NREL PV

Working With Industry

Second Quarter, 1998

Technologies in Transition

Today, three materials are considered front runners for thin-film technologies—amorphous silicon, cadmium telluride, and materials based on copper indium diselenide—and hence, as top candidates for enabling photovoltaics to become competitive for large energy markets.

The technologies founded on these materials have come a long way in the last couple of decades. Amorphous silicon has moved from a curiosity in the mid-1970s to niche consumer markets in the 1980s to larger specialty markets in the 1990s. But to secure a strong foothold in these new markets, modules still have to become more efficient and less expensive, and light-induced instability has to be minimized.

Cadmium telluride and copper indium diselenide are in a different phase of transition. Companies have made and validated prototype modules. Now they face the daunting task of going commercial and figuring out how to go from producing square feet per year to producing square miles per year.

Solving these critical, near-term issues could usher the industry into a sustained era of profits and healthy growth. This could also usher in an era of robust economies and a healthy environment for citizens of the United States and the world.

But for the greater health of the industry and the technology, other issues must be addressed. One is the mid-term question of how to build the scientific and technical base that will provide the foundation for continued technological progress. And beyond this looms the long-term concern of how to develop the technologies to where they can reach the competitive goals.

This and the next edition of *NREL PV Working With Industry* present the Thin Film PV Partnership's strategy for accomplishing this mission. In a few words, that strategy is "national research teams" for each technology and for the environment, safety, and health questions that accompany them. Some of the best and the brightest researchers from industry, universities, and government have joined NREL on these teams, with eyes squarely focused on the task at hand.

Features

Departments

A "Thin" Edge for U.S. Photovoltaics

An Editorial by Tom Surek

Tom Surek is the Technology Manager for NREL's PV Program. A participant in the historic "Cherry Hills" meeting on photovoltaics 25 years ago, he has been involved with NREL PV activities for more than 20 years.

Every trip back to Europe, especially to my birthplace in Budapest, Hungary, is accompanied by a fair dose of nostalgia. And memories of war and conflict. There was a kind of war raging in Europe again this July. The United States lost. So did Japan. Then England and Germany lost. Then Brazil. France came up the big winner. That was the World Cup of Soccer, of course.

Another kind of war took place at the magnificent, historical Hofburg Palace Congress Center in Vienna, Austria in July. The Second World War of Photovoltaics—rather, the Second World Conference and Exhibition on Photovoltaic Solar Energy Conversion. Photovoltaics was the winner this time. There were no losers, but there was plenty of competition.

Maybe it's just part of my job to keep an eye on other national programs, but my focus kept returning to the intense international competition in this very global technology and marketplace. Throughout the conference, I kept measuring how the United States was faring in the various technologies—from research to manufacturing to the markets. The good news is that we are doing much better than we did on the soccer field.

The U.S. PV industry and research community were well represented at this meeting of nearly 2000 participants from more than 60 countries, more than 1000 technical papers, and some 140 exhibits. I was overwhelmed by the magnitude of the meeting and the technical details. But certain trends were evident, at least from my perspective. The U.S. leadership in the markets, mostly served by crystalline silicon technologies at this time, is under challenge from Europe and Asia (mostly Japan). Major planned expansions, fueled by market subsidies and manufacturing incentives overseas, will likely cut into the edge we now enjoy in these technologies. Significant increases in PV research budgets in Europe and Japan are also having an impact on the extent of fundamental research and innovation overseas—an area that was a stronghold of the U.S. programs until recent years.

There is one area where U.S. technological leadership was still clearly evident—thin-film photovoltaics based on amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS). These technologies are the result of more than 20 years of support from the U.S. Department of Energy National Photovoltaics Program and the private sector. Large-scale manufacturing of a-Si is under way in the United States, and CdTe manufacturing is getting started here, too. First-ever commercial products of CIS were introduced in Vienna by a U.S. company. Of course, as the global nature of the PV business dictates, these same U.S.-developed technologies are the basis of new manufacturing facilities overseas, including the recent Dunasolar venture in Budapest, which I had the opportunity to visit during this trip.

I am convinced that the success and leadership we enjoy in these thin-film technologies can be attributed, in no small way, to the "national research teams" described in this issue. This model of government/industry/university partnership is now being emulated by others overseas. But, for now at least, my scorecard gives the "thin" edge to U.S. photovoltaics.

Contact Tom Surek at 303-384-6471.

PV Web Sites

NREL Photovoltaics ....*http://www.nrel.gov/pv*
What's PV? • Info • PV News • Partnerships • Research Projects • Facilities

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

National Center for Photovoltaics ....*http://www.nrel.gov/ncpv*
DOE PV • NREL PV • Sandia PV • WCPEC Papers

The Center for Basic Sciences ....*http://www.nrel.gov/basic_sciences*
Capabilities • Optoelectronics • Biological Sciences

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

Renewable Resource Data Center ....*http://rredc.nrel.gov*
General Information • Information by Resource (Biomass/Solar/Wind)

Million Solar Roofs..........................*http://www.MillionSolarRoofs.org*
Initiative Goals • Scope • Solar Technologies

NREL International Programs ....*http://www.nrel.gov/business/international/intl_graphics.html*
Applications • Countries • Supporting Activities

The National ES&H Team: Safety First

Paul Moskowitz and Ken Zweibel are in complete agreement about this: The thin-film PV industry has a stellar record of dealing proactively with environment, safety, and health issues. “Industry members are tackling these issues now. They're not hanging back and waiting for full commercialization before confronting them,” says Moskowitz.

Moskowitz of Brookhaven National Laboratory (BNL) and NREL's Zweibel co-chair the National Thin Film ES&H Team, a confederation of some 50 individuals from industry and government, and, periodically, from utilities and universities. The work of the team centers around in-plant safety, toxicology, new product acceptability, and recycling. According to Moskowitz, “The two most important issues are that manufacturing is performed in a way that is safe for those involved, and that we get the product right at the point of manufacture so it doesn't cause problems downstream.”

Zweibel puts it in perspective: “There's really very little that's out of the ordinary in terms of manufacturing or product use, but we're addressing the key issues and trying to lay the groundwork for public understanding.”

