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Harnessing the Sun with Thin-Film Photovoltaics

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HARNESSING THE SUN WITH THIN-FILM PHOTOVOLTAICS

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ABSTRACT

Photovoltaic (PV) technologies have a substantial role in meeting electric power needs in the next century, especially with an expected competitive position compared to conventional power-generation and other renewable-energy technologies. Thin-film photovoltaic modules based on CdTe, $CuInSe_2$ or Si can potentially be produced by economical, high-volume manufacturing techniques, dramatically reducing component cost. However, the translation of laboratory thin-film technologies to first-time, large-scale manufacturing has been much more difficult than expected. This is due to the complexity of the processes involved for making large-area PV modules at high rates and with high yields, and compounded by the lack of a fundamental scientific and engineering base required to properly engineer and operate manufacturing equipment. In this paper, we discuss the need to develop diagnostics tools and associated predictive models that quantitatively assess processing conditions and product properties. Incorporation of the diagnostic sensors into both laboratory reactors and manufacturing facilities will (1) underpin the development of solar cells with improved efficiency, and (2) accelerate the scale-up process through intelligent process-control schemes. "Next-generation" high-performance (e.g., >25% conversion efficiency) thin-film PV modules will also be assessed, along with critical issues associated with their development.

INTRODUCTION

Electric power is the engine that drives a technology-based society. As the demand for more electric power increases and present power plants reach end-of-life, the need for environmental benign means of generating electricity becomes an imperative. It can be argued that conversion of sunlight directly to electricity using photovoltaics is the only means of generating electricity without changes to the environment because the only fuel consumed is external to the Earth. Photovoltaic technologies are still in their infancy, but have the potential to play an important role in meeting electric power needs in the next century, provided that PV systems can be made competitive (considering cost and value) with conventional power generation and other emerging renewable energy technologies. Further, in the next 20 to 50 years, PV can be expected to play a significant role in the reduction of "green house gases" if the manufacturing capacity can be greatly expanded.

Presently, the annual electricity generated worldwide is ~15,000 TWh (1.5 X 10^{16} Wh) and the installed capacity is about 3500 GW [1]. The contribution by PV is small with an installed capacity of 0.95 GW and manufacturing capability of producing ~0.2 GW per year as of 1998. In 1998, the worldwide module shipments were >150 MW. In the last 5 years alone, the world PV module sales have increased by some 82MW, with an average annual growth in excess of 20%. Since 1995, the U.S. portion of the world module market has been declining slightly, to its 1998 market share of 35.4% (53.7 MW).

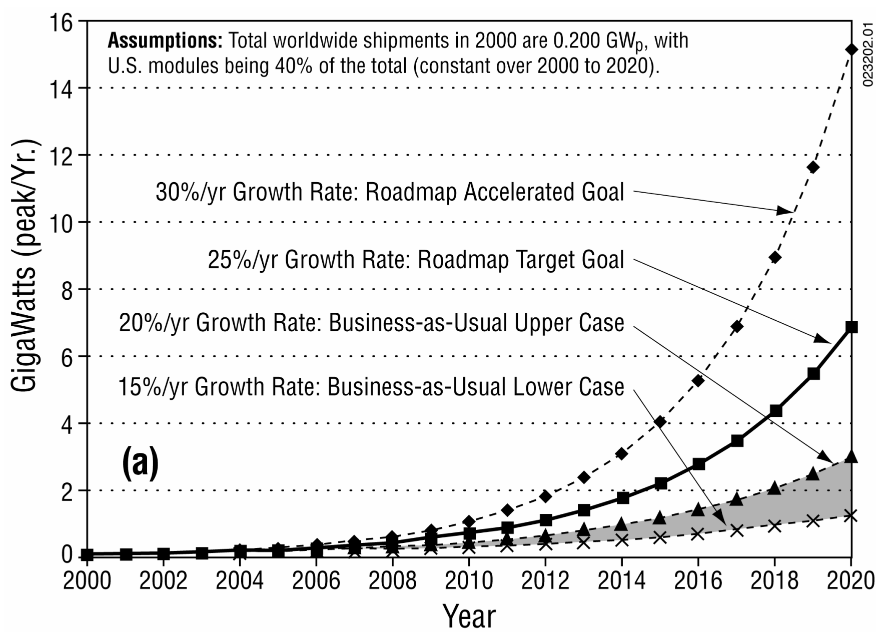

Fig. 1. Growth curves, showing shipments in GW_p as a function of time, for various annualized growth rates. (Taken from "The Industry Developed PV Roadmap", 1999.)

