applying them to EPV's manufacturing methods.

For further information, contact Rommel Noufi (303/384-6510).

Photo by Warren Gretz

After the active CIGS layers are deposited in the reactor (background), a high-quality ZnO layer is deposited by a radiofrequency sputtering system (foreground).

Great Things Are Coming Soon in the III-V Lab!

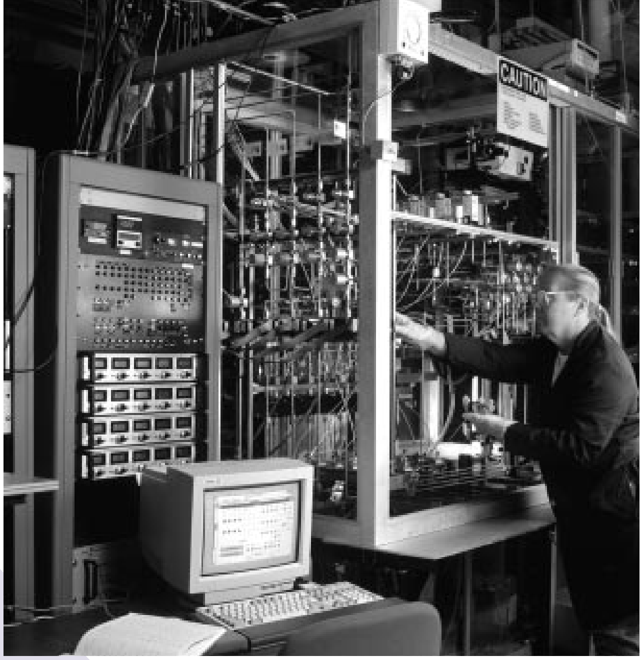

Photo by Jim Yost

The current MOCVD system is being modified so it can be attached to the high-vacuum linear transfer line.

Within several months, the III-V Materials and Devices Lab will expand its capabilities as an "old idea" is combined with a "new" one, to help researchers make highly efficient PV devices.

The "old idea" is a linear transfer line that connects a molecular-beam epitaxy (MBE) growth chamber and an analytical chamber. This 6-inch-diameter, stainless steel tube is evacuated to very low pressure and has a sample-introduction port on one end. Up to six samples can be loaded and then moved through the line via a magnetically coupled trolley. Eventually, three transfer arms will extend perpendicular to the 35-foot-long transfer line. Currently, two of these arms, which have mechanical handling controls, allow samples to be moved into the MBE unit or the analytical chamber.

The MBE unit—also known jokingly as a Mighty Big Evaporator—is an apparatus for depositing high-quality materials commonly used to fabricate high-efficiency III-V solar cells such as GaAs single-junction and GaInP/GaAs tandem cells. The properties of these materials and devices are very sensitive to surface conditions, including surface oxides produced by exposure to air. This linear transfer line allows researchers to move the sample from the growth chamber to the analytical chamber without exposing it to air. The analytical chamber contains scanning tunneling microscopy, atomic force microscopy, and low-energy electron diffraction for studying the atomic structure and microscopic features of the surface as it emerges from the growth chamber.

Several research facilities have a larger MBE/analytical chamber/transfer line system than NREL's. So what is the "new idea" that is brewing in the lab? It is attaching an MOCVD—metal organic chemical vapor deposition—unit to this transfer line. NREL researchers will then be able to study MOCVD-grown materials in much the same way as MBE-grown materials.

The new MOCVD system will be similar to the stand-alone version that to date has produced three solar cells with world-record efficiencies: 25.7% for 1-sun, AM0; 29.5% for 1-sun, AM1.5 global; and 30.2% for 2-terminal concentrator. Usually, with MOCVD, one can grow good material but not be sure of how or why. Optical ports for in situ characterization can be added, but this usually compromises the quality of the material. With the new MOCVD system, researchers will be able to monitor and characterize the growth of state-of-the-art solar cells *in situ*.