Moskowitz sees the team approach as invaluable. “We gain from sharing information, experience, and solutions in a way that a single individual or organization could never match. This way, we enhance the safety of not only the individual worker or factory, but of the entire industry. A lot of people are willing to work with us on this.” He's heartened that this willingness extends to industry partners sharing ES&H information that cuts across the boundary of intellectual property.

The thin-film partners behave in a way that affirms a powerful belief that their products will be a major force in the energy marketplace. Recycling of thin-film modules and their components will be a large-scale need in 20 years, yet it's a hot topic right now. After all, building the recycling infrastructure for a major industry will probably take that long. Recycling is being investigated both for reasons of environmental stewardship and to recover materials that are valuable. The national ES&H team was instrumental in two companies—Solar Cells, Inc., (SCI) of Toledo, Ohio, and Drinkard Metalox of Charlotte, North Carolina—being awarded Small Business Innovative Research grants to investigate their promising approaches to stripping PV films off glass substrates. The work is going so well that both companies have been awarded Phase II grants to continue their process development and commercialization.

ES&H team members stay in touch via their own e-mail list, which is used to share information, solve problems, and discuss issues. But their best method of communication is meeting face-to-face on particular issues in a targeted 2–3-day workshop, such as the one held in July of this year in Keystone, Colorado. The workshop was attended by 25 persons from the federal sector (NREL, BNL, Sandia National Laboratories), industry (SCI, BP Solar, Siemens Solar, ASE Americas), and universities (Princeton, Chalmers).

Three of the workshop papers were especially illuminating. The first covered recycling lessons learned by the Rechargeable Battery Recycling Corporation, which was established by a consortium of nickel cadmium battery manufacturers. The second discussed the technologies developed by SCI to deposit cadmium telluride (CdTe) thin films and recycle off-spec CdTe modules. The third paper included estimates of the life-cycle energy and CO_2 costs associated with PV modules used in both central-station and building-integrated applications. These estimates demonstrate that the energy payback time for advanced thin films used for building roofing tiles or siding can approach zero years, because they would be used to replace energy-intensive building components.

Because of all this ES&H teamwork, the thin-film industry stands well-prepared to confront material and processing issues. “And it's been done at the beginning, rather than at the end, of the pipeline,” says Moskowitz.

For more information, contact: Paul Moskowitz at 516-344-2017 or Ken Zweibel at 303-384-6441.

Warren Gretz, NREL/PIX06345

Paul Moskowitz and Ken Zweibel inspect gas-monitoring control panels at NREL's Solar Energy Research Facility. Moskowitz is Division Head of BNL's Environmental and Waste Technology Center; his PV credentials date back to 1978 when he was principal investigator for the lab's PV Program. Zweibel, the Project Leader for the Thin Film PV Partnership, has authored two books on PV and has been involved with thin films at NREL since 1979.

Getting Fat by Thinking Thin—A

"Fat" is not a word you'd normally find in the photovoltaic lexicon. Times have been lean as members of the PV community have labored toward the future's promise.

Today, that promise seems close enough to taste. For the last 4 years, the world PV market has grown by an average of more than 20% per year. Industry is building new manufacturing capacity to meet demand and has finally grossed more than one billion dollars of business in a year.

But this must be kept in perspective. Although PV has been brought to the consciousness of many and the industry has bootstrapped itself from consumer products to rooftop arrays, the industry is not yet generally profitable. And the technology seems to have progressed only from begging morsels to gnawing on bone.

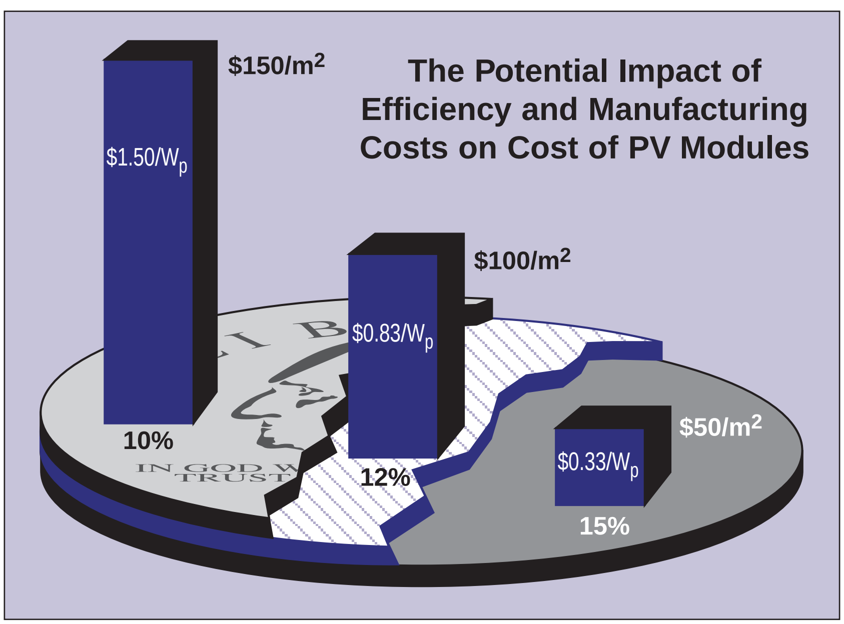
The question remains: "How do we get to the meat? How does PV get to be a major player in large energy markets and become one of the world's most important industries?"

The Thin-Film Mantra

According to Ken Zweibel, Project Leader of the Thin Film PV Partnership, "People in industry and the DOE PV Program have long recognized the long-term strategy that must be followed."

Simply put, PV must become competitive with conventional sources of electricity generation. For this to happen, modules must have a stable conversion efficiency of about 15%, must last for 30 years, and be manufacturable for about $50/m2. Effectively, this means that PV module costs must be dropped five- to tenfold to under $0.40 per peak watt.

The traditional mantra on how to get to these goals is this: thin films. Thin-film devices use very little material. They are open to highly automated manufacturing processes, for increased throughput and yield, and for labor savings. And thin-film processes are tailor-made for large-scale manufacturing, for cost reductions through economies of scale.



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To make PV competitive with conventional sources of electricity generation, the national goals for thin films call for 15%-efficient modules manufactured at a cost of $50 per square meter, which would yield power for about $0.33 per peak watt.

