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Photovoltaics R&D: At the Tipping Point

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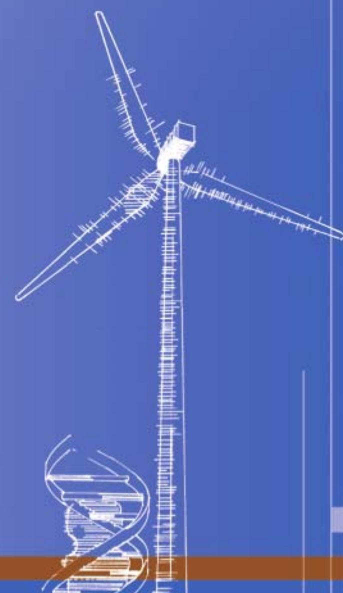
Presented at the 2004 DOE Solar Energy Technologies Program Review Meeting
October 25-28, 2004
Denver, Colorado

Conference Paper
NREL/CP-520-37553
January 2005



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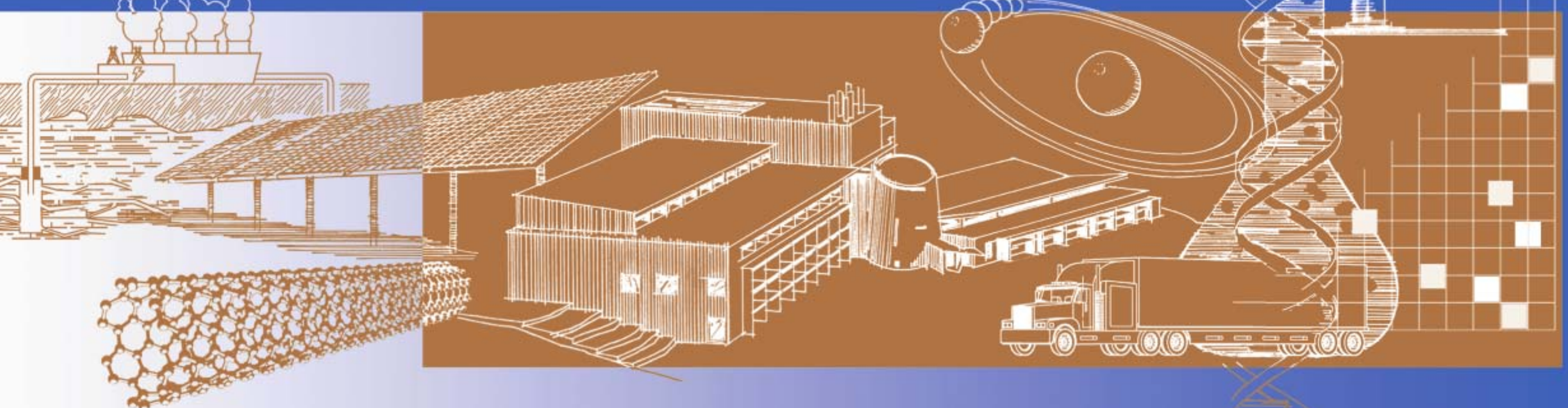

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ABSTRACT

" . . . with robust investments in research and market development, the picture changes dramatically."[1]. Thus, the realigned U.S. Photovoltaic Industry Roadmap highlights R&D as critical to the *tipping point* that will make solar photovoltaics (PV) significant in the U.S. energy portfolio—part of a well-designed plan that would bring "2034 expectations" to reality by 2020. Technology improvement and introduction depend on key, focused, and pertinent research contributions that range from the most fundamental through the applied. In this paper, we underscore the successes and relevance of our current systems-driven PV R&D programs, which are built on integrated capabilities. These capabilities span atomic-level characterization, nanotechnology, new materials design, interface and device engineering, theoretical guidance and modeling, processing, measurements and analysis, and process integration. This presentation identifies and provides examples of critical research tipping points needed to foster *now and near technologies* (primarily crystalline silicon and thin films) and to introduce *coming generations of solar PV* that provide options to push us to the next performance levels (devices with ultra-high efficiencies and with ultra-low cost). The serious importance of science and creativity to U.S. PV technology ownership—and the increased focus to accelerate the time from laboratory discovery to industry adoption—are emphasized at this *"tipping point"* for solar PV.