MBE has always been viewed as an expensive, esoteric, yet powerful, research tool. With in situ probes like reflection high-energy electron diffraction, growth processes can usually be studied without sacrificing material quality. However, because growth rates are typically slow, MBE has not been considered a viable tool for solar-cell production. Researchers at NREL are exploring the possibility of significantly increasing the MBE growth rate to values comparable to those of MOCVD. Ultimately, this may lead to higher solar-cell efficiencies, lower manufacturing costs, and a better understanding of MBE and MOCVD growth processes.

For further information, contact Jerry Olson (303/384-6488).

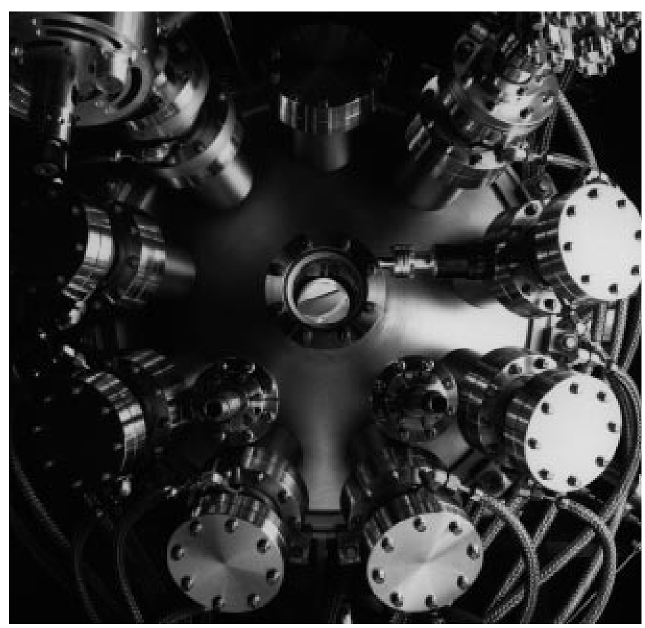

Photo by Jim Yost

The MBE system, now attached to the transfer line, will soon be ready to deposit elements for fabricating high-efficiency III-V cells.

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.

Rommel Noufi visited **Energy Photovoltaics (EPV)** of Princeton, NJ, to finalize the statement-of-work for a CRADA that will explore and develop NREL-developed patented processes with a view to applying NREL's intellectual property to EPV's CIS manufacturing equipment. (Rommel Noufi, 303/384-6410)

From April through June, 707 module measurements were performed outdoors under prevailing clear-sky conditions and on the SPIRE 240 solar simulator. Samples were evaluated from **APS/Chronar, ASE Americas, AstroPower, BP Solar, CEL India, ECD, EPV, Golden Photon, Kyocera, Photocomm, Siemens, Solar Cells Inc., Solarex, Solec**, **Solems**, and **United Solar Systems Corp.**

NREL engaged in several technology transfer activities with **Lockheed Martin** (Littleton, CO), **ASEC,** and **Solec International** (Hawthorne, CA). The **Lockheed Martin** work established measurement procedures and equipment for evaluating CdS/CIS cells and modules. The **ASEC** work verified successful implementation of suggestions for equipment and procedures provided earlier to ASEC for multijunction GaInP/GaAs tandems performance measurements. The **Solec International** work involved hardware and software suggestions for improving their custom flash simulator. A draft work statement and confidentiality agreement for a potential funds-in CRADA with **EBARA Solar** (Large, PA) were submitted to NREL's technology transfer and legal offices.