Two Decades of Support and Progress

"Looking to thin films to get us to our long-term goals is nothing new," Zweibel reminds us. "Working with U.S. industry and universities, DOE has been pursuing these pathways almost since the inception of the terrestrial PV Program."

That's two decades of support for thin films. Twenty years of meeting with failures and successes, forming partnerships and coalitions, and leading the world in thin-film technologies. Twenty years of winnowing out some technologies and supporting the more promising ones that industry was willing to develop: technologies based on copper indium diselenide (CIS), cadmium telluride (CdTe), and amorphous silicon (a-Si).

National Teams

For these chosen technologies, the question quickly becomes how to balance the immediate, profit-driven, proprietary interests of industry with the intermediate concern of building the technological base and the long-term issue of reaching the competitive goals. Fortunately, in the early 1990s, people such as Lloyd Herwig of DOE and Werner Luft of NREL pushed for an approach that could surmount the conundrum—national teams.

The idea is this: Each technology would form a national research team comprising the nation's best research and engineering talent drawn from industry, universities, and national labs. Each team would meet periodically and set up forums for exchanging information and for dynamic discussion of issues.

With national teams, all sectors would benefit. Industry would be able to influence research toward solutions of the pragmatic problems it faced. Academia could have its basic and theoretical expertise tapped for applied R&D. And national labs could apply their materials growth and characterization expertise to "real-life situations" while still performing basic R&D for long-term progress.

Recipe for National Teams

And the DOE/NREL Thin Film PV Partnership could offer an arena in which the efforts of the national teams may thrive, provide general guidance toward national goals, and furnish funds for research. The Thin Film PV Partnership is an $11 million per year subcontract program with Technology and R&D Partners. R&D Partners are primarily universities, national labs, and centers of excellence. Members of industry are Technology Partners who share the cost of the subcontracts. To date, the Technology Partners have invested more than $20 million on three phases of thin-film R&D, while NREL has contributed about $30 million. In addition to the Thin Film Partnership, in-house thin-film research and measurements at NREL support the teams at a level of about $6 million annually.

Since early 1994, the Thin Film PV Partnership has spurred the formation of national teams for each of the three thin-film technologies. The national team for a-Si was the first to be formed, in a joint effort with the Electric Power Research Institute (see page 6), and teams for CIS and CdTe followed closely behind.

The teams are alike in that they investigate cell and module conversion efficiencies, manufacturing cost, and material and device reliability. But they are also different, being driven by the specific concerns of the individual technology. This difference has translated into structural differences for the teams. The issues facing a-Si, for example, revolve around device efficiency and light-induced instability. So the team has formed subteams based on the perceived long-term solution to these issues, namely, a triple-junction approach.

Prototype CIS-based devices exhibit high cell efficiency and high module stability. But the technology is making a transition to first-time manufacturing. So the subteams are nucleated around how to solve each company's manufacturing problem, most notably to investigate ways in which to best deposit large areas of CIS material.

Prototype CdTe devices also exhibit high cell and module efficiencies. There are three companies gearing up for pilot production, with one of these (Solar Cells, Inc.) proffering an especially promising deposition concept. Nonetheless, there are issues involving contacting and stability and whether production modules can reach high efficiencies. Consequently, CdTe subteams have formed around these issues, with the subteams being actively involved with the companies. (Articles on the CIS and CdTe teams will appear in the next issue of *NREL PV Working With Industry*.)

Beyond Cost

Issues confronting PV go beyond cost and efficiency. To be successful, the technology must also be acceptable in other ways. Photovoltaics, for example, has been touted as an environmental champion, especially in terms of energy production. But to be a true champion, the technology must also be environmentally beneficial in other ways, including material usage, manufacturing processes, and system disposal. To address these issues, therefore, the Thin Film PV Partnership formed, in 1995, a fourth national team—the ES&H team (see page 3).

Beyond Teams

The issues and concepts being explored by the four teams are not the only ones worth pursuing. They are just the ones that have reached the maturity that demands the concerted effort represented by national teams.

The PV Program, however, has a history of exploring a wide range of promising concepts. Today is no different—the Thin Film PV Partnership is examining other ideas that have the potential of reaching the stature that one day may demand a national team effort. This includes polycrystalline silicon thin films, an approach that espouses the use of thin layers of silicon on a low-cost substrate.

This technology has seen promising results with depositions on ceramics, glass, and silicon templates, and with the production of the first monolithic minimodule (by AstroPower). But before the technology enters the mainstream, researchers must improve material properties, increase deposition rates, design efficient devices, and incorporate effective light-trapping techniques.

A Thin, Tight Race

With national teams, each of the technologies has a good chance to successfully address the technical issues, surmount the challenges, and reach the long-term goals. Success in the endeavors of any of the technologies will lead to huge electricity markets. And soon, the questions being asked of the technologies may change from “Can they get there?” to “How soon will they get there?” and “Which will get there first?”

The only good bet at this point is that whatever technology gets there first, it won't be alone for long.

For more information, contact Ken Zweibel at 303-384-6441.

The a-Si Team: Making a-Si the First S

Amorphous silicon was the early darling of thin-film technologies—the initial hope for dropping module costs to where PV could compete with conventional electricity generation. But technological progress sputtered as a-Si got entwined in the twin nemeses of light-induced (Staebler-Wronski) instability and low efficiency. And, for some, that's where the technology was destined to stay, never to cross the threshold that would lead to significant energy markets.

So it may be with some wonder when you hear someone like Terry Peterson, Manager of Solar Power for the Electric Power Research Institute (EPRI), claim that “amorphous silicon will beat the other thin-film technologies to the long-term goals for commercial power modules.”

But can a-Si get there first? After all, the DOE Program goals call for stable, 15%-efficient modules that can be manufactured for $\$50/m^2$. And if you look at the leading candidates, you'll notice that CIS and CdTe have cell efficiencies in the 16% to 18% range and modules whose long-term stability seems quite promising—levels that a-Si has yet to approach.

But a-Si has something the others don't—more than 10 years of manufacturing knowledge and momentum. Devices can be manufactured in a number of ways, in a number of configurations, with different types of substrates. Structures can be designed and engineered to alleviate some of the inherent material difficulties. And the material is becoming better understood all the time.

