NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

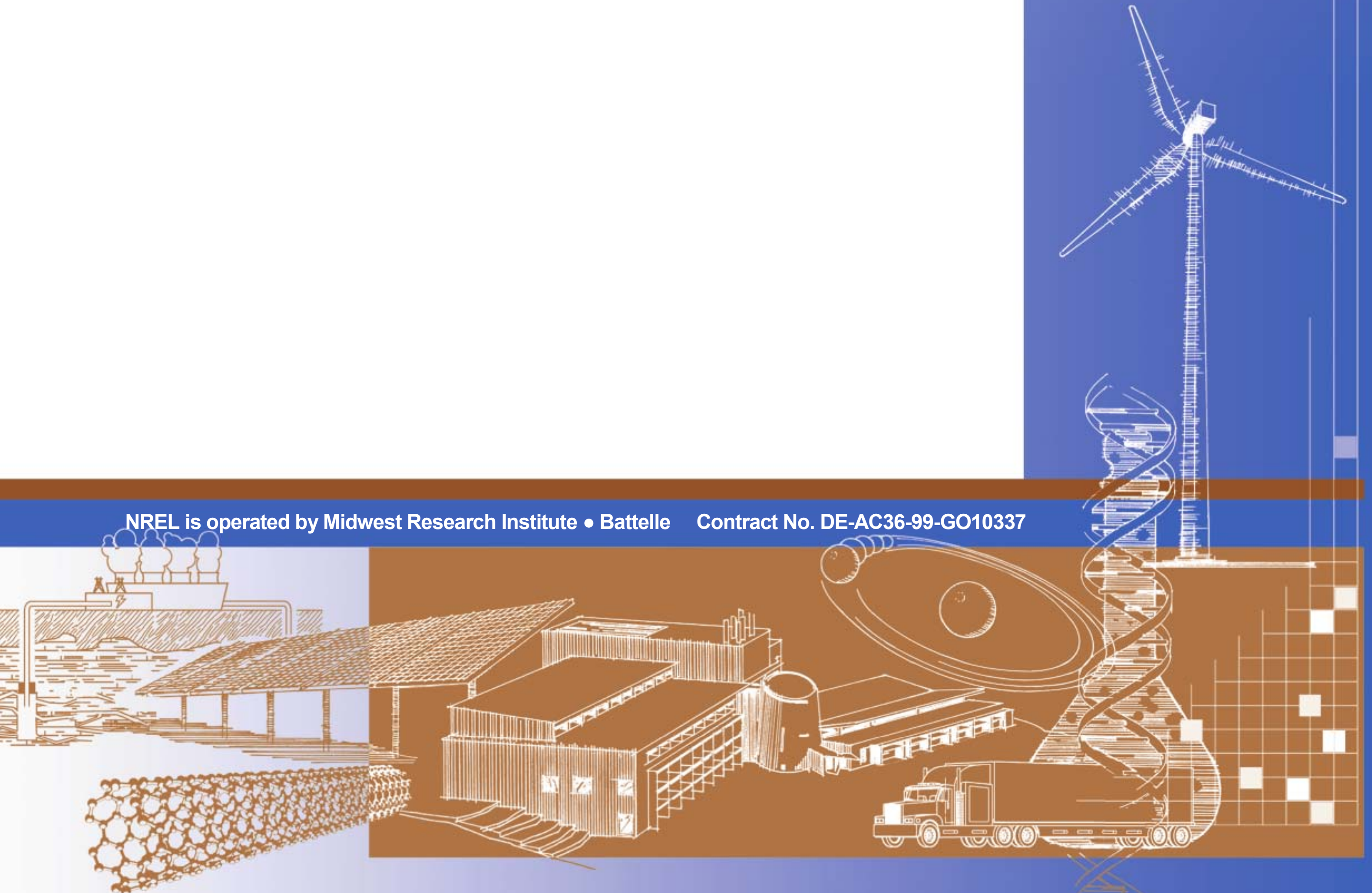
Polycrystalline Thin-Film Photovoltaics: From the Laboratory to Solar Fields