From April through June, the **Measurements and Characterization Branch** evaluated 4480 components, devices, and PV materials for 26 research and industry groups for properties ranging from composition and microstructure to cell and module performance. (Larry Kazmerski, 303/384-6600)

The low-temperature, far-IR FTIR spectra of six polycrystalline silicon samples for **Crystal Systems, Inc.** of Salem, MA, were measured to determine dopant/impurity levels. **NREL's John Webb** also measured the FT-Raman spectra of three amorphous/partially microcrystalline silicon films provided by **Solarex Corp.,** to estimate crystallinity. (John Webb, 303/384-6703)

NREL's work with **Shubendu Guha** of **United Solar Systems Corp.** of Toledo, OH, to make a high-efficiency, more-stable hot-wire n-i-p solar cell has progressed to the point of optimizing a microcrystalline p+ layer. After three unsuccessful attempts, researchers concluded that more hydrogen dilution of the diborane gas is still required. (Dick Crandall, 303/384-6676)

From April through June, the **PV Cell Performance lab** performed 505 one-sun and concentrator I-V, 277 QE, and 184 dark I-V measurements on PV cells for a variety of groups in support of in-house research, contract deliverables, the Thin-Film Partnerships and PVMaT programs, and the PV industry: **Applied Solar Energy Corp., ASE Americas, AstroPower Corp., Colorado School of Mines, ECD, EPV, FSEC, Golden Photon, IEC, IMEC (Belgium), ISET, Lockheed Martin, MV Systems, Noranda (Canada), Russian Academy of Sciences, Siemens, Solar Cells Inc., University of Neuchatel Switzerland**, **University of Toledo, University of Utah, Udhaya (India),** and **Washington State.** (Keith Emery, 303/384-6632)

Bhushan Sopori worked with **Labsphere** engineers to incorporate procedures for calibrating and analyzing the internal LBIC into PVSCAN5000. Other modifications will greatly improve the system's signal-to-noise ratio. (Bhushan Sopori, 303/384-6683)

John Thornton met with an **Association of American Railroads** contractor investigating PV for controlling air brakes on freight cars. If PV is selected, there may be a substantial market, with more than 1.2 million freight cars in use on U.S. railroads. (John Thornton, 303/384-6469)

John Thornton attended a meeting of **Kansas City Power and Light** in Kansas City, MO, which included **EPRI** and local development officials, to study the possibility of converting the old Union Station to a science museum that would highlight renewables and exhibits on smart buildings and the utility of the future. (John Thornton, 303/384-6469)

Twenty-four representatives for PV manufacturers, utilities, and research and testing labs attended the National Electric Code Article 690 - Solar Photovoltaic Systems, Technical Review Committee meeting at Sandia National Lab, Albuquerque, NM, in March. This committee is being coordinated by **SEIA** under subcontract to **NREL** to provide an industry-wide review and revision of Article 690 to better accommodate evolving PV technology and applications. (Dick DeBlasio, 303/384-6760)

The **Indian Renewable Energy Development Agency** recommended **NREL** work with the **Ramakrishna Mission** in West Bengal, India, to define DOE/NREL's rural electrification initiative. NREL will collaborate with the Mission to write a work statement for a small PV systems procurement. **The Indian Ministry of Non-Conventional Energy Sources** will cost-share 50/50. (Jack Stone, 303/384-6470)

NREL's William Wallace and **Simon Tsuo** will assist the **World Bank** in a technical and economic assessment of renewable energy opportunities in China to be conducted in 1995/1996. (William Wallace, 303/384-6476)

Subcontracts

Subcontracted research with universities and industry, often cost-shared, constitutes an important and effective means of technology transfer in NREL's PV Program. From April through June 1995, we awarded 55 subcontracts (examples listed below) totaling more than $8.5 million. For fiscal year 1995 to date, we made 137 awards totaling nearly $21.2 million. For further information, contact Kathy Summers (303/384-6595).

Springborn Laboratories, Inc.
Module Encapsulant Development
$457,201 (7/95–7/96)

AstroPower, Inc.
Large-Area Silicon Film Panels
$841,320 (6/95–12/95)

University of Florida
CIS Solar Cell Processing
$250,000 (5/95–5/96)

North Carolina State University
High-Efficiency Cascade Solar Cells
$160,000 (1/95–10/95)

Iowa Thin Film Technologies, Inc.
Manufacturing of a-Si on Polymer
$485,268 (7/95–1/96)

International Solar Electric Technology, Inc.
High-Efficiency CIS Modules
$496,421 (4/95–4/96)

