RECEIVED
NOV 15 1993
OSTI
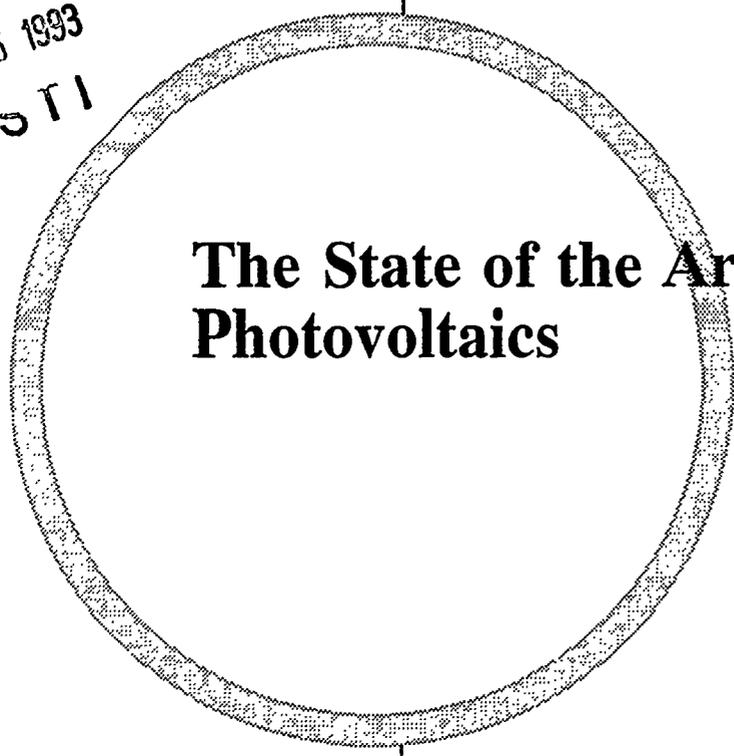
The State of the Art of Thin-Film Photovoltaics

T. Surek
Presented at the
K. W. Böer Solar Energy Medal of Merit
Award Ceremony
University of Delaware
Newark, Delaware
February 16, 1993

◆NREL

MASTER

NOTICE

DISCLAIMER

Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.

The State of the Art of Thin-Film Photovoltaics

Thomas Surek
National Renewable Energy Laboratory
Golden, Colorado 80401, USA

Abstract

Thin-film photovoltaic technologies, based on materials such as amorphous or polycrystalline silicon, copper indium diselenide, cadmium telluride, and gallium arsenide, offer the potential for significantly reducing the cost of electricity generated by photovoltaics. The significant progress in the technologies, from the laboratory to the marketplace, is reviewed. The common concerns and questions raised about thin films are addressed. Based on the progress to date and the potential of these technologies, along with continuing investments by the private sector to commercialize the technologies, one can conclude that thin-film PV will provide a competitive alternative for large-scale power generation in the future.

1. Introduction

Photovoltaics (PV) is a semiconductor technology that directly converts sunlight to electricity. PV does this without pollution, noise, or moving parts, except for the sun trackers that are used in some systems. The fuel for PV, sunlight, is freely available and abundant; in the U.S., the total sunlight received in a year is about 2.4×10^{16} kWh, more than 10,000 times our annual use of electricity [1]. While the amount of sunlight varies with latitude and climate, the difference between the sunniest parts of the U.S. (the desert Southwest) and some of the cloudiest (the East and Northwest) is only about a factor of two: This implies that the cost of PV-generated electricity will vary by a factor of about two; this is less than the variation in electricity rates across the U.S. Another advantage of PV is its modularity. Systems can be designed from a few watts (or even milliwatts in the case of consumer products powered by indoor lighting) to many megawatts. This modularity, along with the fairly rapid construction times for photovoltaic systems (typically less than 1 year for multi-megawatt systems), allows the user, such as a utility, to add PV rapidly in the increments needed to generate power.

The first practical application for PV was to power satellites in the U.S. space program. The attractiveness of PV for space power is its reliability and high power-to-weight ratio. For these reasons, there is an important and growing market for PV to provide power for satellites for applications ranging from communications to weather to the military. The impetus for terrestrial PV came about as a result of the energy crises of the 1970s. This resulted in a U.S. national program (as well as other programs in developed countries) to lower the cost of PV-generated electricity. The result of nearly 20 years of research and development (R&D), at a cost of some $1.2 billion to the U.S. government (through the Department of Energy [DOE] and its predecessors) and the investment of more than $2 billion by the private sector in the U.S., has been a reduction in PV costs of more than twenty-fold. Today, PV-generated electricity costs about 30 to 50 cents/kWh depending on system size and application. Photovoltaic systems have proven to be reliable, and there is a growing market worldwide and a PV industry to supply products to these markets (Table 1). Another important result of the R&D is that new PV technologies have evolved, based on innovative ways of conserving crystalline silicon materials (today's workhorse in the PV industry and markets), new thin-film materials, and concentrator systems, which hold the promise of further significant cost reductions for photovoltaic systems.

The cost of PV-generated electricity, in fact, remains the single major barrier to its widespread utilization. The genesis of thin-film PV, including the efforts of early pioneers such as Karl W. Boer, is undoubtedly the result of attempts to address, from the outset, the cost issue in PV. The vision of researchers in thin-film PV has constantly focused on "cost," with the following objectives:

- to find semiconductor materials that can absorb sunlight in very thin layers (about 1 micron versus the several hundred microns used in crystalline silicon) — the thinner layers should result in lower material costs;

- to be able to deposit the thin films on readily available low-cost substrates, such as glass, plastic or metal foil;

- to be able to deposit the thin films by simple, scalable processes — the thinner layers should result in faster processes and lower capital costs;

- to be able to fabricate entire modules (i.e., inter-connected solar cells) during the processes of film deposition and, hence, to reduce handling costs; and, finally,

- to be able to convert sunlight efficiently to electricity while meeting the above cost-related objectives.