1. The Tipping Point

In his recent best-selling book *The Tipping Point*, Malcolm Gladwell scrutinized *"that magic moment when an idea, trend, or social behavior crosses a threshold, tips, and spreads like wildfire"* [2]. Our PV technology can be characterized by such tipping points during its history. For example, the Bell Laboratories discovery of the crystalline-Si solar cell, whose 50^{th} anniversary we celebrated this year, is one. It set in motion the mechanisms underlying modern photovoltaics, creating a reliable power source for our space program and heralding the potential of solar electricity as viable for terrestrial markets, as well. The Bell Labs discovery "tipped" PV into the *real* applications arena from its position for many years as merely a research curiosity. The world markets in PV have been growing, intensified by the energy issues surrounding fossil fuels for the past 25 years. But, it was the impetus provided by the genuine concern for the environment in Germany and the onset of several disasters in Asia that "tipped" the markets for widespread PV adoption in Europe and Japan. The newly published U.S. PV Industry Roadmap [1] clearly establishes that this solar technology is at a tipping point *now* in the United States. Energy security and independence, environment, electrical grid integrity and protection . . . have brought us to the threshold. At this critical point, there are two directions that such a clean energy epidemic might spread. *First*, we can remain on our current path, which continues to diminish U.S. market share and erodes the research leadership that this country still commands. Or, *second*, we can make the required research and policy investments. The *latter* takes hold of these markets here for our U.S. companies, with direct benefits to our country with U.S. jobs and economy, and ensuring U.S. technology ownership now and for the coming generations of solar photovoltaics. The *former*, however, *outsources* PV to our foreign competition. Further, the roadmap highlights R&D as critical to this tipping point in both making PV a significant part of the U.S. energy portfolio and accelerating those current 2020, 2030, and 2050 expectations by 10 to 25 years. What course we take *now* determines not only how fast we can realize this clean, secure energy—but also, who will own it and its economic benefits.

The National Center for Photovoltaics (NCPV) and the U.S. PV Subprogram have continued to provide recognized technology leadership through their R&D efforts. This proceedings contains summaries of these activities in more detail. It was requested that this paper highlight accomplishments in the materials and device areas, specifically those provided through the NREL / industry / university partnerships. (The accomplishments for the systems portions of the PV technology led by Sandia National Laboratories were designated to another paper in this section of the proceedings.) Our purpose is to demonstrate that PV R&D has several technologies and pathways that stand at their tipping points to contribute to the system-driven goals of the U.S Department of Energy's (DOE) Solar Energy Technologies Program [3] and the accelerated targets of the U.S. PV Industry Roadmap [1].

2. Approaches

The R&D activities can be categorized into two general areas—with research-device progress on these shown in Fig. 1. The first area is to improve *current and near technologies*—primarily crystalline Si and thin films. These two technology paths are high priority because both are expected to be the foundation of the industry over the next few decades. Thin films are certainly less mature in their overall evolution, but they offer performance and cost potential