University of Delaware
Demand-Side Management Opportunities in PV
$100,000 (6/95–6/96)

Colorado School of Mines
Electrochemical Deposition of CdTe
$216,842 (4/95–4/96)

State University of New York
Solar Resource/Utility Load Matching
$49,974 (6/95–2/96)

American Institute of Architects
PV in Buildings: Design Guide
$68,553 (6/95–12/95)

University of Washington
Dye-Sensitized PV Heterojunctions
$38,900 (6/95–6/96)

University of Utah
Electrical Processes in Thin Films
$183,299 (4/95–4/96)

University of South Florida
University of Delaware
Solar Cells, Inc.
Historically Black Colleges and Universities
Student Internships
$4,200–$8,400 (6/95–9/95)

Publications

Dissemination of research results is an important aspect of technology transfer. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings. 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 Leslee Pohle (303/384-6492).

Dalal, V. (April 1995). Comprehensive Research on the Stability and Electronic Properties of a-Si:H and a-SiGe:H Alloys and Devices: Final Subcontract Report, 10 March 1991 – 30 August 1994. 108 pp., NREL/TP-411-7695. Work performed by Iowa State University, Ames, IA. NTIS No. DE95004088.

Hall, R.B., Rand, J.A., and Cotter, J.E. (April 1995). Development of Large-Area Monolithically Integrated Silicon-Film Photovoltaic Modules: Final Subcontract Report, 1 May 1991 – 31 December 1994. 33 pp., NREL/TP-413-7702. Work performed by AstroPower, Inc., Newark, DE. NTIS No. DE95004089.

Zhou, T.X. (June 1995). Fabrication of Stable, Large-Area Thin-Film CdTe Photovoltaic Modules: Final Subcontract Report, 10 May 1991 – 28 February 1995. 32 pp., NREL/TP-413-7991. Work performed by Solar Cells, Inc., Toledo, OH. NTIS No. DE95009222.

Kroposki, B., Mrig, L., Whitaker, C., and Newmiller, J. (May 1995). Development of a Photovoltaic Module Energy Ratings Methodology. NREL/TP-411-8005. NTIS No. DE95009221.

Strand, T., Hansen, R., and Mrig, L. (May 1995). Technical Evaluation of a USSC Integrated/Direct Mount PV Roofing Module System at NREL. NREL/TP-411-8006. NTIS No. DE95009217.

Basol, B., Kapur, V., Halani, A., Leidholm, C., and Minnick, A. (June 1995). Novel Two-Stage Selenization Methods for Fabrication of Thin-Film CIS Cells and Submodules: Final Subcontract Report, 1 March 1993 – 31 March 1995. 28 pp., NREL/TP-413-8008. Work performed by International Solar Electric Technology, Inglewood, CA. NTIS No. DE95009229.

More Power for Crunching

Advances in computing power have helped most groups at NREL. But perhaps the Solid-State Theory Group, whose work is extremely computer-intensive, has benefited the most. These scientists develop theoretical “experiments” that typically involve computer-modeling of various classes of solids and determine properties as diverse as band gaps in semiconductors, crystal structure at surfaces, and long- and short-range order in alloys. This work helps support and guide experimental research in various labs at NREL where, for instance, thin-film devices are being designed.

Computer modeling, which involves the solution of systems of partial differential equations, requires considerable number-crunching capability. To handle these types of calculations, the group has purchased four IBM RS-6000 work stations. Even with the improved computational speed, due in part to the technology of reduced instruction set computing, individual modeling runs may take up to two weeks to complete.

To help visualize the resulting calculations, one work station can generate 3-dimensional ball-and-stick plots. For example, a map of constant electron density can be plotted above the 3-D model of a corresponding gallium arsenide surface. The map, colored according to the height above the surface, can then be compared with data obtained with a scanning tunneling microscope.