For the potential of PV to be realized, the introduction of new manufacturing facilities needs to be accelerated while reducing the cost to be a competitive level with other energy sources. Recognizing these needs, and the growing foreign interests in this research and technology, the U.S. PV industry is developing "The PV Industry Roadmap"—a guide to research, manufacturing, equipment, markets, and policy through the year 2020 and beyond. This roadmap suggests a 25% growth in the U.S. PV shipments, shown in Fig. 1. For comparison, the business as usual (15-20% annual growth) and accelerated (30%) scenarios are also represented. The goal is to have 3.2 MW (or about 15%) of the new U.S. electrical generation capacity provided by PV in the year 2020. This represents about 50% of the US sales in that year. The cumulative module shipments to the domestic markets would be at least 30 GW over the 2000-2020 timeframe.

With that stated, it is important to identify where we are and what potential areas of technological investments exist. Present-day crystalline-Si technology is quickly approaching its limit in terms of production costs. The thin-film technologies are in a premanufacturing development path with several amorphous silicon (a-Si), CdTe, and $CuInSe_2$ plants in start-up phases. Unlike for crystalline Si, equipment for the thin-film technologies is largely unique and custom designed. In addition, the processes involved for making large-area, high-volume, thin-film PV modules are very complex. As a result, the translation of the laboratory results to large-scale manufacturing has been much more difficult than expected. The situation is further compounded by a lack of the fundamental scientific and engineering base required to properly engineer and operate manufacturing equipment. The larger the manufacturing line, the greater the complexity—and, hence, the higher the start-up costs.

In this paper, we discuss ways to accelerate the transition of thin-film PV technologies from laboratory results to manufacturing scales and discuss the potential for some viable "next generation" thin-film technologies.

POTENTIAL OF PHOTOVOLTAICS

To provide a perspective on the potential of PV for converting sunlight to electricity, it is interesting to compare thermodynamic and predicted (calculated) limits of efficiency with present-day device performance. In Fig. 2, the best *single-junction* cell results are compared to the maximum-achievable efficiency for both AMO and AM1.5 solar spectra, and for the black-body limit. Single-crystal solar cells have reached more than 90% of their ultimate performance, while the best thin-film devices are typically 55%-65% of their ultimate performance. The single crystal solar cells provide a benchmark limit for the thin-film devices. For most thin-film technologies, laboratory cells have only demonstrated about 75% of their potential based upon "best" cell parameters (V_{oc}, J_{sc}, FF). (Note: Some device modeling suggests that the attainable limits for these thin-film and polycrystalline cells are 80%-90% of the predicted AM1.5 limits shown in Fig. 2. Even this leaves a substantial gap for improvement.)

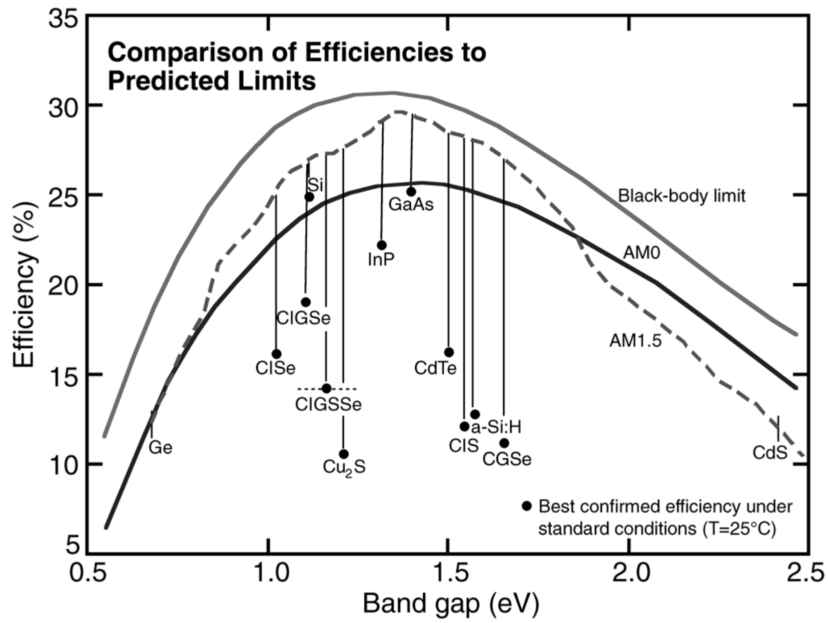

Fig. 2. Calculated AM1.5 efficiencies (dashed line) and AM0 efficiencies (solid line), comparing achieved cell efficiencies (laboratory-best, confirmed) for various technologies with these predictions. Also included is the black-body limits as a function of the semiconductor bandgap.