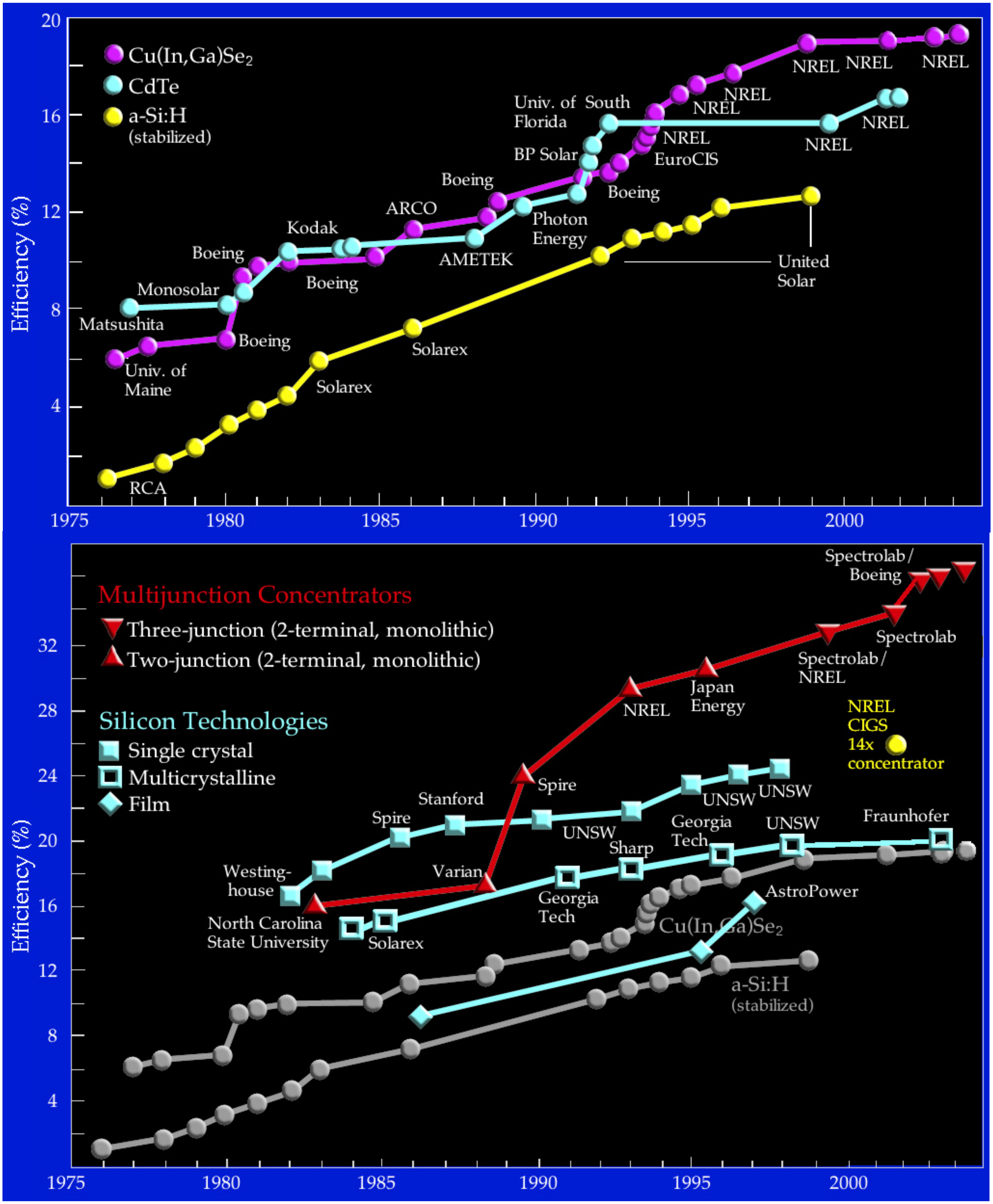

Fig. 1. Evolution of research solar cell efficiencies over the lifetime of the DOE PV Technology Program. Upper figure shows thin-film technologies; lower figure shows Si and concentrators, comparing them to the thin films.

significantly beyond those anticipated for the current commercial PV approaches. However, crystalline Si research remains a priority—because a rising host of improvements and second-generation Si devices (e.g., thin and thin-film Si, innovative device designs, heterostructures) offer equally important possibilities for the same economic targets. New efforts in process research, process integration, and diagnostic development cultivate critical links between even the most fundamental studies and manufacturing in an entirely new research approach aimed at cutting the time between laboratory discovery or invention to industry introduction and use.