Parallel processing is another way to handle large problems without resorting to Cray supercomputers outside NREL. The trick is to split up a problem so that portions can be solved simultaneously on individual machines that are linked—for instance, by clustering work stations using a fast network. The main bottleneck is the communication time involved in swapping information from one machine to another. But linking a whole room of work stations together, even at $50K each, is considerably less expensive than purchasing a $20 million supercomputer. One project proposed by this group that will use parallel computing is to extend first-principles methods for electronic structure to large semiconducting systems.

For further information, contact Alex Zunger (303/384-6672) or Sverre Froyen (303/384-6612).

The purpose of this quarterly report is to encourage cooperative research and development by providing the U.S. PV industry with information on the activities and capabilities of the laboratories and researchers at NREL.

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NREL Report No. TP-410-7708. NREL is a national laboratory operated for the U.S. Department of Energy under Contract No. DE-AC36-83CH10093.

News at Press Time...

Golden, CO ... NREL organized several successful meetings aimed at assessing progress and research issues and transferring research results. The **13th NREL Photovoltaics Program Review Meeting** (May 16–19) was attended by more than 300 delegates, including 11 from foreign countries. More than 30 people attended the **3rd NREL PV Standards and Codes Forum** (June 26–28) and the **PV Radiometric Measurements Workshop** (July 24–25). The **2nd NREL Conference on the Thermophotovoltaic Generation of Electricity** (July 17–19) attracted almost 100 participants. Upcoming meetings (see PV Calendar) on point defects in crystalline silicon and PV performance and reliability are expected to draw industry and university specialists in the field, in addition to strong participation by NREL researchers.

Golden, CO ... In a news release dated July 11, 1995, NREL announced that it expects to award about 10 subcontracts this summer, totaling about $40 million, in the **Phase 4A** portion of the **Photovoltaic Manufacturing Technology (PVMaT)** program. The total amount includes about 50% cost sharing by the industrial partners. NREL is negotiating with **Ascension Technology, Inc.** (Billerica, MA), **AstroPower, Inc.** (Newark, DE), **Evergreen Solar, Inc.** (Somerville, MA), **Iowa Thin Film Technologies, Inc.** (Ames, IA), **Omnion Power Engineering Corp.** (East Troy, WI), **Skyline Engineering** (Temple, NH), **Solar Design Associates, Inc.** (Harvard, MA), **Solar Electric Specialties Co.** (Willits, CA), **Trace Engineering** (Arlington, WA), and **Utility Power Group** (Chatsworth, CA). For more information, contact Mike Coe (303/275-4085).

New Equipment, from page 3

to create a map that highlights elemental locations and concentrations throughout an area of the sample.

The Auger electron spectroscope is also a state-of-the-art machine with many similarities to the XPS. Rather than an X-ray source, though, electrons are generated that bombard the sample, and electrons are measured by the analyzer. The spot size of 300–500 angstroms is much smaller than older AES equipment.

This resolution should allow grain-by-grain analysis of thin-film material, as well as new capabilities for detailed mapping.

Convenience is an added feature as the collected data can be put on different computer platforms. Collected originally on an HP Apollo, the information can be moved to a Macintosh or PC via the Internet. Using a Mac in his office, Niles can analyze data using state-of-the-art data reduction techniques such as Voigt fitting of high-energy resolution core line emission, target factor analysis, and contour mapping.

For further information, contact Sally Asher (303/384-6450) or David Niles (303/384-6624).

University Corner

We selected 16 undergraduate students from seven Historically Black Colleges and Universities (HBCUs) to participate in NREL's **HBCU Photovoltaic Research Associates Program.** The students will conduct research and take courses toward a potential career in photovoltaics. The participating HBCUs are: **Central State University** (Wilberforce, OH), **Clark Atlanta University** (Atlanta, GA), **Hampton University** (Hampton, VA), **Mississippi Valley State University** (Itta Bena, MS), **Southern University** (Baton Rouge, LA), **Texas Southern University** (Houston, TX), and **Wilberforce University** (Wilberforce, OH). Six of the students are participating this summer in an internship program to gain hands-on experience in PV. Three are working with researchers at NREL, and the others are at the **University of Delaware,** the **University of South Florida,** and **Solar Cells, Inc.**