The work of the past 20 years has, to a large extent, turned this vision into reality. Several semiconductor materials and related alloy films (e.g., amorphous silicon, thin-film polycrystalline silicon, cadmium telluride, copper indium diselenide, and gallium arsenide) can be deposited on low-cost substrates (ranging from soda-lime glass to stainless steel) using a variety of scalable, potentially low-cost deposition processes (ranging from sophisticated vacuum-based techniques to simple wet chemical processes to heating in air). Entire modules (in sizes greater than 1 m^2) can be fabricated during the deposition process by simply scribing the thin films between deposition steps, with sunlight-to-electricity conversion efficiencies that are reasonably high and continually improving.

This paper reviews the state of the art of thin-film PV technologies. Section 2 presents a brief over-view of the various thin-film materials and approaches, including the key research issues. A brief review of crystalline silicon technologies is provided to set the framework for the thin-film discussions. The discussion in Section 3 takes a different approach to reviewing the progress and issues in thin-film PV. Rather than simply extolling the advantages of and progress in thin films, as usually presented by proponents of the technologies, the discussion examines the questions and apprehensions that are often raised by skeptics of thin-film PV technologies.

2. Overview of Thin-Film Technologies

The selection of suitable thin-film materials for PV applications is based on a number of factors involving optical, electrical, and chemical properties (light absorption, band gap, resistivity, defects, doping, carrier mobility, etc.) in addition to the ability to deposit films with suitable physical properties (thickness, uniformity and continuity, grain size and morphology, etc.) in a potentially low-cost manner. Other important considerations include the ability to fabricate suitable device structures (junction formation and contacting) and the stability and reliability of the materials and devices under exposure to sunlight and the environment. Over the years, several candidate thin-film materials (e.g., copper sulphide) were examined and ultimately rejected from further consideration. Five groups of thin-film materials have emerged as leading candidates and are receiving support both in federal government programs and through private sector investments. A brief review of these materials is presented below; there are many excellent overviews of the status and prospects of these technologies in the literature [1-10].

Crystalline Silicon: Thick Film and Thin Film

It is important to review briefly the status of crystalline silicon (x-Si)-based PV technologies since x-Si modules dominate today's PV markets. The status and progress in x-Si provides an important context for the current and future development of all thin-

2

film technologies. Most x-Si modules are fabricated from silicon wafers that are sliced from single-crystal ingots grown by the Czochralski technique or from polycrystalline ingots that are cast in a graphite or quartz crucible (these are sometimes referred to as "thick-film" silicon technologies). Both ingot growth techniques require relatively large amounts of energy to melt the silicon charge, and the wafering results in a loss of some 70% of the silicon material (kerf loss). The resulting wafers are several hundreds of microns thick, far greater than is necessary or useful for efficient silicon solar cells. The thinning and handling of the wafers, and the requirement to interconnect individual wafers in modules, are additional cost elements in these ingot-based technologies. In spite of these shortcomings, significant advances are being made in improving the energy efficiency and cost of the growth techniques; reducing the cost and material losses in wafering by techniques such as unidirectional wire saws; improving cell efficiencies by advanced cell designs, metallizations, and surface treatments for light trapping; and automation of the cell and module fabrication sequences for higher productivity and yield. The net result to date of these improvements is that x-Si modules are being sold for about $4 per peak watt ($W_p$). Industry projections are that, with further improvements and scale-up, manufacturing costs of less than $2/$W_p$ can be realized.

Over the past 20 years, significant efforts have been expanded by the private sector and by the government R&D programs to reduce the cost of x-Si PV by growing or depositing the silicon material in a sheet or film form. Sheet (or ribbon) growth techniques, such as edge-defined film-fed growth (EFG) or dendritic web growth, typically result in 200 to 400-micron-thick material that is then cut into the appropriate size for solar cells (typically 100 cm^2). In Mobil Solar Energy Corporation's EFG process, an octagon-shaped, thin-walled tube (approximately 10 cm on a side and 300 microns thick) is grown to lengths of about 5 m; silicon wafers are obtained by cutting the tube with a laser. Texas Instruments (TI) recently announced the development of prototype modules of 9.1% efficiency based on their Spheral Solar^{TM} silicon approach [11]. The basic objectives in these thick-film, sheet-based approaches, including that of TI, are to reduce the energy needed

for the crystal growth process and to eliminate the costly wafering and attendant material losses inherent in the ingot growth techniques.

In thin-film silicon approaches, the silicon film (mostly polycrystalline) is grown or deposited on some suitable low-cost substrate. Further cost savings over the sheet growth techniques can be realized here since 100 microns of silicon are sufficient to absorb more than 90% of the sunlight. The film thickness can be further reduced (to perhaps 20 to 30 microns) by appropriate light trapping and device designs. Several deposition techniques (e.g., physical and chemical vapor deposition [PVD and CVD], electrodeposition, solution growth, laser ablation, melt coating) have been researched over the years to deposit films on low-cost substrates ranging from metals (e.g., steel and aluminum) to graphite to ceramics (e.g., alumina). Invariably, the efficiency of the solar cells was low as a result of small grain sizes and impurities resulting from interactions with the substrate. There is a current resurgence of interest in thin-film polycrystalline silicon as a result of AstroPower's development of their Silicon-Film^{TM} solar cell [12]. In AstroPower's proprietary process, a thin polycrystalline silicon layer is deposited on a low-cost substrate. This is the only thin-film silicon approach that has entered the commercial development phase to date. AstroPower is fabricating 225-cm^2 solar cells, the largest x-Si cells to date, and installed 15 kW of prototype module product at Virginia Power in April 1993 as part of DOE's PV for Utility-Scale Applications (PVUSA) project. The continuing interest in developing crystalline silicon-based PV technologies is driven by the abundance of the material and the proven reliability of x-Si PV modules and their acceptance in the marketplace.