The second area involves positioning the United States for technical leadership, decision-making, and ownership for the host of *next-technology options*, including some that have been called "third generation." These options include those with efficiencies (and perhaps principled on a different physics) beyond the conventional (*ultra-high efficiency* devices such as "multi"-multijunctions, thermophotovoltaics/thermophotonics, intermediate bandgaps, quantum dots) and those with costs below current targets (*ultra-low cost* approaches, including organics, quantum-layer and ultra-thin films, and biomimetics). Also, approaches that provide both electricity and chemical harvests (e.g., photoelectrochemical cells) can partner clean solar with clean fuel production.

Performance (i.e., efficiency, reliability, durability) has not reached a limit. In fact, as we increase our understanding of these devices, we see that innovation, creativity, and technology advancement have continued to move the perceived "limits" to higher attainable levels. Figure 2 provides a glimpse of where the core program and enhanced R&D investments can take us for these technologies. We are at the tipping point to the next levels for many of these. Some suspend at the precipice to demonstrate technical worth; others are at the brink of first-time commercial introduction. How effectively we make decisions and how quickly we reach our targets depend on many factors—but the U.S. PV industry clearly defines a pathway that gives a real chance "*to do things right.*"

3. Progress

The 25-year advancement of the terrestrial PV technologies supported by DOE is represented in Fig. 1. Over this timeframe, Si cells doubled and thin films more than tripled in efficiency. Multijunction devices have gone from concept to abandonment to reality—and now are approaching 40% efficiency for terrestrial concentrator applications. New materials and novel approaches have been introduced with technical promise not envisioned at the onset of the DOE Program. Excellent progress? *Yes*. The technology works well, and it is a real business. The final answer? *No.* Solar photovoltaics is real—*now* and for our future. It is both the now and the future that we must take hold of.

Thin Films. The perennial bridesmaid of the PV technologies continues to show substantial progress. A sizeable number of headline research cells and record modules have been confirmed in this past period, and they are summarized in Table 1. Amorphous Si:H, copper-indium-gallium-diselenide (CIGS), and cadmium telluride (CdTe) remain the primary thin-film program technologies. The CIGS technology continues to lead from a record-efficiency metric—and the 19.5% of this 4-µm-thick device is nearly the same as its 250-µm-thick multicrystalline Si research counterpart. Thin-film CdTe (16.7% cell) continues to show manufacturing progress, with large-area production-level modules measured above 10%.

The thin-film CIGS cell provides some insight into the value of the program and how effectively it functions to bring about technology advancement from a strong partnership among its industry / university / Laboratory components. The CIGS technology experienced a 60%–70% improvement from the 12% efficiency that it had reached in the mid-1990s (see Fig. 1). How did this happen? What was the research *tipping point*? It grew initially from Program or "motivational" influences that unleashed a chain of scientific discoveries and understanding that guided improvements. First, there arose a real commercial interest and need ("context"), which was then augmented by the DOE Thin Film Partnership ("the few"). In parallel, a considerable foreign competition ("a few more") provided both an enhanced research base and a motivation for additional funding from the United States. In turn, these gave birth to coordinated theory, modeling, deposition, and characterization projects that led to materials and device understanding and development. New areas of interface and materials engineering, defect analysis, development of special measurements—and the parallel advent of the nanotechnology age—all provided pathways traceable to the *science-based improvement* of the technology. Every aspect of the device was meticulously investigated and optimized—from grain boundaries, to compositional gradients, to heterointerfaces, to window and transparent semiconductors, to contacts—nanoscale through macroscale, accounting for every photon and electron and hole within the structure. This investment of persistent and coordinated financial and intellectual resources to the needs of the industry tipped this thin-film technology to levels of performance beyond the expectations of the 1980s ("stickiness factor"). New physics, new understanding, and new methods provided the guidance for improvement. This combination of the three agents of change defined by Gladwell—*the Law of the Few, the Stickiness Factor, and the Power of Context*—tipped this mini-technical epidemic.