The **Thin-Film PV Partnership Program** solicitation resulted in 4 new awards to universities (R&D partners) in cadmium telluride (CdTe) and copper indium diselenide (CIS) research. The subcontractors and areas of research are: **Colorado School of Mines** (electrodeposition of CdTe solar cells), **University of Florida at Gainesville** (effects of S/Ga alloying in CIS solar cells), **University of South Florida** (CdTe and CIS solar cells), and **University of Toledo** (laser scribing of CIS and CdTe). These new R&D partners in the program joined other R&D partner universities (the **Institute of Energy Conversion at the University of Delaware** and **Colorado State University**), as well as NREL in-house researchers, to form several "research teams" with industry technology partners. The teams address key technological issues in CdTe and CIS—as well as in environment, safety, and health—aimed at accelerating the progress in thin-film PV. The teams are modeled after the successful research teams in amorphous silicon.

Professor Teh Yu Tan of **Duke University,** principal investigator on an NREL subcontract on defect studies in crystalline silicon, received the Alexander von Humboldt U.S. Senior Scientist Award. This is the highest award granted to U.S. scientists by Germany, and it enables the recipient to spend 6–12 months in Germany to conduct research with a host institute of the awardee's choice. Professor Tan is spending the summer at the **Max Planck Institute of Microstructure Physics** in Halle, Germany, to work with its director, **Professor U. Goesele,** on defects in semiconductors.

Thirty-eight college and university teams started **Sunrayce 95,** making it the largest North American solar-powered car race ever held. The race began in Indianapolis, IN, on June 20, proceeded across the Great Plains, and ended in Golden, CO, on June 29. The U.S. Department of Energy and General Motors Corporation led the list of sponsors for this educational event. By the time the solar cars crossed into Colorado, the **Massachusetts Institute of Technology** (MIT) and the **University of Minnesota** were at the lead. MIT maintained a mere 19-minute lead over Minnesota as the race approached the National Renewable Energy Laboratory, and MIT's "Manta" went on to win Sunrayce 95 with a total elapsed time of 33 hours and 11 minutes over the 1150-mile course.

PV Calendar

August 13–16, 1995. Workshop on the Role of Point Defects in Silicon Device Processing. Sponsor: NREL. Copper Mountain, CO.*

September 7–8, 1995. PV Performance and Reliability Workshop. Sponsor: NREL. Lakewood, CO.*

September 9–16, 1995. International Solar Energy Society World Congress. Sponsor: ISES. Harare, Zimbabwe.

September 13–15, 1995. Renewable Energy Technologies Symposium and International Exposition. Sponsor: NREL. Golden, CO.*

September 17–20, 1995. International Energy Agency Photovoltaic Power Systems Conference. Sponsor: IEA. Sun Valley, ID.

September 18–20, 1995. PV CON '95—A Conference on Photovoltaic Technology. Sponsor: Solid State Physics and Materials Science Specialist Group of the South African Institute of Physics. Kruger National Park, South Africa.

October 8–13, 1995. 3rd International Symposium on Quantum Confinement: Quantum Wires and Dots. Sponsor: The Electrochemical Society, Inc. Chicago, IL.

October 23–27, 1995. 13th European Photovoltaic Solar Energy Conference and Exhibition. Sponsor: European Commission; Ademe, Agence de l'Environnement et de la Maîtrise de l'Energie, France. Nice, France. WIP, Sylvensteinstr. 2, D-81369 München, Germany, phone +49-89-720 1232; fax +49-89-720 1291.

May 12–17, 1996. 25th IEEE Photovoltaic Specialists Conference. Sponsor: IEEE, NREL/Washington, D.C. Office. Washington, D.C., Eldon Boes, 202/651-7525.

June 15–21, 1996. World Renewable Energy Congress IV. Sponsor: NREL. Denver, CO.*

[* Contact NREL Conference Coordinator, 303/275-4358].

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