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The Role of Polycrystalline Thin-Film PV Technologies for Achieving Mid-Term Market-Competitive PV Modules

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

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1617 Cole Boulevard, Golden, Colorado 80401-3393
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THE ROLE OF POLYCRYSTALLINE THIN-FILM PV TECHNOLOGIES FOR ACHIEVING MID-TERM MARKET-COMPETITIVE PV MODULES

B. von Roedern, K. Zweibel, and H.S. Ullal
National Center for Photovoltaics
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

This paper reviews the current commercial status of $CuInSe_2$ alloys (collectively, CIS) and CdTe-based photovoltaic (PV) modules, comparing the performance of commercial products with the results achieved for solar cell and prototype module champions. We provide an update for these PV cell and module technologies, and also compare CIS and CdTe performance levels to the results achieved by the crystalline Si PV industry. This comparison shows that CIS and CdTe module technology presently offers the best (and perhaps only) approach for significantly exceeding the cost/performance levels established by crystalline Si PV technologies. A semi-empirical methodology is used for comparing "champion" solar cell and prototype module data with performance achieved on manufacturing lines. Using a conservative assumption that thin-film technologies will eliminate the 40% of PV module costs arising from the Si wafer or ribbon, we estimate the future performance of all established PV module candidates, and conclude that, based on 2004 knowledge about each PV technology, CIS and CdTe should provide cost-competitive advantages over crystalline Si.

INTRODUCTION

Figure 1 shows the best verified champion cell performance achieved in each of the thin-film PV technologies. Table 1 shows champion large-area modules produced by a number of entities. Note that aperture-area efficiencies are reported in this table, whereas commercial efficiencies listed below use total module-area efficiency values. This paper will provide a measure for estimating mid-term commercial product performance based on demonstrated and verified champion cell efficiency values.

TECHNOLOGY — DRIVER FOR PERFORMANCE

After investing in a commercial manufacturing line, two pathways lead to increased performance of the manufactured product. The first approach is to optimize the chosen process for optimum performance and yield. Once an optimum has been obtained in this manner, one has to decide which aspects of the manufacturing process should be upgraded to ensure further increases in module performance. Because such upgrades often require massive capital investment and "downtime" (i.e., loss of

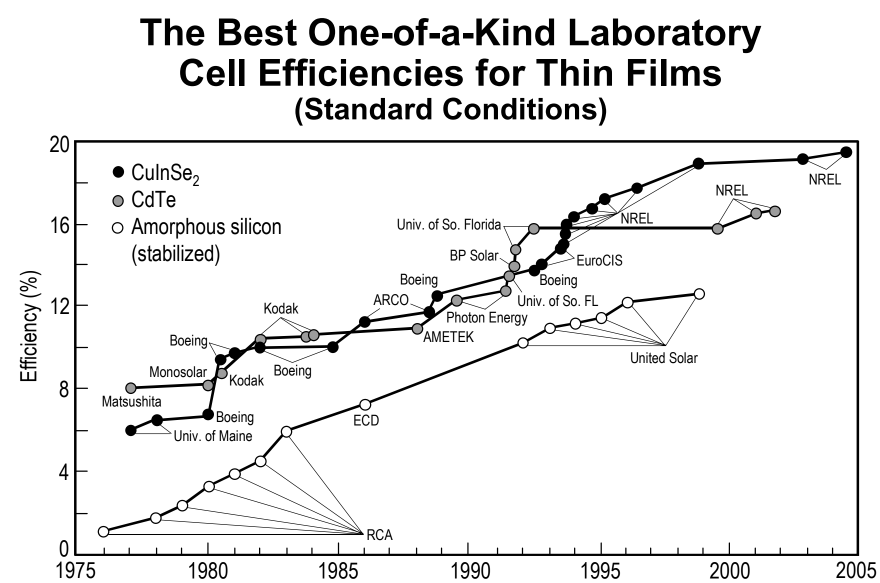

Fig. 1: Development of "champion" solar cell efficiencies. The progress made from about 1980 to 2000 is significant.

Table 1: Best Large-Area, Thin-Film Modules
(standard conditions, aperture-area)

Company	Device	Aperture Area (cm^2)	Efficiency (%)	Power (W)	Date
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
Global Solar	CIGS	7085	10.1*	71.2*	09/04
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

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manufacturing capacity), it is important that the upgrades will deliver the expected performance improvement. It appears that during the most recent years, the activities of the Thin Film Partnership's Technology Partners (Shell Solar – CIS, Global Solar – CIS, EPV – CIS, and First Solar – CdTe) focused on achieving progress via the first approach, optimizing for high yield and high performance while maintaining a chosen process. Significant progress was made, resulting in several megawatts of modules being sold (see Table 1 for "champion" module and Table 2 for commercial module performance).

