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Advances in Photovoltaics at NREL

Bolko von Roedern

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Bolko von Roedern

National Renewable Energy Laboratory (NREL), MS 3212, Golden, CO80401-3393

ABSTRACT

This paper discusses the critical strategic research and development issues in the development of next-generation photovoltaic technologies, emphasizing thin-film technologies that are believed to ultimately lead to lower production costs. The critical research and development issues for each technology are identified. An attempt is made to identify the strengths and weaknesses of the different technologies, and to identify opportunities for fundamental research activities suited to advance the introduction of improved photovoltaic modules.

Keywords: Photovoltaics, solar cells, thin films, supporting research

1. INTRODUCTION

The worldwide production of photovoltaic cells and modules in 1998 amounted to over 150 MWp. Assuming an average efficiency of 10%, this amount of power corresponds to an overall cell area of 1.5 million square meters or 1.5 square kilometers. While these numbers appear substantial, they are small-scale compared to other optically coated products, such as window panels with low-emissivity coatings that reach manifold larger manufacturing volumes. It is important to remember that solar cells are not a simple semiconductor layer spread out over large areas. A solar cell can be considered the most challenging electro-optical device. The reason for this is that in order to produce efficient solar cells, the semiconductor materials used have to have very good carrier collection properties for both minority and majority carriers. In many other large area electronic devices, such as displays or sensors, device performance is predominantly governed by the majority carrier properties, which poses less stringent constraints on device optimization schemes.

High manufacturing costs have limited the sales potential for photovoltaic modules; nevertheless, a true photovoltaic industry has developed. Figure 1 illustrates the worldwide growth of photovoltaic cell and module shipments since 1986, broken down in "traditional" crystalline Si technology based shipments and thin film technology (amorphous silicon and cadmium telluride) based shipments.[1] It appears that an exponential growth pattern of this industry has been established in recent years. Roughly, 40% of the worldwide shipments have originated from manufacturers in the United States. NREL runs comprehensive programs to assist the U.S.-based photovoltaic manufacturers to: (a) lower manufacturing cost and improve performance of existing products; (b) develop next generation photovoltaic module technology; and (c) establish an R&D base, both through in-house research efforts at NREL and through subcontracts with universities, in support of various established and emerging technologies. In addition, NREL, in collaboration with a smaller photovoltaics group at Sandia National Laboratories, supports system and module evaluation efforts by carrying out performance measurements and accelerated degradation tests. The performance is also assessed by monitoring and analyzing the long-term performance of demonstration arrays, that in some instances are built using pre-commercial modules or components. Many of these projects are carried out within the National Center for Photovoltaics (NCPV).

There are other potentially interesting PV technology developments, such as the development of photovoltaic concentrators using ultrahigh-efficient solar cells. To date, as can been seen from Figure 1, these technologies have not managed to garner any significant market share, even though this technology has been developed for a while and successful prototype and demonstration systems have been built. I believe that this is largely due to the fact that current PV systems are typically small, low-power installations, often in remote locations. For such applications, the performance and reliability of a flat plate system outweighs the modest performance advances of concentrator systems that have to rely on accurate tracking mechanisms to keep the concentrator modules focussed on the sun. Concentrator systems seem to be more suited for larger photovoltaic generators (>20kW) for which there is currently little commercial demand. Because of their promising prospects as terrestrial high-efficiency concentrator cells as well as for space solar arrays, research activities continue to develop very high-efficiency cells based on III-V semiconductors.[2] However, in this paper this approach will not be discussed.