Preprint

B. von Roedern, H.S. Ullal, and K. Zweibel

Presented at the 2006 IEEE 4th World Conference on
Photovoltaic Energy Conversion (WCPEC-4)
Waikoloa, Hawaii
May 7–12, 2006

Conference Paper
NREL/CP-520-39838
May 2006



NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

POLYCRYSTALLINE THIN-FILM PHOTOVOLTAICS: FROM THE LABORATORY TO SOLAR FIELDS*

Bolko von Roedern, Harin S. Ullal, and Ken Zweibel
National Center for Photovoltaics (NCPV)
National Renewable Energy Laboratory (NREL)
1617 Cole Boulevard
Golden, CO 80401-3393 USA
Tel: (303) 384 6480; Fax: (303) 384 6430; E-mail: bolko_von_roedern@nrel.gov

ABSTRACT

We review the status of commercial polycrystalline thin-film solar cells and photovoltaic (PV) modules, including current and projected commercialization activities.

INTRODUCTION

Major technical progress has occurred in the area of thin-film PV technologies, particularly those based on cadmium telluride (CdTe) and copper indium diselenide ($CuInGaSe_2$, CIGS). Some of the many advances made in material research, device development, manufacturing technology, reliability testing of modules and systems, technical R&D issues relating to CdTe and CIS, and commercial efforts under way in the United States and worldwide are reported in this paper. Perhaps most important is the commercial success in transitioning First Solar's CdTe modules from pilot development to a mass-produced commercial product. A 1,400-kW thin-film CdTe solar field has been installed in Dimbach, Germany, using First Solar modules. Several thin-film PV systems varying in size from 400 to 1,400 kW_p have been installed in Germany and the United States using First Solar CdTe modules.

CIS module technology has received tremendous world-wide interest, and commercial module development activities are actively pursued by more than a dozen entities. Shell Solar Industries (SSI) is marketing a new thin-film power module (80-W_p power, trade-named "Eclipse") for various applications. Edge seals developed in collaboration with the National Thin Film Module Reliability Team have been used in this product. Global Solar Energy has also fabricated a thin-film CIGS power module with an aperture-area conversion efficiency of 10.2% and power output of 88.9 W. The highest aperture-area conversion efficiency of 13.0% for a thin-film CIGS power module has been achieved by Würth Solar in Germany with a corresponding power output of 84.6 W.

To gauge progress with the polycrystalline thin-film cell and module technologies, we first look at "champion" cells and modules fabricated to date. All of these thin-film cell efficiencies reflect "total-area" performance, and module aperture-area conversion efficiencies are used. Most results have been independently confirmed by NCPV/NREL. Table 1 summarizes the results of new high-performance noteworthy CIGS polycrystalline thin-film solar cell results. Table 2 shows the results of "champion" modules made by the various groups/organizations worldwide. Note that aperture-area efficiencies are reported in this table, whereas commercial efficiencies use total module-area efficiency values. Reviewing these champion cell and module results provides some insight as to the capabilities of the respective PV technologies. Achieving these cell and module results is a testimony to talented solar cell researchers who have developed the necessary processing know-how for achieving such state-of-the-art prototypes.

STRENGTHENING THE SCIENCE BASE

To a very significant degree, processing of high-efficiency CIGS and CdTe PV solar cells and modules depends on the know-how of experienced researchers. Some process details necessary to produce champion-level solar cells and modules are published in the scientific literature. However, not enough detail is usually provided such that the results could be reduced to a commercial product by other experienced researchers without further experimentation. In part, this may be due to the fact that the underlying mechanisms that link cell processing and cell performance are not understood in sufficient detail. Some research activities are geared toward improving the influence of cell processing and material properties on cell performance. Many analytical studies of CIGS and CdTe cell absorbers focus on characterizing micro- and nanostructures of CIGS and CdTe materials [1, 2]. Detailed analyses of the cell-junction chemistry is also under way [3]. By applying surface analytical methods to actual solar cells, much more detailed knowledge of the energy-band diagrams and the chemical composition of solar cell interfaces is expected.