Amorphous Silicon

Hydrogenated amorphous silicon (a-Si:H) and related materials that include amorphous alloys with germanium and carbon (a-Si,Ge:H and a-Si,C:H) have been the most researched of the thin-film materials to date. With an ongoing interest worldwide in the fundamental nature of amorphous materials, there is a large infrastructure of university researchers looking at various basic aspects of these

3

materials. Private-sector investment in these amorphous silicon (a-Si) materials has been spurred not just by the potential use of these materials in PV, but by a significantly greater existing market for these materials in other optoelectronic applications (xerography, flat panel displays, etc.).

While several approaches to deposit a-Si materials were (and are being) researched, the predominant approach today is some form of plasma-enhanced chemical vapor deposition (PECVD) (or glow-discharge method). The scalability of the glow-discharge method has been amply demonstrated with module areas in excess of 1 m^2. Suitable substrates include glass, stainless steel, and various plastics (e.g., polyimide), with the latter two substrates used in a continuous, roll-to-roll configuration (over 600 m in the case of stainless steel). A major impediment to more rapid development of a-Si PV is an inherent light-induced degradation of the materials and devices, the so-called Staebler-Wronski effect. This degradation results in a decrease in conversion efficiency during the first few weeks of exposure to sunlight, after which the efficiency remains essentially stable. A significant portion of the fundamental studies in a-Si is aimed at understanding and resolving this light-induced instability. Two practical solutions to the instability problem have evolved: (i) by depositing thinner absorber layers, there is less degradation; and (ii) by depositing several absorber layers in series (i.e., multijunctions), the efficiency of light absorption, hence the conversion efficiency, can be increased. Such dual- and triple-junction device configurations (e.g., a-Si/a-Si, a-Si/a-SiGe, a-Si/a-Si/a-SiGe, a-SiC/a-Si/a-SiGe) have resulted in initial efficiencies of 12% to 13% in laboratory-size *solar cells* (typically 1-cm^2 area), with demonstrated stabilized efficiencies of over 10%. Stabilized efficiencies of *submodules* (approximately 0.1-m^2 area) are near 9%, while commercial-size power *modules* (typically 0.3-m^2 or larger in area) stabilize in the 6% to 7% range. Figure 1 shows the results of recent light-soaking tests carried out at the National Renewable Energy Laboratory (NREL) on seven groups of submodules from different manufacturers [13].

Worldwide, some 17 companies are in various stages of commercial development of a-Si for PV
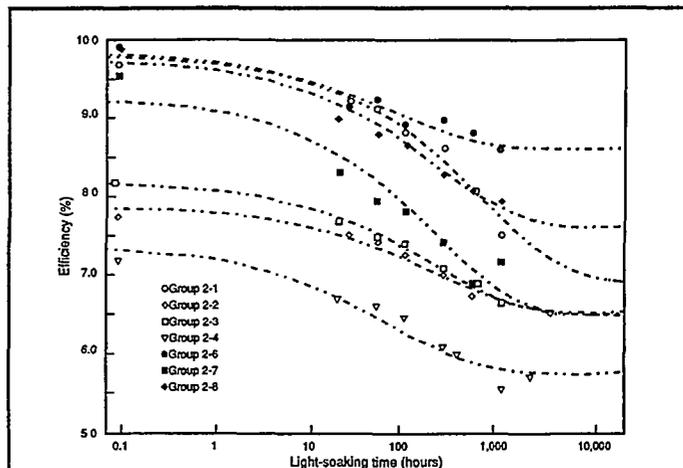

Fig. 1: Results of recent light-soaking tests at NREL on multijunction amorphous silicon modules (see Ref. [13])

applications; there are seven companies in the United States (see Table 1). The predominant market for a-Si PV, pursued mostly by the Japanese companies, has been to provide power for various consumer products (watches, calculators, etc.) that require only small amounts of power and are used

PV Module Manufacturers—World and U.S.

	Number of Companies* World	U.S.	1992 MW Shipped
Crystalline silicon	30	7	42.0
Amorphous silicon	17	7	14.8
Cadmium telluride	5	3	1.0
Copper indium diselenide	7	5	—
Concentrators	10	10	0.1
Totals	**69**	**32**	**57.9**

*Includes companies developing prototype modules

Table 1: PV Module Manufacturers — World and U.S. (after PV Energy Systems, Inc.)

mainly under indoor lighting. The recent advances in stabilized module efficiencies, along with the scale-up in a-Si manufacturing facilities discussed below, should result in increasing penetration of a-Si modules into the PV power markets.

Cadmium Telluride

Cadmium telluride (CdTe) has nearly the optimum band gap for a high-efficiency solar cell. This feature has led to interest by the research community in developing high-efficiency thin-film devices and

4

to development efforts by the private sector to commercialize the technology. Through these efforts, several potentially low-cost approaches have been demonstrated, including electrodeposition, close-spaced sublimation, sputtering, screen printing, metalorganic CVD, evaporation, and various wet chemical methods. To date, some 15 different groups worldwide used a variety of approaches for depositing thin-film CdTe to achieve greater than 10%-efficient solar cells. Although there were several efforts in the early 1980s to scale-up the processes, only one company (Matsushita Battery in Japan, using screen printing) introduced a PV product. Today, some 1 MW of small CdTe modules are made by this method for consumer products, mostly calculators (see Table 1).

Efficiency achievements in CdTe during the recent past (1991-1992) have been exceptional, with researchers at the University of South Florida achieving 15.8% efficiency [14]. These unprecedented advancements are paralleled by the rapid developments by industry to scale up the technology. In the U.S., two companies have developed prototype CdTe modules in pilot-scale production: Solar Cells, Inc. (SCI), in Toledo, Ohio (using close-spaced sublimation) and Golden Photon, Inc. in Golden, Colorado (using wet chemical processes developed by the predecessor company, Photon Energy). After only a 2-year development effort, SCI recently fielded a 1-kW experimental system at their facility (Fig. 2).