To further boost its sales for power generation applications, Shell Solar announced development of an 80-W CIS module to better compete with crystalline Si modules that today have power ratings ≥55 W. EPV and ISET were qualifying and improving their new CIS deposition schemes (using "hybrid" vacuum deposition or nano-particle precursors, respectively). At the same time, NREL, through further adjustments to its established "3-stage" deposition process, achieved a new champion cell with an efficiency of 19.5%, slightly bettering the previous 19.3% record [1].

In 2004, First Solar established a "generation 2" manufacturing line that eliminates previous bottlenecks in module throughput. The new line is designed for producing 25 MW of CdTe modules annually and expected to be in full operation in 2005. Dr. Wu et. al. from NREL demonstrated the performance enhancements from using cadmium stannate (Cd_2SnO_4) transparent conductive oxide electrodes, in conjunction with tin zinc oxide ($ZnSnO_x$) buffer layers. Using these, the 16.5%-efficient champion CdTe cell was previously prepared [2]. New buffer layers were also evaluated in conjunction with commercially produced SnO_2 transparent conductive electrodes, demonstrating superior performance [3]. These processes appear to be the next logical step for implementation into manufacturing.

An important aspect of CdTe PV technology is to ensure long-term stability. Experimentally, cells or coupons from modules are tested, usually under 1-sun intensity illumination and open-circuit voltage conditions and a device temperature of about 65°C for thousands of hours. Degradation is typically observed to "stabilize" and can be minimized (in a few circumstances, there is no degradation, or even an improvement in performance after stressing), through optimized processing. Presently, it is not always clear to what degree changes in the device stability are due to details in cell design and to what degree effects like corrosion are the cause for degradation. However, published work by the Colorado State University group and unpublished work from First Solar have revealed that the details of the $CdCl_2$ treatment, essential for achieving good device performance, can indeed significantly affect the amount of observed degradation [4]. Until better understood, each change in cell or module process must also be evaluated for long-term stability. Past work has often focused on eliminating the Cu "doping" that is applied with many back-contacting recipes. However, recent work may suggest that rather than eliminating the Cu-content of the back contact, it may be more important to incorporate Cu in such a way as to not cause a stability problem [5]. CIS technology continues to experience "transients," i.e., after exposure of the modules to elevated temperatures in the dark, which happens to be the condition during the final module lamination process, module power may drop by up to ~20%, but this loss is restored with subsequent illumination during exposure [6], and has not been observed to lead to degradation in long-term outdoor exposure experiments.

The Thin Film Partnership has also initiated a program that investigates module reliability, durability, and module packaging (encapsulation) issues. This work is useful for identifying manufacturing defects arising from the module wiring and "package," and is now considered required to gain confidence that long-term performance can be guaranteed.

Table 2: Module Efficiency from Survey of Manufacturers' Websites and "Performance Ratios"

Eff. (%)	Module	Temp. Coeff. (%P/°C)	Technology	Performance Ratio champion cell-product
16.9	SunPower SPR210	na *('low')*	FZ-Si, sp. j.	16.9/24.7[7]= 68%
16.1	Sanyo HIP190BA2	-0.33	CZ-Si, "HIT" j.	16.1/24.7[7]= 65%
14.3	BP7180	-0.5	CZ-Si, sp. j.	14.3/24.7[7]= 58%
13.3	Kyocera KC187G	V_{OC}=-0.12	MC-Si, s.p.	13.3/21.2[8]= 63%
13.3	Shell Ultra175-P	-0.43	CZ-Si, s.p.	13.3/21.2[8]= 63%
13.0	RWESchott ASE-300-DGF/315	-0.47	EFG (ribbon) Si, s.p.	13.0/21.2[8]= 61%
12.8	Sharp ND-167-U1	na	MC-Si, s.p.	12.8/21.2[8]= 60%
11.5	GEPV-165M	*(up to)*-0.5	CZ-Si (Reclaimed), s.p.	11.5/21.2[8]= 54%
11.0	WürthSolar WS31050/80	-0.36	CIGS	11.0/19.5[1]= 56%
9.4	Shell Solar ST-40	-0.6	CIGSS	9.4%/19.5[1]= 48%
7.6	First Solar FS55	-0.25	CdTe	7.6/16.5[2]= 46%
6.4	Mitsubishi Heavy MA100	-0.2	a-Si, single-junction	6.4/10.0[9]= 64%
6.3	Uni-Solar US-64	*(-0.21)*	a-Si, triple-junction	6.7/12.1[7]= 52%

s.p. = "standard" diffused junction screen printed cells; sp.j. = cells employing alternative junctions ("HIT," point contacts, buried laser grooves)

PROJECTIONS OF FUTURE PERFORMANCE

A pragmatic method was developed for predicting future performance and potential market impact of all technologies.We sought to avoid comparing favorable projections for one PV technology with less favorable projections of another one. The method relies on comparing 2004 commercial product efficiency data with 2004 laboratory solar cell champion data to assess how thin-film PV technologies in the future may compete with the mainstream crystalline Si products. The first input to this method is derived from a survey of manufacturers' Web sites (shown in Table 2).