A Head-Start Program

Besides, a-Si has a head start in teaming. In 1992, a full 2 years prior to the formation of national teams for other thin-film technologies, EPRI initiated a national a-Si research team. Among those participating in the process that defined the team were Werner Luft, then of NREL, and David Staebler, who along with Chris Wronski discovered a-Si’s instability when exposed to light. While monitoring the success of EPRI's program, Luft saw to it that NREL formed its own national a-Si team. And in 1994, the two teams merged to become the Amorphous Silicon National Research Team of the Thin Film PV Partnership.

According to team co-chair, Bolko von Roedern, “Before, we had separate unconnected efforts. And universities were left out on their theoretical limb, with their work not being woven into progress of applied technology. Now, we have a coherent, integrated approach that marries the strengths of industry with academia. And we have a methodical way of recording what works and what does not.”

Moreover, the team, which comprises more than 40 top researchers from industry, universities, and NREL, has devised a technological approach and a team structure that it feels should enable a-Si to surmount its obstacles and reach the national goals.

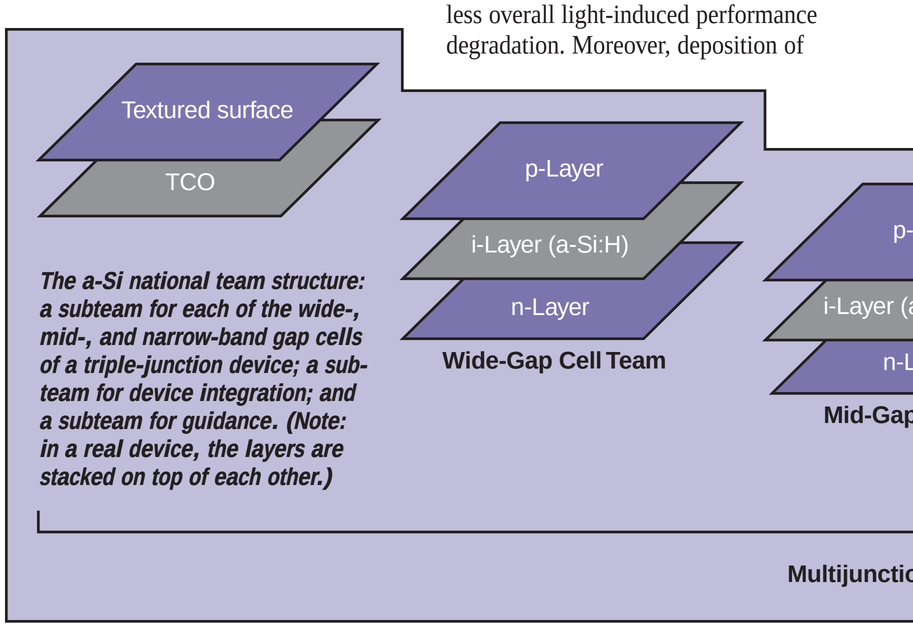
Teaming with Confidence

The technological approach is based upon a triple-junction/triple-cell device in which each cell uses a p-i-n structure with an extremely thin intrinsic layer. Triple-junction devices capture a larger portion of the solar spectrum and more efficiently convert it to electricity. And thin layers decrease the magnitude of light-induced instability. This is because photogenerated charge carriers in thin cells have less distance to travel to the junction, thus having a higher probability of being separated and collected. Incomplete collection results in recombination losses that are commonly believed to be controlled by the properties of a “dangling bond defect pool” in the intrinsic layer of the device.

The team structure mirrors the technological approach. The national team is divided into five subteams: three to optimize each of the individual cells, one to integrate the results of the three cell teams, and one to provide guidance.

The *wide-gap team* is investigating a cell with a provisional band gap of about 1.9-eV for absorbing the blue/green portion of the solar spectrum.The team's goals are to demonstrate a cell that has a stabilized output of 68 W/m^2, with a short-circuit current density of 82 A/m^2, a fill factor of 0.75, and an open-circuit voltage (V_{oc}) of 1.1 V.

This team has come close to some of its targets, achieving cells that exhibit more than 50 W/m^2, with a V_{oc} greater than 1.05 V. But the team needs to increase the V_{oc}, improve the i/p interface, and further optimize hydrogen dilution. Hydrogen dilution changes the bulk material properties and the characteristics of the Staebler-Wronski effect, causing the device to exhibit less overall light-induced performance degradation. Moreover, deposition of



The a-Si national team structure: a subteam for each of the wide-, mid-, and narrow-band gap cells of a triple-junction device; a subteam for device integration; and a subteam for guidance. (Note: in a real device, the layers are stacked on top of each other.)

uccessful Thin Film

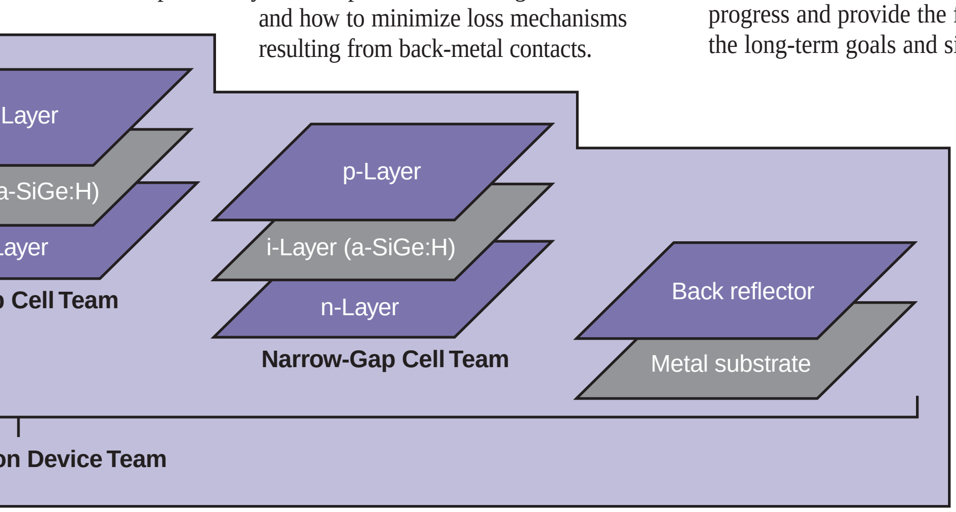
the layers near the i/p interface with hydrogen dilution has resulted in devices with higher V_{oc} values that also degrade less.