Improved understanding of the solar cell operation is particularly important to assist commercial manufacturers with improving module performance, manufacturing yields, and product stability. Although the leading thin-film PV module manufacturers have now established manufacturing processes resulting in adequate performance, yield, and

---

*This work has been authored by an employee or employees of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

stability, the development of such manufacturing processes has often taken more time and resulted in somewhat lower commercial product performance than was originally expected or anticipated. Better understanding of solar cell device operation can also assist in helping manufacturers decide when to "tweak" established processes and when to substitute or add processes to enhance commercial product performance.

Although greater knowledge of the semiconducting CIGS and CdTe properties is very important, one may ask the question of how much value can ultimately be derived from detailed knowledge of semiconductor material properties. While often the case is being made that "much more" is known about the silicon semiconductor compared to CIGS and CdTe, this begs the question of why—despite this greater knowledge base—solar cells and modules made from the latter materials have demonstrated generally higher efficiencies than devices made from thin-film silicon (<50 µm thick).

CIGS TECHNOLOGY

A typical CIS-based solar cell structure is a MgF_2/ZnO/CdS/CIS/Mo/glass "substrate" configuration. Low-cost, soda-lime glass is used for device fabrication. In addition, polymers, metal foils, and stainless steel are also used for device fabrication. The highest world-record, total-area efficiency achieved thus far by NREL scientists for a thin-film CIGS solar cell is 19.5% measured under the AM 1.5 global spectrum [4]. Using a single-layer buffer layer of ZnS(O,OH) and CdZnS(O,OH), it is remarkable that champion efficiency levels (>18%) were attained using alternatives to CdS as the heterojunction partner [5]. A 17.1% total-area conversion efficiency has been demonstrated for a thin-film CIGS solar cell using a thin absorber layer thickness of 1.1 µm [6]. The device parameters of these solar cells are included in Table 1. The CIGS film is deposited by the physical vapor deposition method, the CdS [CdZnS (O,OH)] by the chemical-bath deposition (CBD) technique, and ZnO either by chemical vapor deposition or sputtering. Studies why CBD CdS results in the highest efficiency cells have been conducted [7]. This issue is of technological importance, because many module manufacturing processes would prefer vacuum deposition of CdS (or alternatives) layers, rather than depositing them by a wet-chemical process. Aside from evaporating CIGS films, two other deposition approaches have been developed. The first one relies on vacuum deposition (such as sputtering) of the metal Cu:Ga and In precursors that are then reacted into the compound semiconductor by annealing in H_2Se atmosphere ("selenization"). The other method relies on creating nanoparticle "inks" (or "paints") that are applied using non-vacuum coating techniques and then reacted into semiconductor films [8, 9].

Some work is being carried out on cells with $CuGaSe_2$ and $CuInS_2$ absorbers. The Florida Solar Energy Center has achieved world-class efficiency for a $CuInS_2$ (result included in Table 1) [10]. However, for the latter cells, efficiencies >13% could not yet be demonstrated; a further drawback is the necessity to wet-etch the $CuInS_2$ absorbers in a cyanide etch to achieve solar cells and modules with reasonable performance. Sulfurcell in Germany has developed a manufacturing process for this cell technology, and has delivered its first commercial product. A research topic receiving significant emphasis is the development of CIGS cells with thin absorber layers of 1 µm or less. These will reduce the per-watt usage of expensive and rare metals (In, Se), and can possibly increase manufacturing productivity. It is often found that for absorber thicknesses up to 0.7 µm, reasonable cell performance can be maintained, while significant losses in V_{OC}, FF, and J_{SC} have been reported as the thickness is reduced to below 0.7 µm. However, this is still preliminary, and further research is required to ascertain if and how such losses may be overcome.