Crystalline Silicon. Some 94% of current world market sales are for this PV product. Some have believed that because crystalline Si commands the market share, no further research is necessary! In fact, Si technology has continued to advance, and several cell designs have been validated with efficiencies above 20%. Crystalline Si has been the main foundation of the DOE PVMaT and the PV Manufacturing R&D projects. Georgia Tech maintains the DOE University Center of Excellence in silicon photovoltaics. The DOE-NREL Universities Program has focused on

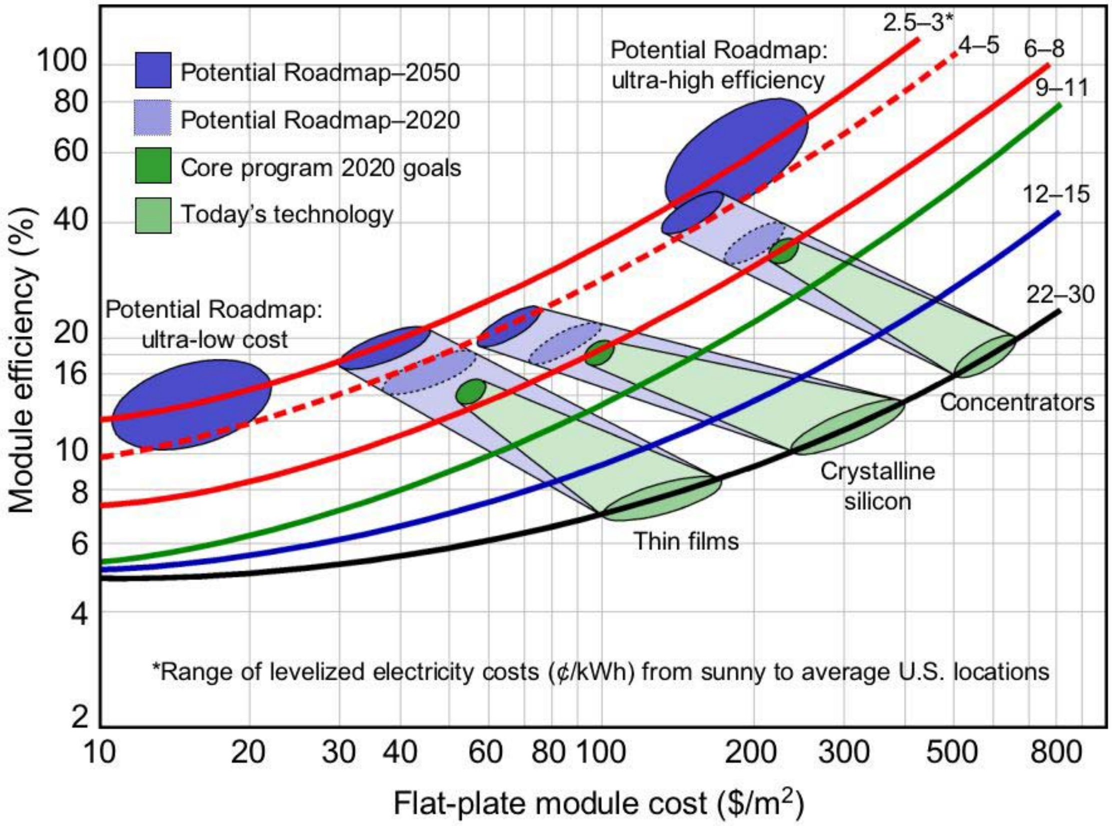

Fig. 2. Representation of the performance-cost potential of the PV technologies under the current U.S. DOE funding expectations and those proposed by the PV roadmap (shown as "Potential Roadmap"). The roadmap R&D and policy investments are expected to accelerate the program by 10-20 years. (Evaluation by T. Surek and L.L. Kazmerski, 2004)

Table 1. Recent headline performances for cell and module technologies supported under the U.S. DOE PV Subprogram. These represent a set of these efficiency records confirmed during the past year.