In column 5 of Table 2, we show the ratio of the current commercial performance (column 1 value) to the current champion cell performance of the respective PV technology, referring to such a relationship as c/c ratio. We note that the c/c ratio for various PV technologies varies between 46% and 68%. There seems to be a trend established that with manufacturing maturity the c/c ratio

Table 3: Projected Future Commercial Performance of Commercial Modules Made With Different PV Technologies, and Their Relative Performance and Relative Cost Performance

Technology	Future commercial module efficiency, based on 2004 technology knowledge (%)	Relative performance rating (Standard, s.p. silicon = 1)	Relative cost divided by relative performance (about proportional to future $/W_p$ module cost differences with standard crystalline Si) assuming 40% thin-film module cost advantage
Silicon (sp. j.)	19.8	1.18	0.85 (highly competitive)
Silicon (s.p.)	17.0	1.00	1.00
CIGS	15.6	0.92	0.65 (highly competitive)
CdTe	13.2	0.78	0.77 (highly competitive)
a-Si (1-j)	8.0	0.47	1.28 (not competitive)
a-Si (3-j)	9.7	0.57	1.05 (about the same)

s.p. = "standard" diffused junction screen-printed cells; sp. j. = cells employing alternative junctions ("HIT," point contacts, buried laser grooves) gradually increases, presumably because (1) champion cell improvements become harder, and (2) module efficiencies have time to catch up. However, even for crystalline Si, values >70% have not yet been obtained. Based on these trends, we assume that a c/c-ratio of 80% will likely be a reasonable figure to estimate the best future commercial module performance based on champion cell performance known today. Thus, in Table 3, we list expected future commercial product performance based on today's champion cell performance and a c/c ratio of 80%. In practice, we expect product performance to improve gradually from today's values as manufacturing processes are optimized. A value of 80% is our current best estimate of what could be achieved for a mature process after advanced process control schemes have been implemented into manufacturing. This methodology can be upgraded in the future once new champion cell performance is obtained, or when better commercial-product-based values for the cc ratios have been established.

The comparison of thin films and crystalline Si PV technology is further complicated by the fact that it is not clear what market share different Si technologies will attain in the future. In the past, Si PV "technology" was usually broken down by type of Si substrate. But, as Table 2 reveals, the Si wafer type (single-crystal, cast ingot, ribbon) has resulted in little differentiation regarding the performance of today's commercial product; rather, what matters is whether the cells are made by conventional processing (diffusing an emitter and collector and contacting the emitter with screen-printed finger grids, designated as 's.p.' in column 4) or by alternative junction-formation processes currently used only for limited product lines [10]. The latter "special junction" technologies are designated as 'sp. j.' in column 4 of Table 2. We express today's commercial performance as a ratio of today's champion cell performance for each specific technology, given in the last column of Table 2.

In the second column of Table 3, we estimate future commercial performance based on today's cell champion performance, *assuming a c/c ratio of 80% for all technologies*. These efficiency values of future CIS- and CdTe-based modules appear very reasonable when they are compared to aperture-area efficiencies already achieved for one-of-a-kind module prototypes shown in Table 1. The projected crystalline Si module efficiencies also look very reasonable, showing that a fair comparison is being made. The third column calculates a relative module performance ratio, using a value of 1.00 for standard (s.p.) crystalline Si module technology. The last column in this table calculates a projected cost ratio for these technologies. It assumes a 40% cost advantage for thin-film modules, based on the knowledge that in a crystalline Si module, typically 40% of the manufacturing costs are incurred by manufacturing the silicon wafer or ribbon required for manufacturing the solar cells. This is a component and materials cost minimized in thin-film modules. Hence, for the thin-film technologies, relative cost levels are reduced by multiplying the relative performance by 0.6, to account for the cost of wafers or ribbons eliminated, enabling a comparison based on a ratio of $\$/W_p$ module manufacturing cost. That is, the number in the final column should be approximately proportional to future cost differences between the technology options and the standard crystalline Si technology.

The 40% figure for thin films may be conservative, since calculations using existing estimates suggest it could be as high as 60% in some cases where thin-film capital costs are already low (e.g., for CdTe or some third-generation thin films). The reader can easily recalculate the projected cost comparison using a different cost-advantage percentage based on their own cost estimates. Other nuances are also possible (e.g., adding some cost disadvantage to the higher performance sp.j. crystalline Si approach; or assuming that a champion cell efficiency enhancement will occur faster in one technology than such progress may occur in the other technologies). One of the possible strengths of our approach is to figuratively wash our hands of these second-order perturbations and assume that they just average out. Thus, we are able to get a single final number (Table 3, far right column) with which to compare vastly different technologies.