The reliability of CdTe modules remains a cause for concern. Although there does not appear to be an inherent degradation, such as the light-induced instability in a-Si, CdTe modules have been seen to degrade if they are not properly encapsulated. Additionally, some CdTe contacts (e.g., gold and gold/copper) are known to be unstable. Outdoor tests at NREL over the past 4 years have shown mixed results. Some encapsulation and contacting schemes have shown good stability, while others have been less reliable. The recent SCI modules have passed the NREL qualification tests for thin-film modules [15]. The other common concern with CdTe modules —the perceived risks of cadmium — will be addressed in the next section. In addition to the reliability issue, which will ultimately be ad-
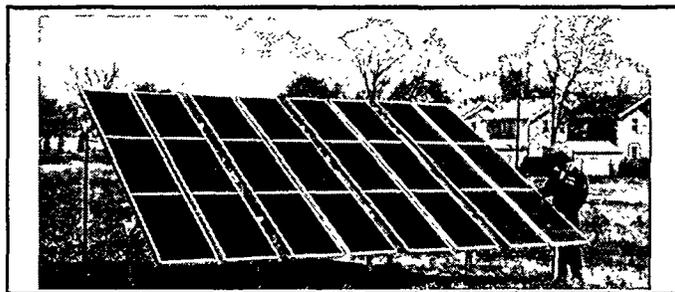

Fig. 2: 1-kW array of CdTe modules installed near the Solar Cells, Inc., facility, Toledo, Ohio (courtesy of Solar Cells, Inc.).

dressed as part of the broader module manufacturing issues, research activities in CdTe focus on the stability of contacts, improving the CdS window layers, understanding of doping and defect complexes, and the role of heat treatments on film chemistry and grain morphology.

Copper Indium Diselenide

Copper indium diselenide ($CuInSe_2$ or CIS) was the first of the new thin-film materials (after silicon and GaAs) to demonstrate a 10%-efficient solar cell. The early demonstration of device stability, along with continuing improvements in laboratory cell efficiencies, has attracted the interest of researchers and industry in CIS-based PV technologies. At the recent IEEE Photovoltaic Specialists Conference, a record 16.9% active-area efficiency device was announced by a consortium of European researchers, EUROCIS [16]. NREL has verified a total-area efficiency of 13.7% for a CIS device fabricated by Boeing. Much of today's research to achieve higher efficiencies is centered on the use of alloys, either by substituting sulphur for selenium or gallium for indium. Such alloying allows researchers to increase the bandgap of CIS from its 1.0-eV value in the unalloyed material. Improvement and/or replacement of the CdS window material is another subject area of active research. In-house research at NREL focuses on layered structures of the alloys and on developing a simplified, universal process for the fabrication of CIS-based cells [17].

To date, high efficiency devices have been fabricated by PVD of the constituent elements or by selenization of the metal precursors (Cu,In) in hydrogen selenide (H_2Se). Other variants of the selenization process have also evolved with the aim to avoid using toxic H_2Se. All these techniques

5

Module Outdoor Stability
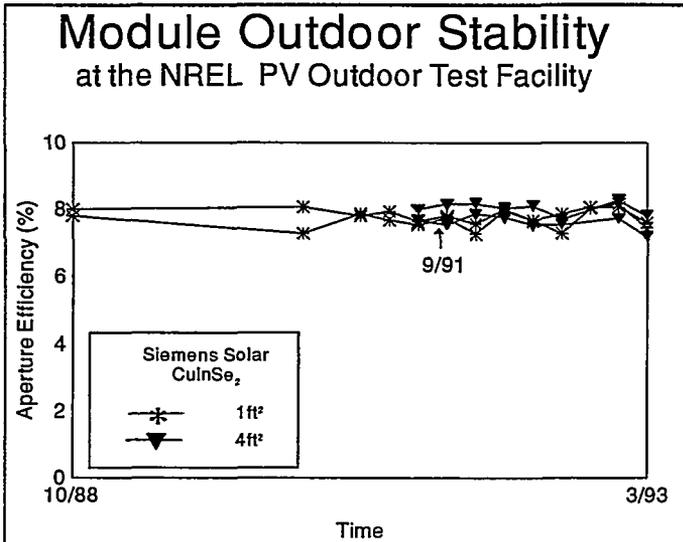### at the NREL PV Outdoor Test Facility

Fig. 3: Module outdoor stability results on copper indium diselenide modules tested at NREL

have demonstrated the scalability of the processes, at least to submodule sizes. The current unchallenged leader in CIS technology is Siemens Solar Industries (SSI), formerly ARCO Solar, but several companies are now pursuing CIS technology (see Table 1). ARCO Solar achieved a 0.1-m^2 submodule efficiency of 11.2% in 1988; SSI followed this with a 9.7%-efficient, 0.4-m^2-area module prototype in 1991. The latter accomplishment represents the highest efficiency known for a thin-film power module. Another significant result is the stability of CIS modules based on more than 4 years of outdoor tests at NREL (Fig. 3). Within experimental error, there has been little or no degradation of the modules tested to date.

In spite of these accomplishments, projections of CIS's low-cost potential, and contrary to earlier expectations, there are no commercially available CIS modules today. SSI's own analysis of the technology [18] indicates that commercial viability requires further efforts on manufacturability issues such as process yield, reproducibility, and predictability. Achievement of low-cost manufacturing of CIS-based modules will require improvement of materials utilization, process simplification, scale-up to larger-area substrates, increased process speed, and elimination of hazardous materials in processing and the module product [18].