Cell	Efficiency (%)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Area (cm^2)	Organization/Date/Comments
Thin-film ZnO/CdS/CIGS	19.5	0.69	35.22	79.9	0.409	NREL (8/2004)
Thin-film CGS	10.2	0.83	18.61	66.8	0.419	NREL (4/2004)
Thin-film ZnO/CdS/CIS	15.0	0.49	40.50	75.2	0.403	NREL (9/2004)
Thin-film ZnO/CIGS (no CdS)	18.5	0.67	35.11	78.8	0.402	NREL [5/2004)
Thin-film CdTe (transparent)	13.9	0.81	29.97	69.2	0.406	NREL (9/2004)
Thin-film CdTe-CIGS Tandem (mechanical stack)	15.3 13.8 (CdTe) 1.5 (CIGS)	0.79	25.55	68.9	0.406	NREL (11/2004) (13.8 top cell; 1.5% bottom) Transparency of top cell is 50%
GaInP/GaAs/Ge Monolithic Multiple Junction Concentrator	37.3	3.04	2435.39	88.3	0.264	Boeing-Spectrolab (3/2004) Under 175.2x concentration (I_{sc} = .643 A; P_{max} = 1.724 W)
a-Si:H/Floatzone Crystalline Si Heterojunction	16.9	0.64	33.11	79.2	1.004	NREL/Georgia Tech (9/2004) ["HIT"-type structure]

Module	Efficiency (%)	Power (W)	Aperture Area (cm^2)	Manufacturer/Date
CdS/CdTe	10.2	67.4	6624	First Solar (2/2004)
CdS/CIGS (on flexible stainless steel)	10.1	71.2	7085	Global Solar/ITN (9/2004) (ITO/ZnO/CdS/CIGS/Mo/ss)

critical applied and fundamental research areas identified by the U.S. industry. NREL has sponsored the annual *Workshop on Crystalline Silicon* for 14 years, which is a forum that has brought together researchers from PV and the Si electronics industry to exchange technical ideas and serves as the sounding board and provides guidance for research needs for PV technology. Growing from the most recent Workshop, a "White Paper" is being formulated to guide DOE on crystalline Si research needs. Although these efforts have provided substantial contributions, the U.S. program lags behind the basic and applied efforts and investments currently under way in Europe and Japan. In response, the NCPV has recently established a new "Crystalline Silicon Program," uniting the ensemble of resources in the PV Technology Subprogram in a new partnership. The NCPV has redirected some of its resources over the past year to build this area, responding to our industry's guidance—both at the University Center of Excellence and in its own internal R&D programs. Several significant contributions have already appeared. Collaborative work between NREL, Georgia Tech, and SunPower enhanced the understanding of the Si heterojunction (a-Si:H/crystalline Si cell)—reporting key aspects to achieve high efficiencies (the abrupt interface and uniform, thin a-Si:H layers), with a record cell efficiency confirmed. Initial work on realistic paths to thin-film devices on glass substrates is under way. A revived activity aimed at supportive measurement and characterization techniques for Si technology has begun, including some activities aimed at meeting new and in-line diagnostics needs. However, all this must be expanded to help the industry close the performance gap between research cells and manufactured modules; to facilitate innovative manufacturing, processing, and in-line diagnostics development as part of the "manufacturing centers of excellence" called for in the industry roadmap; and to provide an R&D foundation for those next-generation Si technologies cited earlier. This is a priority for the NCPV and the DOE PV Subprogram.

<u>High-Performance and Next-Generation PV</u>. Exploring and evaluating options that could take PV to the next levels has been at the foundation of U.S. PV research since the formation of the terrestrial program. From these options, many of our current cells evolved from concept to the mainstream. These programs dealing with advanced and exploratory R&D have been the "poster child" of the decision-making process in the PV program—a reflection of the "stage-gating" procedures we are now formalizing within the systems-driven process.

Much of this R&D is designed to explore the ultimate performance limits of PV technologies. The "High Performance PV Project" was initiated in 2002, with the goal to "double the conversion efficiencies" of current technologies—aimed at thin-film multijunctions and pre-commercial concentrators. Although slowed by under-support, some significant progress has been made based on the innovation and creativity of the partners in this effort, and thus helping to give the United States early technical leadership.