Table 3 suggests that based on today's technology status and manufacturing know-how, future CIS and CdTe thin-film PV modules will be able to compete with future crystalline Si modules, even if crystalline silicon technology successfully transitions to higher cell efficiencies using cells manufactured with special-junction schemes. The future of a-Si may depend more on its special value in the building-integrated PV (BIPV) marketplace or on issues such as silicon feedstock availability. Third-generation thin films that might be even less efficient may have even greater problems making a sizable impact.

Lessons to be learned from this are that technology and demonstrated cell performance remain an important yardstick in determining commercial product potential. Unless stable laboratory cell efficiencies >12% are demonstrated, any existing or new thin-film PV technology has little chance of being a strong contributor in the mainstream power module PV markets. We believe that our analysis is valid for standard modules sold as a commodity. For BIPV products, low performance may constitute somewhat less of a penalty than for standard modules. On the other hand, it can be expected that market conditions (including the debit caused by the need to offset balance-of-systems costs with higher efficiencies) will be such that higher efficiency modules will command somewhat higher $\$/W_p$ prices.

Although people in the crystalline Si field have a quantitative understanding of how to go from standard screen-printed processes to high-efficiency special-junction devices, such information is not yet available for most thin-film technologies. Development of a better numerical understanding to be able to predict with much greater confidence how much a new thin-film layer, deposition process, or process optimization will contribute to enhanced future commercial product performance appears desirable, albeit difficult.

Based on performance increases observed in recent years, and investments for new manufacturing capacity made or announced, we project a rapid increase in the share of thin-film PV modules in U.S. PV module manufacturing. From a survey and estimation of the current manufacturers, which includes Uni-Solar making amorphous silicon roofing laminates, the following volumes were and are projected to be produced by U.S.-based manufacturers of thin-film PV modules. The result is shown in Fig. 2.

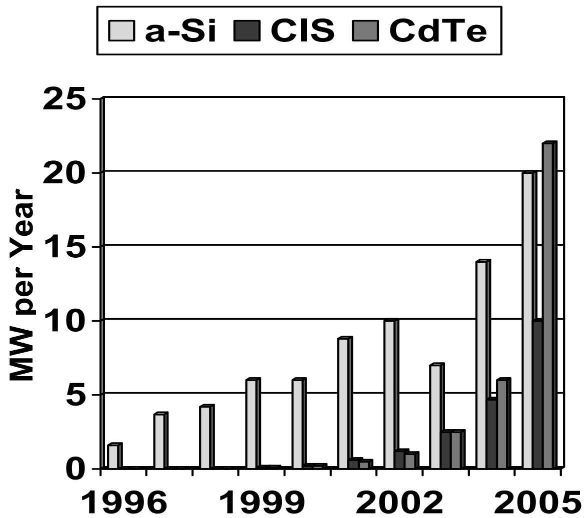

Fig. 2: Past and projected shipment of U.S.-produced thin film PV modules (MW_p per year).

This paper provides at top-down view on the comparison of different PV technologies, based on the actual status of today's commercial reality and established R&D achievements. Another top-down approach is to use the PV module learning curve and to add either a new slope or an entirely new line for thin-film technologies [11]. There are also many "bottom-up" studies on the cost of PV systems that have historically provided ambitious cost projections [12, 13]. At some time in the future, top-down and bottom-up cost estimates will have to approach each other. Presently, the bottom-up estimates make many assumptions about expected performance. Only after high-volume manufacturing has been implemented will it be known what performance levels can be obtained without compromising low-cost manufacturing techniques. A much better quantitative understanding of how process optimization and process changes will affect the performance of commercial modules would shorten the required development periods to achieve large-scale manufacturing of high-performance thin-film PV modules.

CONCLUSIONS

We showed how cell and prototype module efficiencies will likely remain important for all PV technologies, as they will be related to commercial product performance in future years.

Based on 2004 knowledge about the technologies, the performance of CIGS and CdTe modules should be high enough to allow them to be competitive with crystalline Si. This includes presumed progress in both thin-film and crystalline Si PV technologies.

Reliability and customer acceptance remain significant hurdles for thin-film PV to expand its market share. The NREL Thin Film Partnership has begun to address these issues as part of its programs.

Forecasting PV costs is not an idle matter, though some of the issues are much debated. Much of the future of PV as an energy-significant technology rests on meeting very ambitious cost goals. Establishing a set of approaches and being able to begin the process of comparing them is useful within this debate.

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