Gallium Arsenide

Gallium arsenide (GaAs), like CdTe, possesses a nearly ideal band gap for high conversion efficiency. But unlike CdTe, high-efficiency GaAs devices have been fabricated only on single-crystal films; these require the use of high-quality substrates (single-crystal GaAs, germanium, and silicon wafers have been used successfully). Polycrystalline GaAs devices of 10% efficiency have been fabricated on films grown on graphite substrates. An innovative approach to reusing GaAs substrates is the CLEFT (cleavage of lateral epitaxial films for transfer) process. In this process, large area (up to 7.5-cm diameter) films of GaAs, approximately 5 microns in thickness, are cleaved from the single-crystal substrate after the device is fabricated. The substrate can then be reused. Solar cells of 23.3% efficiency (4-cm^2 area) and a mini-submodule of 21% efficiency (16-cm^2 area, with four interconnected CLEFT cells) have been fabricated. While this approach and others, such as GaAs-on-silicon, offer the promise of greater than 20%-efficient flat-plate modules, significant questions remain regarding the scalability and automation of these approaches to produce large-area modules. At least for the near term, it appears that GaAs-based solar cells will be used primarily in space power markets and possibly in terrestrial concentrator systems.

3. Concerns About Thin-Film Photovoltaics

There has been significant progress over the past 20 years in the various thin-film PV technologies. As described above, several thin films are now ready to challenge the more established thick-film crystalline silicon technologies in as-yet limited PV markets. The promise of significantly lower costs for thin films, the major driving force for their inception, also holds the promise of greatly expanding terrestrial PV markets. In spite of the significant progress, thin-film PV has many doubters and detractors, often within the PV community itself. This section addresses eight common concerns that are often raised in connection with thin-film PV technologies.

The Efficiency of Thin Films Is Too Low!

It is often argued, based on PV system cost analyses, that a module efficiency of 15% or greater will be required for large-scale PV systems to be cost competitive (e.g., in utility bulk power applications). Others present equally plausible arguments that the module price and the installed system cost (both in $/W_p$) are the key measures rather than the module efficiency itself, and that there should be ample applications and markets for lower-efficiency modules. While these arguments will be ultimately settled in the marketplace, the achievement of higher efficiency modules is clearly desired and needed.

Research accomplishments to date, as described in the previous section, provide the best argument against this concern. Table 2 summarizes the status of *cell, submodule, and module* efficiencies in the various thin-film materials. Recent rapid progress in laboratory cell efficiencies is very encouraging, as are the efforts to scale-up the devices to submodule and module sizes. Some of the prototype module efficiencies are now approaching those of crystalline silicon modules sold commercially a few years ago. It is therefore reasonable to assume that 8% to 10%-efficient thin-film modules will succeed in near-term markets. More importantly, experts predict still higher efficiencies achievable in these materials (perhaps up to 20%), thus it is reasonable to predict that 15% or higher efficiency thin-film modules can be achieved in the future.

Thin Films Have Stability and Reliability Problems!

This issue arose primarily as the result of the light-induced degradation in amorphous silicon materials and the contacting and environmental problems seen in CdTe. Others also argue that many thin-film devices contain a multiplicity of very thin layers (a few to tens of angstroms thick in some cases) and interfaces that will be subject to interdiffusion or some environmental effects in the long term.

While it is true that there is limited actual outdoor experience on thin-film modules, the results to date are encouraging. Stabilized efficiencies of a-Si modules are constantly improving. CIS modules appear to be stable (Fig. 3), and properly encapsu-

Efficiencies of Thin-Film Photovoltaics			
Material	Cell (%)	Submodule (%)	Module (%)
Amorphous Silicon	12-13[a]	9	>7
Cadmium Telluride	15.8	10	7
Copper Indium Diselenide	16.9[b]	11	10
Thin-Film Silicon	14.9	11[c]	8-9
Gallium Arsenide	23.3	21[d]	--

[a] Initial, unstabilized efficiency; [b] Active-area efficiency; [c] 100-cm²-area cell; [d] 16-cm²-area mini-module

Table 2: Efficiencies of Thin-Film Photovoltaics

lated CdTe modules have not degraded after some 3 years of outdoor tests. There does not appear to be an inherent degradation of the devices as a result of diffusions of species at the various interfaces. Most of the thin-film module types have passed the rigorous NREL qualification procedures [15], but it is as yet unclear that passing these tests will guarantee 30-year life for these modules in the field. Clearly, this issue will need to be resolved by the manufacturers themselves, who will have to provide the appropriate long-term warranties for their products. Recently, one x-Si (thick film) manufacturer, Solarex Corporation, offered a 20-year guarantee that their modules will deliver at least 80% of their minimum rated power [19]. Thin films must clearly compete with the more established (and accepted) x-Si technologies in the marketplace.

Thin Films Are Not Manufacturable; Equipment Costs Are High and Yields Are Low!

There are both positive and negative aspects of the experience to date concerning this issue. Laboratory devices have been successfully scaled to prototype modules, although not as yet achieving the laboratory efficiencies on the larger-scale modules (Table 2). The experience with a-Si is most encouraging; the industry produces some 15 MW of modules in both continuous and batch systems based on the glow-discharge method (Table 1). Scale up of CIS, CdTe, and thin-film silicon technologies is also progressing, as described in the previous section. But understanding of manufacturability issues is

clearly lacking (e.g., ref. [18]), and more efforts are needed in duplicating the prototype, "best" efficiencies in commercial-scale production.

Equipment costs in the thin-film technologies vary depending on the nature of the deposition processes (e.g., vacuum versus non-vacuum) and associated module fabrication steps (e.g., laser versus mechanical scribing versus cell interconnects, module encapsulation, etc.). As with all manufacturing operations, process throughput and yield are extremely important. Much of the current research is aimed at increasing deposition rates, improving material utilization, and achieving process reproducibility. With better understanding and control of the manufacturing steps, including simplification of the processes, thin-film proponents predict that equipment costs will be only a small portion (perhaps 10% to 20%) of the overall module manufacturing costs.