The *mid-gap team* explores concepts with which to produce an a-SiGe:H cell that converts the mid-range of the spectrum with a stabilized power output approaching 50 W/m^2. But this team's primary aim is to study why some forms of a-Si are more stable than others. To do this, the team not only investigates hydrogen dilution schemes using different growth methods, but it also studies deuterium dilution schemes in which a-Si is deposited using different mixtures of SiD_4/D_2. The research by this team suggests that different mixtures and different methods of deposition change the microstructure of the deposited material, which alters the stability.

The team also performs theoretical studies to get an insight into degradation mechanisms and investigates alternative deposition approaches. An example of significant progress in degradation studies is the recent publication of an improved model of the Staebler-Wronski effect by NREL's Howard Branz in the *Solid State Communications* journal. One of the new deposition approaches being studied is hot-wire deposition, which holds promise for producing more stable a-Si devices and may also offer a deposition rate that is an order of magnitude greater than the technique that is the current industry standard—glow discharge.

The goal of the *narrow-gap team* is to produce a stable cell that converts the red portion of the spectrum with a power output of 40 W/m^2. Team members have already reached their goal—but they got there primarily because of high short-circuit current. So, the focus of the group is to increase the fill factor and the open-circuit voltage to acceptable levels. The team is attempting to do this by synthesizing better a-SiGe:H alloys using a variety of deposition techniques.

The *multijunction device team* integrates the results from the other teams in an attempt to produce a 15%-efficient device. Integration is a multifaceted task that requires modeling to determine how to best connect the individual cells while minimizing losses between interfaces; how to employ optical coupling, back reflectors, texturing, and internal reflection to increase the probability of absorption and carrier generation; and how to minimize loss mechanisms resulting from back-metal contacts.



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The *functional guidance team* sees that the other teams balance short- and long-term needs. This team also encourages the other teams to document what does and doesn't work and to bring outstanding issues to closure. For example, the guidance team has encouraged NREL to demonstrate the capabilities of the hot-wire deposition technique and to prove that it is worth pursuing. This has recently been accomplished through demonstration of near-record performance for cells deposited at high rates.

An Award Winner

A flexible structure allows the national team to pursue long-term visions while also working on more pragmatic short-term goals that fit industry's needs. For example, through cost-shared efforts, the partnership companies (United Solar Systems Corp., Energy Conversion Devices, and Solarex) are also working on their proprietary approaches, which are enhanced by the research and progress of the national team.

One of these—a triple-junction approach led by United Solar—has resulted in stabilized cell efficiencies greater than 12%, commercial modules whose stabilized efficiencies approach 8%, and a 50% reduction in efficiency losses caused by light-soaking. This won United Solar and the national team a joint, 1998 R&D 100 Award for technological innovation. It also won United Solar a prestigious *Discover* award for its PV roof-shingle product.

Subhendu Guha of United Solar thinks teaming has paid off. “The national team,” he says, “is made up of a very talented pool of people. This has created a charged intellectual atmosphere in which ideas are discussed and innovation thrives.”

Becoming Energy Significant

The United Solar approach is moving the a-Si technology toward commercial module efficiencies of 10% using similar low-cost materials and processes. This will be a big step forward in igniting substantial growth in rooftop and stand-alone markets.

Meanwhile, the national team will assist in this near-term progress and provide the foundation for progress toward the long-term goals and significant energy markets.

For additional information, contact team co-chairs: Bolko von Roedern at 303-384-6480 or Richard Crandall at 303-384-6676.

For the EPRI participation, contact Terry Peterson at 650-855-2594

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.

The **NREL Measurements and Characterization Team** visited the **Solarex** TF1 facility in Virginia in May. This all-day session enhanced and accelerated collaborations between the two organizations, especially in regard to evaluating Solarex material and investigating the measurements and test needs of the Solarex manufacturing facility. Solarex staff gave the NREL team a detailed overview of their manufacturing process, including a meticulous inspection of the manufacturing line. This automated line is designed to have a 10 MW/yr production capacity. Discussions of measurement requirements led to identifying eight priority projects, some of which require special test-sample preparation by Solarex. In addition, several potential in-line measurement techniques were identified as candidates for Solarex to use to monitor material quality during the manufacturing process. The technical information shared by Solarex and NREL participants is expected to have an impact on evaluating the amorphous silicon product and to provide some direction for Solarex processing. Contact: **L.L. Kazmerski, 303-384-6600**

Working together, **Solar Cells, Inc.**, (SCI) and NREL's in-house **Cadmium Telluride Team** produced a thin-film CdTe solar cell with an NREL-verified total-area conversion efficiency of 14.1%. Not only is this the first time SCI has reached this level, but several cells were produced with efficiencies in the range of 13.3% to 14.1%. The cell structure is MgF_2/glass/SnO_2/CdS/CdTe/metal contact. A conductive/resistive bilayer SnO_2 top-contact and a MgF_2 antireflective coating were deposited at NREL by **X. Li** and **J. Keane (CIS Team)**, respectively. The glass used for the device fabrication was water-white glass supplied by **AFG Industries**, which has less absorption loss compared to soda-lime glass. The most significant improvement was in the J_{sc} of 25.5 mA/cm^2. Because a bilayer SnO_2 was used in the device fabrication, a much thinner CdS layer was used successfully in the cell, resulting in an increased short-wavelength response. This was verified by NREL's quantum-efficiency measurement, which showed that most of the current increase came in the blue response, resulting in higher solar-cell efficiency. Contacts: **Harin Ullal, 303-384-6486; Pete Sheldon, 303-384-6533**