Certainly, the work on *multijunction concentrators* has drawn attention to the area of ultra-high efficiencies. The Boeing/Spectrolab GaAsP/GaAs/Ge monolithic device currently leads with a verified efficiency of 37.3% (175.2x concentration, 24.3°C, 0.264 cm^2 area)—with similar research cells in Japan and Germany being a few efficiency points behind. Further optimization of this 3-junction structure is ongoing, but other approaches are under way. Adding a 1-eV GaInAsN junction to this successful 3-junction structure or the development of a lattice-mismatched monolithic cell hold promise to exceed 40% efficiency. The progress has been significant in this area with the added investment by the industry—and a 40%-efficienct research concentrating cell is likely before the current 39% 2007 target [4]. Uniting the III-V semiconductors with Si has received some additional interest because of the success of these monolithic devices. Recently, a two-junction GaAsNP/Si dual-junction cell was demonstrated (voltage addition and tunnel junction). It is expected that improved nucleation of the III-V on the Si will provide another pathway toward an ultra-high efficiency concentrator based on a less expensive and higher efficiency Si bottom cell.

The *polycrystalline thin-film tandem-cell* work covers a variety of activities and approaches. The target is a 25% cell, which could be attained, for example, by using a 1.7-eV top-cell and a 1.1-eV bottom-cell partner (modeling predictions). The options include CdTe and alloys, CIS and various quaternaries, $CuGaSe_2$, and Si. Monolithic and mechanical stacks are part of a critical-path research plan. Voltage addition has been demonstrated for several monolithic designs, with success of the pertinent interconnect junction. Recently, a CdTe-CIGS 4-terminal tandem was verified at 15.3% efficiency, using a specially developed transparent 13.8%-CdTe top cell. Because of the accelerated work on the special top cell, an efficiency milestone for this program was reached 9 months ahead of schedule. Such excellent progress in this and other tandems gives evidence that these technologies are approaching the critical point of implementation—the position that will tip this toward prototype realization.

<u>Manufacturing R&D</u>. Maintaining *technology ownership* is one of two major themes in the new U.S. PV Industry Roadmap [1]. Support for centers of excellence, universities and national laboratories is called out as critical for this, and specifically for the "…Science and Technology Facility at NREL to shorten by 50% the time between lab discoveries and industry use in manufacturing and products." In this and the previous roadmaps, attention to this manufacturing and processing R&D and to a "manufacturing center of excellence" are priorities—especially since the first major cost reductions remain with the module itself [1]. The national program R&D serves part of this need—the internal research at the Labs and universities, as well as the major PV Manufacturing R&D and Thin-Film Partnership Programs. These latter two programs remain as priorities and are providing a foundation for the center-of-excellence model. The center-of-excellence concept is one that is key to supporting

the industry in meeting the roadmap targets. This will encompass a consortium between industry, universities, and the national laboratories, focusing on broad industry support for now and near-term manufacturing issues—as well as establishing mechanisms leading to adoption by or development of longer-term or advanced manufacturing. This *center* has to address Si and thin films, and needs direct industry input and oversight for its success. The focus should be on projects that provide broad industry support (solutions that can be pursued by a wide group of manufacturers). However, there should still be mechanisms to work on a proprietary basis for critical needs. The former, because of the general benefit produced, should be funded by the U.S. program as part of its support for its industry. The latter could leverage funding from the companies themselves, if necessary. Because of the scope of manufacturing involved (i.e., processing, diagnostics, robotics, packaging, characterization, cells, modules, macroscale processes, nanoscale processes), this may actually involve several operations at several pertinent organizations. Something that should not be lost is that this program should also establish a mechanism to support graduate students to work specifically in these areas of research. This activity is critical to *"training our workforce,"* which is especially important if the roadmap targets are even partially realized.