Efforts aimed at improving the manufacturing of PV modules are an important part of the U.S. DOE's Photovoltaic Manufacturing Technology (PVMaT) project [20]. The objectives of the PVMaT project are to advance PV module manufacturing processes, reduce the manufacturing costs of PV modules, improve module performance and reliability, and generally lay the groundwork for substantially scaling up U.S.-based PV production facilities. The U.S. PV industry participants and DOE are cost sharing this project (more than $100 million total over 5 years). Currently, four PVMaT contractors are concerned with the development of thin-film PV manufacturing processes (three amorphous silicon and one thin-film silicon). Several additional contracts are expected later in 1993.

Thin Films Use Hazardous and Toxic Materials!

All PV manufacturing, indeed all semiconductor manufacturing, deals with hazardous and toxic materials at some stages of the process. Among the key concerns in thin-film PV are those associated with the use of cadmium (in CdTe and CIS modules) and hydrogen selenide (in manufacturing of CIS modules). The use of concentrated silane (in a-Si manufacturing) is another concern; in addition, all PV manufacturing uses various toxic solvents that require careful disposal or recycling. The key is to

understand and control these hazards; this control then becomes part of the overall cost of manufacturing. In some cases (e.g., H_2Se), alternate approaches have already been found that eliminate the hazardous materials.

Environmental safety and health (ES&H) issues are of paramount importance in the DOE PV research programs, with the Brookhaven National Laboratory (BNL) specifically addressing ES&H issues in the research, manufacturing, and deployment of PV modules. The PV industry is also expending significant efforts in this area in order to meet national and local safety and environmental regulations. The careful studies of BNL [21-24], often conducted in collaboration with the PV industry, attest to the overall safety of PV manufacturing and use. Cadmium, in particular, can be recycled both from PV manufacturing waste and from field-deployed CdTe modules after their useful life. Some have even suggested that PV modules may be a way to "tie up" some of the cadmium that enters the U.S. waste stream from products such as nickel-cadmium batteries (the latter is about 1000 metric tons [MT] annually, enough to produce some 10,000 MW of CdTe PV modules). While this approach is clearly not practical in the near term, all studies and experience to date suggest that the overall environmental advantages of PV systems are far greater than any potential hazards associated with their manufacture or deployment. Reasonable precautions during manufacture and recycling of materials are necessary for PV to maintain these advantages.

There Is Not Enough Material for GWs of Modules!

Some skeptics contend that thin-film technologies often use "exotic" materials, and there will simply not be enough of these materials for large-scale production of PV modules. Table 3 lists some of the key materials along with the current annual production levels, proven reserves, and projected amounts for generating a gigawatt (GW or 1,000 MW) of PV electricity. Clearly, there are valid concerns in the case of indium and tellurium as PV production levels enter the multi-GW phase.

Indium use (in CIS modules) can be reduced to less than 10 MT per GW_p by using thinner layers and

Availability of Critical Materials

Material	Annual World Production (MT)	Amount per GW peak (MT)	Proven Reserves (MT)
Indium	120	40	3600
Tellurium	300	50-150	37,000
Selenium	2000	60	130,000
Cadmium	20,000	50-150	970,000
Gallium	35	10 (@ 1:1 Ga:In)	1,000,000

Source: U.S. Bureau of Mines, 1992 Mineral Commodity Summary

Table 3: Availability of Critical Materials

substituting gallium for indium. (Some of the recent successes with high-efficiency CIS cells are based on Ga-alloying.) Indium is nearly as abundant as silver, but production levels are less than 2% of that for silver because of the low demand. Indium availability (or price) may thus be an issue when PV needs compete with a still-limited production level. There are significant proven reserves of tellurium, but very little Te is refined due to low demand. For both In and Te, recycling of manufacturing waste and of field-deployed modules would ameliorate potential shortages. There are huge, untapped reserves of gallium. While the price of the semiconductor feedstock materials is important, the material costs for the substrate and encapsulation are greater than for the thin-film absorber materials.

The Scientific Base for Thin Films Is Too Small!

Much of the progress to date in thin-film PV can indeed be characterized as empirical in nature, with the theoretical understanding often following the empirical developments. As indicated earlier, amorphous silicon has attracted a large infrastructure of researchers in the academic community, but the same is not true for either CIS- or CdTe-based PV. However, there are increasing research activities at universities, and the recent record efficiencies in these materials were both accomplished by university research groups [14,16]. The DOE has recently named the Institute of Energy Conversion (IEC) at the University of Delaware as a *University Center-of-Excellence in Photovoltaic Research and Education.* This is recognition, in part, of the contributions made by IEC in the field of thin-film PV. The continuing efforts by IEC, in collaboration with the

PV industry, will address the understanding of thin-film module fabrication processes. As described in the previous section, there is research underway at NREL and universities on various aspects of the nucleation and growth, reaction chemistry, material characteristics, and device and interface features in thin-film PV materials.

The Private Sector Will Not Invest in Thin Films!

The greater issue here is that the private sector does not adequately recognize the value and potential of PV. Amorphous silicon attracted large private investments, spurred by vast markets other than PV. Today, there is solid support for a-Si PV, with at least two companies building new 10 MW/year production facilities. Advanced Photovoltaic Systems (APS) is expected to complete such a facility in Fairfield, California, later this year, while United Solar Systems Corporation (USSC), a joint venture between Energy Conversion Devices (ECD) and Canon, Inc., of Japan, recently announced their intent to build a 10 MW/year facility for triple-junction a-Si modules in Newport News, Virginia. The latter announcement follows a recently-enacted law in the State of Virginia that offers $0.75 per watt of PV modules produced in the state (up to 6 MW/year) from 1995 through 1999. The unique action in Virginia is indeed a recognition of PV's potential to generate jobs and local economy, in addition to the environmental benefits the PV systems provide.