Fourier transform infrared (FTIR) transmission spectroscopy is a powerful tool for identifiying impurities in silicon, which can be introduced by the silicon processing environment or growth hardware. However, the optically thin polycrystalline silicon now being produced by a number of PV manufacturers poses new challenges and opportunities for process control. **NREL** has developed FTIR spectroscopic software to measure the absorbance coefficients for silicon oxide, silicon nitride, and silicon carbide precipitates, together with oxygen, nitrogen, and carbon concentrations via the literature procedures, to give a more complete picture of the material quality. The NREL FTIR software was used recently to identify a precipitate in thin silicon ribbon material from **Evergreen Solar** (enabling identification of the contamination source) and to verify that improved processing techniques had eliminated the problem. The rapid, precise analysis was key to a significant process improvement. Contact: **John Webb, 303-384-6703**

In April, the **NREL Amorphous Silicon Team**, in collaboration with **United Solar Systems Corp.** (USSC), set a new standard for high-deposition-rate a-Si PV cells. Rapid deposition increases PV module production rates and reduces the capital cost per delivered watt. NREL deposited the cell's active layer in 2 minutes, with an initial solar conversion efficiency of 9.8%. Deposition using the standard industrial technique takes about 35 minutes, and no other group has reached this initial efficiency using deposition rates as high as those achieved in this process. Initial light-soaking tests have begun, and the highest efficiency to date, measured after 1000 hours of illumination, is 7.7%. Using a stainless steel substrate roughened and coated for high reflectivity by USSC, the team deposited an n-type layer by conventional processing followed by hot-wire deposition of a 2100-Å i-layer. USSC finished the cell with a p-type microcrystalline layer and a transparent conductive top contact. This cooperative effort also involves an NREL subcontractor at the University of Colorado and is facilitated by the **Thin Film PV Partnership's National Amorphous Silicon R&D Team**. Contact: **Harv Mahan, 303-384-6697**

Also in April, a **Midway** 254-W_p concentrator tracking system was installed at **NREL's Outdoor Test Facility** (OTF). The system consists of two 127-W_p modules with 335X concentration mounted on a Wattsun two-axis tracker, two Trojan T-105 batteries, and a charge controller. The stand-alone system runs a 35-W metal halide lamp several hours each night. This system is one of the first applications of concentrators in small, stand-alone, power systems. The OTF monitoring should provide insights into the performance and reliability of such systems, and be helpful in developing test standards for stand-alone systems and concentrators. Contact: **Peter McNutt, 303-384-6767**

Dick Ahrenkiel and **Steve Johnson** of **NREL** joined forces with **AstroPower's John Cummings** and **James Rand** for an extensive measurement survey of the AstroPower thin-film polycrystalline material. Both radiofrequency photoconductive decay (RFPCD) lifetime measurements and FTIR optical analysis

Continued on page 11

Subcontracted research with universities and industry, often cost-shared, constitutes an important and effective means of technology transfer in NREL's PV Program. From October 1997 through June 1998, we awarded 117 subcontracts (examples listed below) totaling more than $15 million. For further information, contact Ann Hansen (303-384-6492).

Solarex (3/98-3/01)
Research on a-Si Cells and Modules
$2,162,000 (NREL) $2,538,000 (cost share)

United Solar (3/98-3/01)
High-Efficiency Triple-Junction a-Si PV Technology
$2,700,000 (NREL) $2,700,000 (cost share)

AstroPower, Inc. (4/98-6/01)
Silicon-Film™ Solar Cells by a Flexible Manufacturing System
$2,723,731 (NREL) $2,823,583 (cost share)

MV Systems (4/98-4/01)
Hot-Wire Chemical Vapor Deposited a-Si and Microcrystalline Silicon Solar Cells
$1,050,000 (NREL) $47,203 (cost share)

Energy Conversion Devices (3/98-3/01)
Very High Frequency Plasmas for a-Si:H Triple Junctions at High Deposition Rates
$939,000 (NREL) $778,000 (cost share)

Solar Cells, Inc. (4/98-4/01)
Technology Support for High-Throughput Processing of Thin-Film CdTe
$2,706,400 (NREL) $676,600 (cost share)

BP Solar, Inc. (5/98-5/01)
Apollo Thin-Film Process
$1,750,000 (NREL) $1,750,000 (cost share)

University of Toledo (5/98-5/01)
High Efficiency Thin-Film Cadmium Telluride and Amorphous Silicon Based Solar Cells
$925,000 (NREL) $611,835 (cost share)

Pennsylvania State University (5/98-5/01)
Stable a-Si:H Multijunction Solar Cells with Guidance from Real Time Optics
$825,000

Harvard University (5/98-5/01)
Transparent Conductors and Barrier Layers for Thin Film Solar Cells
$540,000

Colorado School of Mines (5/98-5/01)
Process Development and Basic Studies of Electrochemically Deposited CdTe-Based Solar Cells
$1,410,510

University of South Florida (5/98-5/01)
Advanced Processing Technology for CdTe and High-Bandgap CIGS Solar Cells
$977,550 (NREL) $432,960 (cost share)

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

Branz, H.M. "Hydrogen Collision Model of Light-Induced Metastability in Hydrogenated Amorphous Silicon." *Solid State Communications*; vol. 105(6); February 1998; pp 387-391.

Zweibel, K.; Moskowitz, P.; Fthenakis, V. *Thin-Film Cadmium Telluride Photovoltaics: ES&H Issues, Solutions, and Perspectives*. Research report; 1998; 6pp. NREL TP-520-24057.

The following are a sampling of the NREL papers in the Conference Record of the 26th IEEE Photovoltaic Specialists Conference, 29 September–3 October 1997, Anaheim, California. New York: Institute of Electrical and Electronics Engineers; 1997.

Guha, S. et al. *Triple-Junction Amorphous Silicon Alloy PV Manufacturing Plant of 5 MW Annual Capacity*; pp. 607-610. Work performed by United Solar Systems Corp., Troy, MI, and Energy Conversion Devices, Inc., Troy, MI.

Hasoon, F. S. et al. *Morphology of CdS Thin Films Deposited on SnO_2-Coated Glass Substrates*; pp. 543-546.

Hegedus, S. S.; Buchanan, W. A.; Eser, E. *Improving Performance of Superstrate p-i-n a-Si Solar Cells by Optimization of n/TCO/Metal Back Contacts*; pp. 603-606. Work performed by the University of Delaware, Newark, DE.