THIN FILM TECHNOLOGIES AND PROCESS SCALE-UP

Because of their huge potential to reduce the cost of PV electricity, thin-film PV modules have been investigated, pursued, analyzed, evaluated, and manufactured for more than 20 years. Presently, several manufacturing facilities in the 1-to-10 MW range based on a-Si, CdTe and $CuInSe_2$ technologies are in the start-up stage. There are only limited modules commercially available based on these materials. A critical issue in developing these thin-film facilities has been the limited scientific and engineering basis available to effectively and rapidly scale up laboratory processes. In most cases there are no quantitative relationships among critical process parameters, film growth, and properties to device performance.

For PV to play an important role in generating electricity in the next century, efficient manufacturing facilities in excess of 100-MW capacity are anticipated and predicted. To give a perspective, a 100-MW facility requires a throughput rate of approximately five to six, 50-W modules per minute, assuming three shifts with reasonable maintenance and downtime. Further, a monolithically integrated module is a moderately complex structure requiring a uniform electronic device sized in square meters. Figure 3 illustrates the cross section of such a module.

There are at least eight processing steps required to produce the module: (1) substrate preparation; (2) first contact; (3) first scribe; (4) semiconductor layer, which is typically several steps, depending on the materials; (5) second scribe; (6) second contact; (7) third scribe; and (8) external contacts. This is subsequently followed by an encapsulation process. A 99% yield at each processing step results in an overall process yield of 92%, while 98% yield per process results in an 85% overall yield. It also should be noted that, due to losses, the eventual cost depends critically on the processing stage.

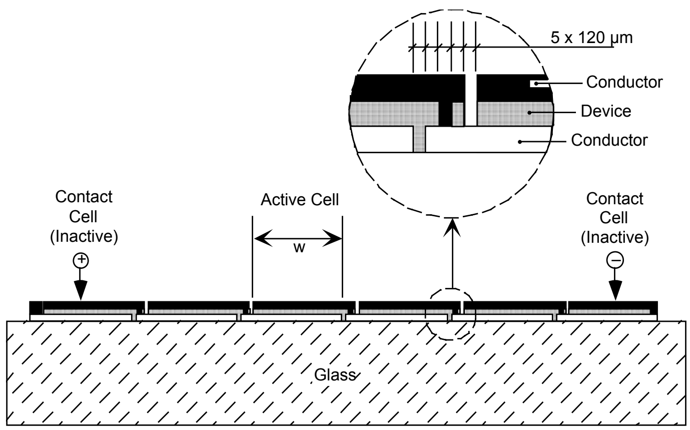

Fig. 3. Cross section of thin-film module, showing interconnection scheme.

A critical requirement for the development of the science and engineering basis needed to effectively and rapidly scale up is the development of diagnostics tools and associated predictive models that quantitatively assess processing conditions and product properties. Incorporation of the diagnostic sensors into both laboratory reactors and manufacturing systems will: (1) underpin the development of solar cells with improved efficiency and (2) accelerate the scale-up process through intelligent process-control schemes. Further in-situ diagnostics tools are also needed for both process and product quality controls. Currently, diagnostic capabilities required for manufacturing are in their infancy, and most manufacturers assess their product only after completion of the module—a stage too late.

Greater use of diagnostics and understanding of manufacturing processes will also improve industry's long-term research capability. Diagnostics will assist in the understanding of thin-film semiconductor growth process, and its dynamics, leading to investigations of alternative processes and chemistries for film fabrication. Diagnostics will improve the process modeling, leading to a more efficient design of manufacturing systems required to further lower the cost of PV modules.

“NEXT GENERATION” TECHNOLOGY

PV can make a significant contribution to the energy supply and to an improved environment in the 21st century, but will require modules with higher performance. We now discuss and evaluate one option in this high-performance PV portfolio—multijunction modules, which have the potential for the highest conversion performance. De Vos[1] has determined the thermodynamic limits of efficiency for solar cells with one to infinite junctions, based on an ideal diode with only radiative recombination between the conduction band and valance band for blackbody radiation. The results are summarized in Table I for unconcentrated sunlight, and the one-junction calculation is also included in Fig. 2. As the number of junctions increases from 1 to infinity, the thermal loss due to absorption of light with energy greater than E_g goes to zero, resulting in a thermodynamic performance limit of 68%. In Table II, the best efficiency for present-day multijunction solar cells is compared to the thermodynamic limit. Based on this, its reasonable to predict that III-V single-crystal multijunction solar cells with conversion efficiencies of near 40% and thin-film multijunction solar cells of more than 25% should be achievable during the next 10 years. However, the real question will be: Can the increased complexity in fabricating these high-performance devices be cost effective when translated to commercial high-performance modules?