The other thin-film technologies are also attracting their share of investors. AstroPower's thin-film silicon is supported by the Dow Chemical Corporation. There is solid investment in cadmium telluride with Solar Cells, Inc. (supported by Glasstech, Inc.), and Golden Photon, Inc. (supported by the Adolph Coors Company). Interest in CIS extends from Siemens Solar Industries to several smaller efforts that are gaining corporate and investor support. Worldwide, some 30 companies are pursuing various thin-film options (Table 1), many involving substantial support by large corporations and support from federal governments as well, particularly in the U.S.

Nobody Will Buy Thin-Film Photovoltaics!

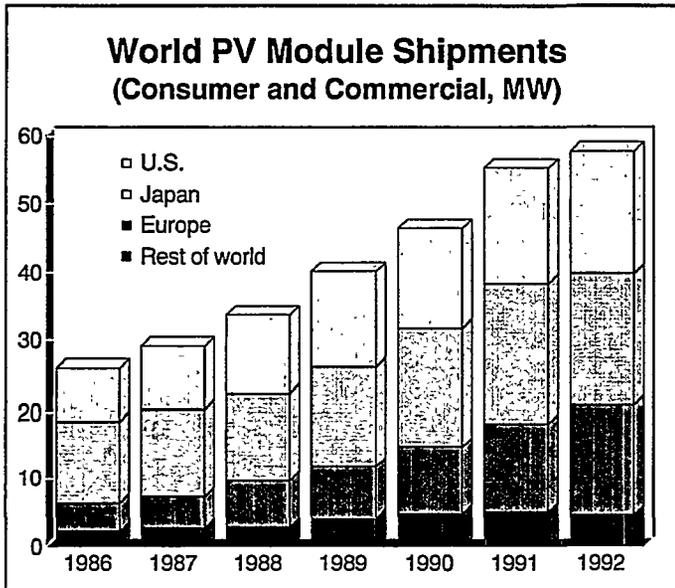Again, the greater issue here is the growth in PV

World PV Module Shipments
(Consumer and Commercial, MW)

PV Market Opportunities
as a function of module price

Fig. 4:   World PV module shipments — consumer and commercial, in MW (after PV Energy Systems, Inc.)

Fig. 5:   PV market opportunities as a function of module price

markets and the acceptance of PV in markets such as utilities and rural electrification in developing countries. Figure 4 shows the growth in worldwide PV shipments; the growth from 1991 to 1992 (approximately 5%) has been less than anticipated. Thin films, for the most part, have been used in consumer markets, but some 6 MW of a-Si power modules were sold in 1992. The largest a-Si system, a 400-kW ac system built by APS as part of the PVUSA project, became operational in 1992. As discussed above, several experimental systems based on other thin-film materials are now operational.

As the price of PV modules decreases, there will be new applications and huge, growing markets for PV products (see Fig. 5). While the exact module prices for entering certain market segments may be debated, there are major opportunities for PV in these markets as shown by a number of studies [26]. Thin-film PV, with the low costs projected by the industry proponents (typically less than $1/W_p$ in optimized production), will be in a position to serve these markets in the near term and the future. But thin films must compete in these markets with the more established x-Si technologies that are also decreasing in price. The bottom line to this concern is that *reliable*, thin-film modules, at the *right efficiency and price*, will be accepted in all markets.
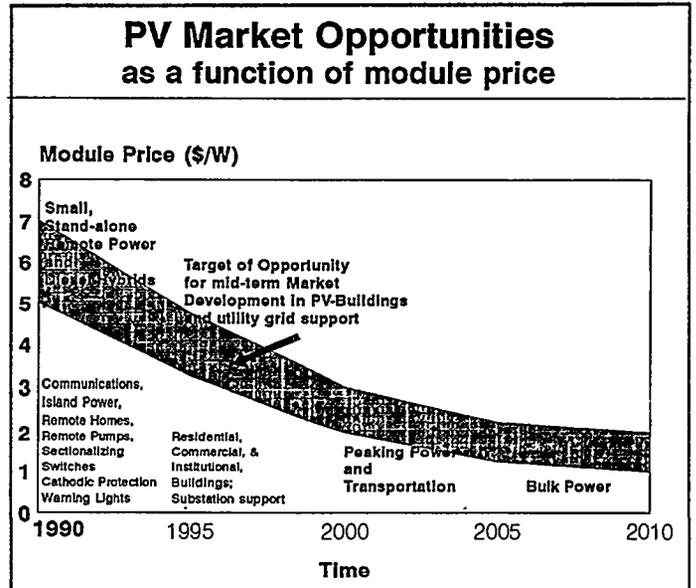
4. Conclusions

Progress in thin-film PV, technologies aimed at significantly reducing the cost of PV-generated electricity, has been both unprecedented and rapid. Is one to conclude that some form of thin-film PV will be the "winner" among the various PV technologies, including thick-film crystalline silicon and concentrators? This author will not attempt to reach such a bold conclusion, in spite of the purported advantages of thin films in reducing the cost of PV systems. The more likely conclusion is that several, if not all, PV technologies will succeed, possibly in different market segments. The ultimate "winner" may well be mankind and the planet Earth when the advantages of PV to generate clean, domestic energy throughout the world are properly recognized and valued. There is no doubt that thin-film PV will play a significant role in this success.

References

[1]   Zweibel, K. (1990), *Harnessing Solar Power—The Photovoltaics Challenge*, Plenum Press, New York.

[2]   Zweibel, K., A. M. Barnett (1993), *Polycrystalline Thin-Film Photovoltaics*, in *Renewable Energy – Sources for Fuels and Electricity*,

T. B. Johansson, H. Kelly, A. K. N. Reddy, and R. H. Williams (Eds.), Island Press, Washington, D.C., p. 437.

[3]   Carlson, D. E., S. Wagner (1993), *Amorphous Silicon Photovoltaic Systems*, in *Renewable Energy – Sources for Fuels and Electricity*, T. B. Johansson, H. Kelly, A. K. N. Reddy, and R. H. Williams (Eds.), Island Press, Washington, D.C., p. 403.