Rand, J. A. et al. *Large-Area Silicon-Film™ Manufacturing under the PVMaT Program*; pp. 1169-1172. Work performed by AstroPower, Inc., Newark, DE.

Ullal, H. S.; Zweibel, K.; von Roedern, B. G. *Current Status of Polycrystalline Thin-Film PV Technologies*; pp. 301-305.

Webb, J. D. et al. *FTIR, EPMA, Auger, and XPS Analysis of Impurity Precipitates in CdS Films*; pp. 399-402.

Wronski, C. R. et al. *Approach to Self-Consistent Analysis of a-Si:H Material and p-i-n Solar Cell Properties*; pp. 587-590. Work performed by Pennsylvania State University, University Park, PA.

University Corner

When **Next-Generation PV Team** members met at NREL in April, their express goal was selecting a focus for future collaborative work. Researchers from the **University of Florida at Gainesville**, **State University of New York at Buffalo**, and **Washington State University** joined those from NREL, **Sandia National Laboratories**, **Lawrence Berkeley Laboratories**, **Oak Ridge National Laboratories**, and **DOE Basic Energy Sciences** (BES) for spirited discussions on the topic. Ultimately, team members were true to the project title (High Efficiency) and to the team title (Next-Generation PV), by choosing to focus on a new GaInAsN material as a third junction for a very high-efficiency, four-junction solar cell—leading to a 45%-efficient solar cell in the long term. **Satyen Deb** (Director, NREL's Center for Basic Sciences and High-Efficiency Project Coordinator), **George Samara** (Sandia, Coordinator for the DOE Center of Excellence for Synthesis and Processing of Advanced Materials), and **Gerry Smith** (BES Materials Science Division) provided the framework for the meeting. **Eric Jones** (Sandia) and **Bob McConnell** (NREL) were chosen as team coordinators, and team members were identified for activities in materials growth, characterization, device physics, and theory. Contacts: **Satyen Deb, 303-384-6405; Robert McConnell, 303-384-6419**

The *American Physical Society News* selected the collaborative research project between the **NREL Amorphous Silicon Team** and the **Cornell Physics Department** as one of its 1997 "Physics Highlights." This work involves the same NREL hot-wire a-Si:H that has improved stable properties compared to other forms of a-Si:H and also exhibits dramatically reduced vibrational damping. A scientific article on the subject appeared in the July 1997 issue of the *Physical Review Letters*. The damping study, together with earlier nuclear magnetic resonance and X-ray absorption results, suggests increased structural order that may contribute to the improved stability of hot-wire material. This work has led to considerable excitement in the physics and amorphous silicon communities, resulting in four invited papers at scientific conferences (three by **R.S. Crandall** of NREL and one by **X. Liu** of Cornell). Contact: **Richard Crandall, 303-384-6676**

The **University PV Research Equipment** Request for Proposal was designed to fund the acquisition of critical PV research and test equipment at universities participating in the **NREL/DOE PV Program**, to enhance their research capabilities and results. NREL received 21 proposals in response to this RFP sent to 48 universities. Seventeen subcontracts will be awarded in mid-August, for a total of $1.06 million. Contact: **Robert McConnell, 303-384-6419**

Texas Southern University held its third annual Summer Academy on Renewable Energy and Environmental Protection (REEP) for minority high school students. The REEP students visited **NREL** in late July and learned about photovoltaics and other renewable energy technologies. Thanks to **DOE**/ NREL honorarium funds from the **Historically Black Colleges and Universities** (HBCU) Summer Intern program, 13 REEP honors students travelled to Port Elizabeth, South Africa. They were hosted by TSU colleagues at the **Port Elizabeth Technikon**, which is involved in a "Rural School Electrification Program" using PV. The REEP group, assisted by the two HBCU undergraduates in NREL's PV Research Associates program, installed a PV system for a school office building located in a rural area of the Eastern Cape in South Africa. They also assessed the quality of local drinking water with chemical test kits and donated books and magazines to rural schools in need. Contact: **Robert McConnell, 303-384-6419**

News at Press Time

NCPV Technical Papers Close at Hand

Internet visionaries have long referred to its potential highest and best use—sharing and exchanging scientific information. The National Center for Photovoltaics (NCPV) is delivering on that promise, with 75 full-text conference papers now available on its Web site (www.nrel.gov/ncpv/). Each paper contains an e-mail link with the first author, to facilitate information exchanges. The latest Web site addition is 26 papers by NCPV (NREL and Sandia) primary authors from the 2nd World Conference on Photovoltaic Solar Energy Conversion. The meeting was held in Vienna, Austria, on July 6–10, 1998. And, in case you missed them, 49 NCPV papers from the 26th IEEE PV Specialists Conference last October are still on the site. These papers have proven so popular that they will remain on the site indefinitely.

Be sure to visit the NCPV site in the first week of October. There's a new look coming, along with greatly expanded content. Contact: **Susan Moon, 303-384-6631**

News Shows NREL Technology Licensed and Soon Flying in Space

Recent news articles are highlighting NREL's GaInP/GaAs (gallium indium phosphide/gallium arsenide) solar cell technology. A news brief in *Compound Semiconductor* describes TECSTAR's expansion of its space-solar-cell manufacturing capability and notes that the company has signed a licensing agreement with NREL for the GaInP/

Industry Updates, Continued from p. 8

were performed on more than 100 wafers (from raw, as-grown material). The results were correlated with cells that were subsequently made at AstroPower from the same sample set. Also, wafer sets that had undergone phosphorous diffusion/gettering were subjected to the same sequence. The correlation was very good between the gettered wafer lifetime parameters and the final cell performance. The correlation between the lifetime properties of as-grown and gettered wafers, as measured by RFPCD, was modest to poor. This translated into a similar lack of correlation between as-grown wafers and final cell performance. These results indicated that the gettering process modifies the lifetime properties significantly and increases the difficulty of screening as-grown wafers by any characterization technique. Contact: **Dick Ahrenkiel, 303-384-6670**