CdTe TECHNOLOGY

For thin-film CdTe solar cells, the typical structure is glass/SnO_2/CdS/CdTe/contacts. A world-record, total-area efficiency of 16.5% has been achieved by NREL scientists [11]. In this particular case, the SnO_2 front contact is replaced by the more promising Cd_2SnO_4 contact. Also, a 13.9% thin-film CdTe solar cell has been fabricated using a semitransparent back contact [11]. First Solar and NREL's champion cells were deposited by vacuum sublimation onto high (>500^{o}C) substrate temperature, whereas other deposition methods such as elecctro-deposition used in the past have also resulted in respectable CdTe cell performance. Areas of research include micro nonuniformity of CdTe films and its impact on device performance, thin CdTe absorber layers, interdiffusion at the CdS/CdTe interface, where S diffuses into the CdTe film, vapor $CdCl_2$ heat treatments, and the role of Cu "doping" that is usually used for often proprietary back-contacting procedures. One interesting fundamental question requiring an answer is whether the maximum open-circuit voltage of CdTe cells could be significantly improved (say from 850 mV to greater than 900 mV) without degradation of FF and J_{SC}. In manufacturing terms, First Solar achieved substantial progress by being able to increase their power ratings of its 60 cm x 120 cm module from 50 and 55 W_p to new ratings now ranging from 55 to 65 W_p (9.3% total area) within the last year.

MODULE RELIABILITY AND COMMERCIALIZATION

The Thin Film Partnership has pursued serious studies aimed at understanding and improving the reliability of CIGS and CdTe PV modules. It is now reasonably well established that CIGS and perhaps CdTe are more moisture sensitive and often require better module encapsulation schemes than crystalline (or amorphous Si) PV modules. Without such improved schemes, it has been difficult for CIGS and CdTe modules to pass the "damp heat" test (1000-hour exposure at 85^{o}C and 85% relative humidity). NREL [12] has embarked on a study to link how cell processing affects the performance during continued "stressing," i.e., light exposure at elevated (typically, 65° to 100^{o}C) device temperature in various atmospheric ambients. It is also well known that electrical bias during such exposure affects the changes observed in cells and modules. Currently, these studies are carried out on naked and encapsulated solar cells. But it is planned to expand them to minimodules, as it has become clear that the cell interconnects are also affecting long-term performance. For CdTe cells, it has been established that the details of the entire cell process, as well as the details of back-contacting, are critical to achieving acceptable device performance and reliability.

As an additional "real-world" test, the Thin Film Partnership has been exposing thin-film PV modules in hot and humid climates at the Florida Solar Energy Center (Cocoa, FL) and Texas A&M University (College Station, TX). The long-term performance of these modules are monitored, and, if necessary, the results and corrective action are discussed with the respective manufacturers.

Growth in the sales of U.S. thin-film PV products between 2004 and 2005 has about doubled. It is estimated that the global thin-film (a-Si, CIS, CdTe, thin-Si) PV production capacity could increase from the present capacity of 120 MW_p to about 435 MW_p by 2007, with U.S. leading with an estimated 240 MW_p capacity by 2007, potentially solidifying a U.S. competitive position [13]. In 2005, U.S. thin-film market share reached 45 MW, or 29% of U.S. PV cell/module production, and met the projections made one year earlier [14]. This is in contrast to world PV production of 1759 MW_p, with a worldwide share of thin-film PV technologies of only 5.4% in 2005. Thin-film modules (including a-Si) are competing directly with crystalline silicon in the market place for the first time. Several large thin-film solar fields varying in size from 400 to 1,400 kW have been installed in Germany and the United States. Table 3 summarizes the large thin-film solar installations worldwide. Figure 1 depicts a grid-connected application. Due to their low efficiencies but low costs, thin-film modules are especially suited to lower overall cost of large (over 20 kW_p) systems, e.g., commercial roofs and ground-mounted installations. More pictures can be found at [16].