Table I. Thermodynamic Efficiency Limits, Unconcentrated Sunlight [2]

# of Junctions	Efficiency	E_g (eV)
1	30%	1.3
2	42%	1.9 - 1.0
3	49%	2.3 - 1.4 - 0.8
4	53%	2.6 - 1.8 - 1.2 - 0.8
infinity	68%	

Table II. Solar Cell Efficiency Records, Unconcentrated Sunlight

Multijunction Solar Cells			
GaInP/GaAS (monolithic)	30.3%	Japan	70% (Ref. 3)
GaAs/$CuInSe_2$ (4-terminal)	25.8%	Kopin/Boeing	60% (Ref. 4)
a-Si/$CuInSe_2$ (4-terminal)	14.6%	ARCO	35% (Ref. 5)
a-Si/a-Si/a-SiGe (monolithic)	13.5%	USSC	30% (Ref. 6)

Current thin-film technologies can be separated into two categories: multijunction a-Si-based modules and single-junction polycrystalline modules. The multijunction a-Si device structure was developed to provide an engineering solution to a fundamental stability issue with a-Si materials. The best laboratory device is a three-junction cell with a stabilized efficiency of 12.7% [7]. Although a-Si-based materials can be made with E_g from 1 to 2 eV, it is difficult to project significant improvements in performance without a major breakthrough in the fundamental properties of the materials. In the polycrystalline thin films, CdTe-based solar cells have achieved a single-junction efficiency of ~16%.[8] The bandgap of CdTe is 1.5 eV, however after processing into a CdS/CdTe solar cell, the bandgap is reduced to approximately 1.4 eV (due to diffusion of sulfur into the CdTe).

Thus, CdTe solar cells would be appropriate for the middle cell of a triple-junction device. Although the bandgap of CdTe can be controlled by alloying with other II-VI materials, to date, there has been limited success at controlling the band gap.

$CuInSe_2$-based solar cells have achieved a single-junction efficiency of 18.8% [9], comparable to that of the best multicrystalline silicon devices of 19.8% [10]. Thus, they are a real alternative to crystalline-silicon technologies. The $CuInSe_2$-based materials can be compared to the III-V materials in that there is a set of ternary compounds that forms a continuous solid solution. In this solution, E_g can be varied from 1 to 2.7 eV for the Cu-based chalcopyrite and from 0.6 to 3.1 eV for the Ag-based materials (as summarized in Table III).

Table III. Candidates for Quaternary Alloys

Low Bandgap		High Bandgap	
Material	eV	Material	eV
$CuInSe_2$	1.0	$CuAlSe_2$	2.71
$CuInTe_2$	1.0 - 1.15	$CuInS_2$	1.53
$CuInTe_2$	1.0 - 1.1	$CuAlTe_2$	2.06
$CuGaTe_2$	1.23	$CuAlTe_2$	2.06
$CuGaTe_2$	1.23	$CuGaSe_2$	1.7
$CuGaTe_2$	1.23	$CuGaS_2$	2.5
$AgInSe_2$	1.2	$AgGaSe_2$	1.8
$AgInSe_2$	1.2	$AgAlSe_2$	1.66
$AgInSe_2$	1.2	$AgInS_2$	1.8
$AgGaTe_2$	1.1 - 1.3	$AgGaSe_2$	1.8
$AgGaTe_2$	1.1 - 1.3	$AgGaS_2$	2.55
$AgAlTe_2$	0.56	$AgAlS_2$	3.13

This set of materials provides a starting and design basis for developing multijunction thin-film polycrystalline solar cells. High-performance, low-E_g cells have been demonstrated, and continuous progress with wider-bandgap materials have been made. The critical issues that need to be addressed for a tandem-cell structure are: (1) development of wide-E_g materials (1.5 to 1.8 eV) for the top cell, with efficiencies exceeding 15%; (2) compatibility of the bottom cell to the growth process needed for the top cell; and (3) an effective transparent interconnect between top and bottom cells. These issues include a myriad of nontrivial scientific and technical problems, many of which interrelate and interact in the device realization. However, the PV technology has advanced to the point that these more complex devices should be considered—especially with their potential place in the coming generation of photovoltaic devices.

CONCLUSIONS

Thin-film photovoltaics can harness the sun—provided the important fundamental science and engineering base is developed, and the introduction of new manufacturing capacity is accelerated. Further, next-generation thin-film technologies, using multijunction devices configurations will be needed if PV is to be an important contributor to environmental, national-interest, and energy-security priorities. To be successful, diagnostics and quantitative processing models are needed both in the laboratory and in manufacturing facilities.

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