A new cooperative research and development agreement between **NREL** and **Energy Conversion Devices** (ECD), Troy, MI, was signed on May 20. This 2-year agreement involves ECD and NREL providing support to upgrade module manufacturing at the **Sovlux** plant in Moscow, Russia. This work is designed to allow the production of large-area building-integrated PV roofing material and to explore the feasibility to recover, repurify, and reuse the high-cost unused process gases such as germane and disilane from the effluent stream of the PV module manufacturing line. NREL has budgeted $196,000 for 2 years of this work, which will come entirely from the NIS-IPP (New Independent States, Initiative for the Prevention of Proliferation) program. ECD has budgeted $400,000 from its own resources. The NREL work will be carried out in several divisions of the **National Center for Photovoltaics**. Contact: **Bolko von Roedern, 303-384-6480**

Recently, a group from **NREL** toured the **Global Solar Energy** (GSE) facility in Tucson. This is one of the few technology-based joint ventures between a PV company (**ITN Energy Systems**, Golden, CO) and a major utility (**Tucson Electric Power** or TEP). GSE is funded by the **Thin Film PV Partnership** and the **Photovoltaic Manufacturing Technology** (PVMaT) project. The venture is now transitioning from the laboratory to first commercial production of CIGS modules. Installation is under way on individual pieces of manufacturing equipment. The goal is to begin 1.5-MW production in 1999, with plans to expand to 10 MW in 2001. During the visit, **Neil Holstad** (Chief Financial Officer of GSE, President of **Advanced Energy Technologies**, and a TEP senior manager) expressed TEP's strong interest in low-cost PV for residential systems. GSE's technology is based on making roll-to-roll CIGS modules on polyimide, similar to approaches using amorphous silicon on flexible substrates (e.g., **United Solar** on stainless steel and **Iowa Thin Films** on polyimide). Initial performance goals are in the 8%–10% range, which would be quite similar to United Solar's capabilities. Contact: **Ken Zweibel, 303-384-6441**

GaAs technology. A second article in *Popular Science* describes the NASA Deep Space 1 Probe (scheduled to launch in October 1998) that features a dozen new technologies, one being the PV power system. This solar array uses the GaInP/GaAs cells invented and developed at NREL and produced by TECSTAR, with concentrating lenses engineered by ENTECH. The 2.6-kW array produces 50% more power per area than a conventional array. NASA's use of concentrating solar arrays reflects a growing interest in the advantages of space concentrator systems (high efficiency, radiation resistance, and reduction in expensive solar-cell area). Success of III-V concentrator systems for space applications may pave the way for the success of their terrestrial counterparts. Contact: **Jerry Olson, 303-384-6488**

NREL Competition Going Smoothly

The Department of Energy announced a full and open competition for the NREL contract last October. In developing the final solicitation, DOE considered public comments gathered from recent meetings in Golden, Colorado, and Washington, D.C., on the draft statement of work and draft criteria to be used in contractor selection. The current NREL contract expires on September 30, 1998, but can be extended to allow sufficient time to complete the competition and for a brief transition period. Midwest Research Institute of Kansas City, Missouri, has held the NREL contract since the laboratory's creation in 1977. Proposals were due by July 30, and oral presentations are ongoing during the month of August. For a week-by-week status report on the competition, visit the DOE Golden Field Office Web site at www.eren.doe.gov/golden. Contact: **John Meeker, 303-275-4748**

PV Calendar

September 20–25, 1998, *1998 World Renewable Energy Congress V*. Sponsor: UNESCO and others. Location: Florence, Italy. Contact: A.A.M. Sayigh. Phone: +44-118-961-1364 Fax: +44-118-961-1365.

September 28–30, 1998, *Utility Photovoltaic Experience Conference (UPEx '98)*. Sponsors: UPVG, others. Location: San Diego, CA. Contact: Taneen Carvell. Phone: 202-857-0898. Web site: *www.ttcorp.com/upvg/upex98mn.htm*

October 6–8, 1998, *Village Power '98*. Sponsor: NREL. Location: The World Bank, Washington, D.C. Contact: Roger Taylor. Phone: 303-384-6432. Web site: *www.rsvp.nrel.gov/rsvp/tour/VPConference/VP98.htm*

October 11–14, 1998, *4th Conference on Thermophotovoltaic Generation of Electricity*. Sponsor: NREL. Location: Denver, CO. Contact: Tim Coutts. Phone: 303-384-6561. Web site: *www.tpv.org/tpv4.html*

November 2–6, 1998, *American Vacuum Society 45th International Symposium*. Sponsor: AVS. Location: Baltimore, MD. Contact: Marion Churchill. Phone: 212-248-0200. Web site: *www.vacuum.org/symposium98*

November 3–4, 1998, *PV Performance and Reliability Workshop*. Sponsor: FSEC. Location: Cocoa, FL. Contact: Dick DeBlasio. Phone: 303-384-6452.

November 19–21, 1998, *ENERGEX '98—The 7th International Energy Conference and Exhibition*. Sponsor: University of Bahrain. Location: Manama, Bahrain. Contact: Dr. W.E. Alnaser. Phone: +973-688381 Fax: +973-688396.

November 30–December 4, 1998, *Materials Research Society Fall Meeting*. Sponsor: MRS. Location: Boston, MA. Contact: Eric Chason, Sandia National Laboratories. Phone: 505-844-8951. Web site: *www.mrs.org/meetings/fall98*

February 10–13, 1999, *World Renewable Energy Congress 1999*. Location: Perth, Western Australia. Contact: Dr. Kuruvilla Mathew. Phone: +61.8.9360.2896, Fax: +61.8.9310.4997.

April 17–21, 1999, *SOLTECH '99*. Sponsors: SEIA, IREC, UPVG, HSEIA. Location: Kansas City, MO. Contact: Sharon Wilson, SEIA. Phone: 202-383-2600. Web site: *www.seia.org/main.htm*

May 2–7, 1999, *Electrochemical Society 195th Meeting*, including *Photovoltaics for the 21st Century* (Symposium K3). Sponsors: ECS, NREL. Location: Seattle, WA. Contact: Robert McConnell, NREL. Phone: 303-384-6419. Web site: *www.electrochem.org/meetings/195/symp.html*

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

Robert McConnell........(303) 384-6419
PV Program Communications

Tom Surek ....(303) 384-6471
Technology Manager, Photovoltaics

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

Gary Cook ....(303) 275-3659
Writer

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

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NREL

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

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