Due to the rapid growth of the world PV market of about 45% annually over the past several years, several new thin-film PV companies have entered the fray. Following is the list of the more established and emerging companies in thin-film PV technologies. In the area of CIS PV technology, the list of companies are as follows: Shell Solar Industries, USA; Global Solar Energy, USA; Würth Solar and Sulfurcell, both in Germany; Energy Photovolotaics, USA; Miasole, USA; NanoSolar, USA; Daystar Technologies, USA; International Solar Electric Technologies, USA; Heliovolt, USA; Showa Shell, Japan; and Honda Automotive, Japan. In the case of thin-film CdTe PV companies, clearly First Solar, USA, is the world leader. Other companies are Antec Solar, Germany; Solar Fields, USA; and AVA Tech, USA.

Table 1: Thin-Film CIGS Solar Cells

No.	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)	Comment
1	0.410	0.6975	35.078	79.52	19.5	Standard CIGS cell [4]
2	0.408	0.7052	35.515	77.90	19.5	CdZnS(O,OH) buffer layer [5]
3	0.402	0.6698	35.112	78.78	18.5	ZnS (O,OH) buffer layer [5]
4	0.409	0.6782	31.93	79.20	17.1	1.1-µm CIGS [6]
5	0.5	0.774	21.6	73.7	12.3	$Cu(In,Ga)S_2$ "champion" [15]
6	0.409	0.8305	20.88	69.13	11.99	$CuInS_2$ [10]

Table 2: Polycrystalline Thin-Film PV Modules (Standard Conditions, Aperture-Area) Ranked by Power

Company	Device	Aperture Area (cm^2)	Efficiency (%)	Power (W)	Date
Global Solar	CIGS	8390	10.2*	88.9*	05/05
Shell Solar	CIGSS	7376	11.7*	86.1*	10/05
Würth Solar	CIGS	6500	13.0	84.6	06/04
First Solar	CdTe	6623	10.2*	67.5*	02/04
Shell Solar GmbH	CIGSS	4938	13.1	64.8	05/03
Antec Solar	CdTe	6633	7.3	52.3	06/04
Shell Solar	CIGSS	3626	12.8*	46.5*	03/03
Showa Shell	CIGS	3600	12.8	44.15	05/03

* NREL Confirmed

Table 3: Polycrystalline Thin-Film PV Installations

Location	Material	Size (kW)	Date
Dimbach, Germany	CdTe	1,400	2004–2005
Reussenkoge, Germany	CdTe	1,040	2005
Fellber, Germany	CdTe	800	2005
Sinzheim, Germany	CdTe	800	2005–2006
Tapfheim, Germany	CdTe	778	2005
Springerville, AZ, USA	CdTe	500	2001–2003
Florsheim, Germany	CdTe	440	2005
Camarillo, CA, USA	CIS	245	2003

Figure 1: Thin-film CdTe 1,400-kW thin-film solar installation.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99GO10337. The authors would like to thank the numerous engineers, scientists, and technicians worldwide whose data have been included in this paper.

REFERENCES

[1] V.G. Karpov, A.D. Compaan, and D. Shvydka, “Random Diode Arrays and Mesoscale Physics of Large-Area Semiconductor Devices,” Phys. Rev. B **69**, 045325 (2004).

[2] Y. Yan, R. Noufi, K.M. Jones, K. Ramanathan, M.M. Al-Jassim, and B.J. Stanbery, “Chemical Fluctuation-Induced Nanodomains in Cu(In,Ga)Se_2 Films, Applied Physics Letters **87**, 121904 (2005).

[3] M. Blum, M. Bär, L. Weinhard, and C. Heske, “Characterization of the Electronic and Chemical Structure at the Thin Film Solar Cell Interfaces,” to be published, DOE Solar Energy Technologies Program, FY2005 Annual Report, Proceedings, Program Review Meeting 11/7-10/2005, Denver, CO.