[4]   Green, M. A. (1993), *Crystalline- and Polycrystalline-Silicon Solar Cells*, in *Renewable Energy – Sources for Fuels and Electricity*, T. B. Johansson, H. Kelly, A. K. N. Reddy, and R. H. Williams (Eds.), Island Press, Washington, D.C., p. 337.

[5]   Nolan, J. F. (1993), *Development of 60 cm x 120 cm Thin Film CdTe PV Modules*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[6]   Carlson, D. E. (1990), *Low Cost Power from Thin Film Photovoltaics*, in *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications*, T. B. Johansson, B. Bodlund, and R. H. Williams (Eds.), Lund University Press, Lund, Sweden.

[7]   Fan, J. C. C., M. B. Spitzer, R. P. Gale (1990), *High-Efficiency III-V Solar Cells*, in *Advances in Solar Energy*, Vol. 6, K. W. Böer (Ed.), Plenum Press, New York, p. 395.

[8]   Benner, J. P. (1991), *Cost Reduction Technology for High-Efficiency Photovoltaics: Research Issues and Progress*, Proceedings of the 22nd IEEE Photovoltaic Specialists Conference, p. 7-11.

[9]   Zweibel, K., H. S. Ullal, B. G. von Roedern, R. Noufi, T. J. Coutts, M. M. Al-Jassim (1993), *Perspectives and Opportunities in Polycrystalline Thin-Film Photovoltaic Technologies*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[10]   Luft, W., B. Stafford, B. von Roedern, R. DeBlasio (1992), *Prospects for Amorphous*

Silicon Photovoltaics, Solar Energy Mater. and Solar Cells (Netherlands) **26**, p. 17-26.

[11]   Schmit, R. R., B. Felder, G. Hotchkiss (1993), *Recent Progress in the Design and Fabrication of Spheral Solar^{TM} Modules*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[12]   Barnett, A. M., R. B. Hall, J. A. Rand, W. R. Bottenberg (1992), *Thin Polycrystalline Silicon Solar Cells on Low Cost Substrates*, in *6th International Photovoltaic Science and Engineering Conference Proceedings*, B. K. Das, S. N. Singh (Eds.), Oxford & IBH Publishing, New Delhi, India, p. 737-744.

[13]   Luft, W., B. von Roedern, B. Stafford, L. Mrig (1993), *Second Controlled Light-Soaking Experiment for Amorphous Silicon Modules*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[14]   Zweibel, K., T. L. Chu, S. S. Chu (1993), *Cadmium Telluride Photovoltaics*, in *Advances in Solar Energy*, K. W. Böer (Ed.), this volume.

[15]   DeBlasio, R., L. Mrig, D. Waddington (1990), *Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules*, Solar Energy Research Institute Report No. SERI/TR-213-3624, DE90000321 (Available from NTIS, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161).

[16]   Hedstrom, J., M. Bodegard, A. Kylner, L. Stolt, D. Hariskos, H. W. Schock (1993), *ZnO/CdS/Cu(In,Ga)Se$_2$ Thin Film Solar Cells With Improved Performance*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[17]   Tuttle, J. R., M. Contreras, A. Tennant, D. Albin, R. Noufi (1993), *High Efficiency Thin-Film Cu(In,Ga)Se$_2$-Based Photovoltaic Devices: Progress Toward a Universal Approach to Absorber Fabrication*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[18] Knapp, K. E., C. Eberspacher, D. Tarrant, G. Pollock (1993), *Manufacturing of Low-Cost High-Efficiency Thin-Film CuIsSe₂ Photovoltaic Modules*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[19] Rever, W. (1993), *Solarex Announces New 20-Year Warranty*, Solarex Corporation News Release, April 25, 1993.

[20] Witt, C. E., R. L. Mitchell, G. D. Mooney, L. O. Herwig, D. Hasti, R. Sellers (1993), *Progress in Phases 2 and 3 of the Photovoltaic Manufacturing Technology Project (PVMaT)*, Proceedings of the 23rd IEEE Photovoltaic Specialists Conference (in press).

[21] Moskowitz, P. D., V. M. Fthenakis, K. Zweibel (1990), *Health and Safety Issues Related to the Production, Use and Disposal of Cadmium-Based Photovoltaic Modules*, Proceedings of the 21st IEEE Photovoltaic Specialists Conference, p. 1040-1042.

[22] Fthenakis, V. M., P. D. Moskowitz, J. C. Lee (1984), *Manufacture of Amorphous Silicon and GaAs Thin-Film Solar Cells: An Identification of Potential Health and Safety Hazards*, Solar Cells (Netherlands) **13**, p. 43-58.

[23] Moskowitz, P. D., K. Zweibel, Eds. (1991), *Recycling of Cadmium and Selenium from Photovoltaic Modules and Manufacturing Wastes: A Workshop Report*, Brookhaven National Laboratory Report No. BNL 47787 (Available from NTIS, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161).

[24] Lee, J. C., P. D. Moskowitz (1990), *Hazard Identification and Characterization of Organometals in Growing III-V Semiconductors for the Production of Photovoltaic Cells*, Solar Cells (Netherlands) **28**, p. 209-222.

[25] Guha, S. (1993), *United Solar Systems Corp. to Build World's Largest Multi-Junction Solar Panel Manufacturing Plant*, News Release, April 20, 1993.

[26] Cody, A., L. Frantzis (1993), *The Market for Solar Photovoltaic (PV) Technology*, Prepared by Arthur D. Little, Inc., for the Electric Power Research Institute, Report No. EPRI TR-102290 (Available from EPRI, Palo Alto, CA 94304).