The new NREL Science and Technology Facility (S&TF) has been established specifically to meet many of these industry and R&D needs. A key component is the "process development and integration laboratory," designed specifically to provide the direct interface with the industry for their needs. The facility itself is slated for initial operations in mid-2006, but the design of the critical process-integration platforms is well under way. In addition, a real, working "industry/university advisory committee" has been established to provide guidance and review of the activities—from conception to conclusion. The first scheduled "platform" will serve the crystalline silicon needs, with one for the thin films scheduled thereafter. The platform provides a set of specifically designed and pertinent characterization tools, controlled-ambient automated sample handling, several materials and device processing systems common to industry standards, and the facility and interface for an industry partner to "roll up" their own specialized equipment to evaluate its capability (without having to interrupt that manufacturer's own manufacturing lines). It is a "users facility" that brings the state-of-the-art diagnostics, control, analysis, and expertise to rub shoulders with the industry engineers to maximize transfer of information. Because the facility is linked with the NREL materials, device, and characterization R&D laboratories, these capabilities and scientists/engineers will also interact with this new way of conducting the business of R&D. Additionally, the systems-driven analysis tools will be incorporated to provide users with real-time access and evaluation assistance. The ensemble of these facility designs and operations is part of the goal to significantly reduce the time from laboratory discovery to industry adoption. This is a tipping point toward U.S. industry leadership, realized by the best products worldwide at best costs—and the expansion of the U.S. markets.

4. Summary

The NCPV continues to lead and support the R&D priorities for the U.S. PV technology, in concert with its industry, university, and national laboratory partners. The program has remained flexible and poised to respond to technology needs. The new *"Crystalline Silicon Project"* is such a response, along with some redirection of NREL internal research and some additional funding into the existing crystalline Si activity. So is the activity of the new Science and Technology Facility in establishing the roadmap-identified priority with a *manufacturing science center of excellence*. Thin-film R&D remains a priority.

Progress based on world-leading science and technology has brought much of this R&D to its "tipping point," at the verge of providing materials, processes, devices, and techniques to either adoption by the industry or to the realization of new technologies. The new U.S. PV Industry Roadmap recognizes the need for enhanced U.S. R&D investments if we *are to tip and cross that threshold causing the flood of solar PV electricity to immerse our U.S. homes, businesses, grids, manufacturing, and federal facilities with this clean, secure power*. Solar photovoltaics is real—*now* and for our future.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the inputs and guidance from the researchers in the NCPV and its two University Centers of Excellence. He especially appreciates the help of Tom Surek, John Benner, Pete Sheldon, Rommel Noufi, Sarah Kurtz, Dave Ginley, Mowafak Al-Jassim, Keith Emery, Martha Symko-Davies, Rick Mitchell, Ken Zweibel, Bob Birkmire, Ajeet Rohatgi, Susan Moon, Irene Passage, Al Hicks, & Don Gwinner. Finally, I want to acknowledge the support of the U.S. Department of Energy under Contract DE-AC36-99G010337.

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SPECIAL RECOGNITIONS

The NCPV wants also to acknowledge and congratulate several among us who received special awards and honors during this year, including:

- Cecile Warner, ASES Solar Woman of the Year (June 2004)
- Timothy J. Coutts, IEEE PVSC Cherry Award (October 2004)
- Ajeet Rohatgi, NREL 2003 Rappaport Award (March 2004)
- Robert Annan, NREL 2004 Rappaport Award (November 2004)
- Bhushan Sopori, NCPV 2004 Rappaport Award (October 2004)
- Bhushan Sopori, US DOE Tech Transfer Award (March 2004)
- Global Solar/ITN and NREL, 2004 R&D 100 Award (November 2004)

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
January 2005	Conference Paper	

4. TITLE AND SUBTITLE
Photovoltaics R&D: At the Tipping Point

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
L.L. Kazmerski

5d. PROJECT NUMBER
NREL/CP-520-37553

5e. TASK NUMBER
PVC51201

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-520-37553

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
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15. SUBJECT TERMS
PV; research and development; tipping point; market; atomic-level characterization; nanotechnology; new materials design; interface and device engineering; theoretical guidance and modeling; processing; measurements and analysis; process integration;

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
Unclassified	Unclassified	Unclassified	UL		