[4] M.A. Contreras, K. Ramanathan, J. AbuShama, F. Hasoon, D. L. Young, B. Egaas, and R. Noufi, “Diode Characteristics in State-of-the-Art ZnO/CdS/Cu($In_{1-x}Ga_x$)Se_2 Solar Cells,” Prog. in Photovoltaics: Research and Applications, **13**, 209 (2005).

[5] R.N. Bhattacharya**,** M.A. Contreras, and G. Teeter, “18.5% CIGS Device Using Single-Layer, Chemical-Bath-Deposited ZnS(O,OH), Japanese Journal of Applied Physics **43,** No. 11B (2004) L1475-L1476, and private communication.

[6] K. Ramanathan, R. Bhattacharya, M. Contreras, J.C. Keane, B. To, R.G. Dhere, and R. Noufi, “High Performance CIGS Thin Film Solar Cells: A Laboratory Perspective,” to be published, DOE Solar Energy Technologies Program, FY2005 Annual Report, Proceedings, Program Review Meeting 11/7-10/2005, Denver, CO.

[7] K. Ramanathan, F.S. Hasoon, S. Smith, D.L. Young, M.A. Contreras, P.K. Johnson, A.O. Pudov, and J.R. Sites, J. Phys. Chem. Solids **64**, (2003) 1495.

[8] V.K. Kapur, A. Bansal, P. Le, and O.I. Asensio, “Non-Vacuum Processing for CIGS Solar Cells on Rigid and Flexible Substrates, Proc. 29th IEEE PV Spec. Conf (New Orleans, 05/2002), 688.

[9] C. Eberspacher, K. Pauls, and J. Serra, “Non-Vacuum Processing of CIGS Solar Cells,” Proc. 29th IEEE PV Spec. Conf (New Orleans, 05/2002), 684.

[10] A.H. Jahagirdar, A.A. Kadam, and N.G. Dhere, “Role of i-ZnO in Optimizing Open Circuit Voltage of $CIGS_2$ and $CIGSe_2$ Thin Film Solar Cells,” this conference.

[11] X. Wu, J. Zhou, J.C. Keane, R.G. Dhere, D.S. Albin, T.A. Gessert, C. DeHart, A. Duda, J.J. Ward, Y. Yan, G. Teeter, D.H. Levi, S. Asher, C. Perkins, H.R. Moutinho, B. To, K. Emery, T. Moriarty, Y. Zhang, S. Wei, and R. Noufi, “Advances in CdTe R&D at NREL,” to be published, DOE Solar Energy Technologies Program, FY2005 Annual Report, Proceedings, Program Review Meeting 11/7-10/2005, Denver, CO.

[12] D.S. Albin, S.H. Demtsu, T.J. McMahon, A. Davies, J.W. Pankow, and R. Noufi, "Polycrystalline Thin Film Device Degradation Studies", to be published, DOE Solar Energy Technologies Program, FY2005 Annual Report, Proceedings, Program Review Meeting 11/7-10/2005, Denver, CO.

[13] K. Zweibel, “The Terawatt Challenge for Thin-Film PV,” NREL Technical Report, NREL/TP-520-38350 (08/2005).

[14] B. von Roedern, K. Zweibel, and H.S. Ullal, “The Role of Polycrystalline Thin-Film PV Technologies for Achieving Mid-Term Market-Competitive PV Modules,” Proc. 31st IEEE PV Spec. Conf (Lake Buena Vista, FL, 01/2005), 183.

[15] R. Kaigawa, A. Neisser, R. Klenk, and M.C. Lux-Steiner, “Improved Performance of Thin Film Solar Cells Based on Cu(In,Ga)S_2,” Thin Solid Films **415**, (2002) 266.

[16] More pictures can be found at http://www.nrel.gov/ncpv/thin_film/pn_general_interest.html.