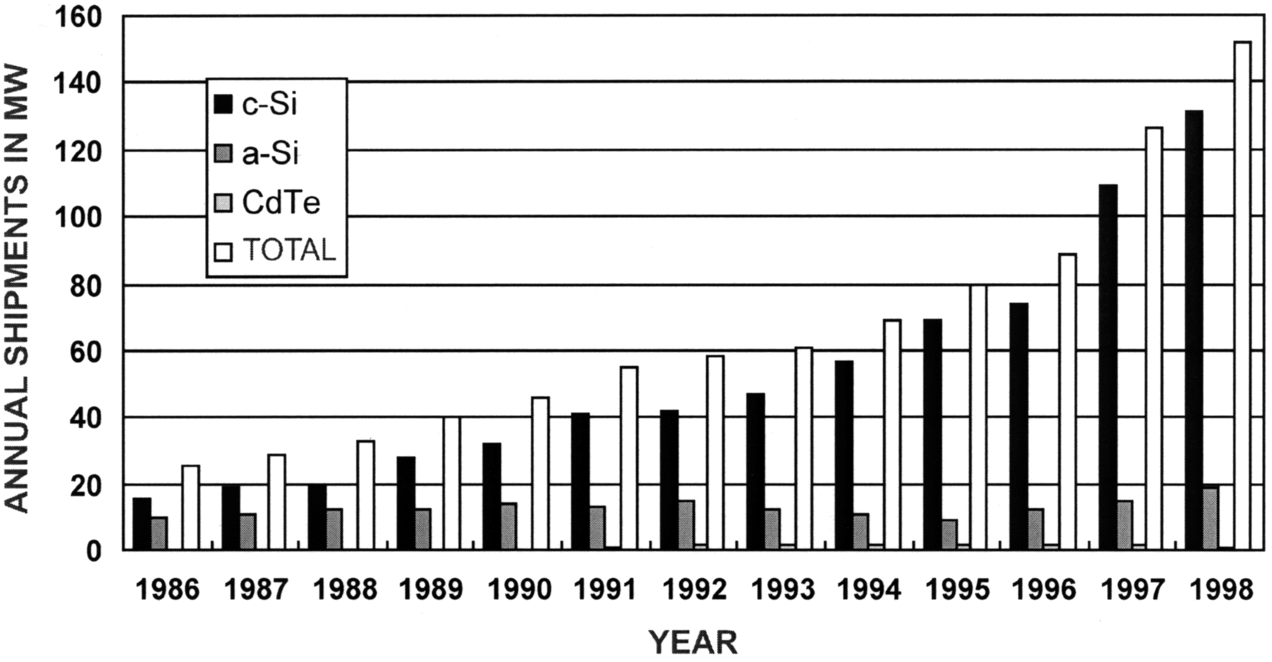

Fig. 1: Annual worldwide photovoltaic shipments by technology

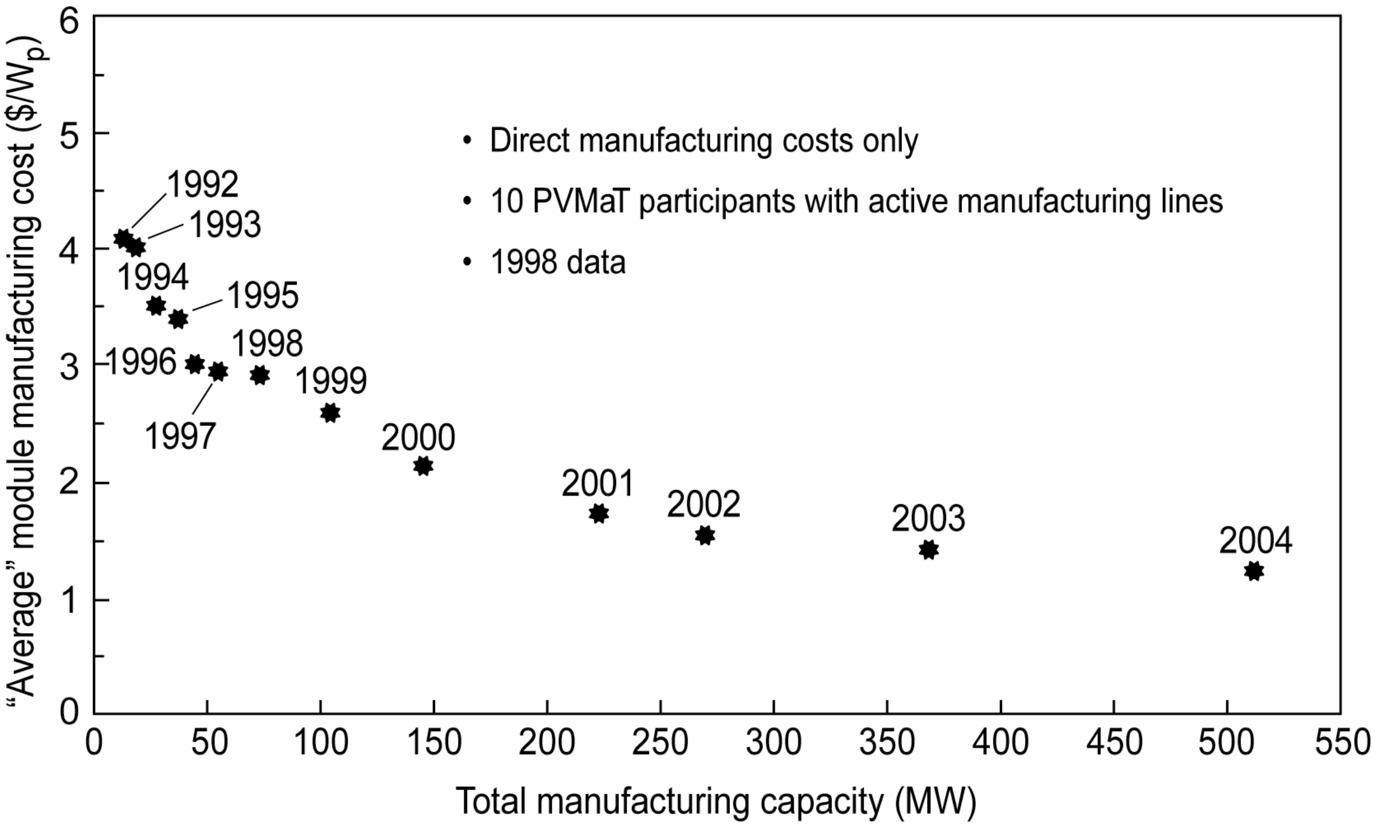

Fig. 2: Actual and projected "average" manufacturing cost and manufacturing volume experienced or predicted by 10 participants of NREL's PVMaT program.

The NREL Photovoltaic Manufacturing Technology (PVMaT) Project received company-confidential manufacturing cost data from a fair representation of U.S.-based manufacturers and published the average values without revealing the cost structures of individual companies.[3] Figure 2 shows the development of manufacturing cost with time, and future projections made by the responding manufacturers. Note that these are weighted average values including different photovoltaic technologies manufactured or to be manufactured by the companies responding to the survey of the PVMaT Project. Because of the current commercial trends, I believe that it would be appropriate to review the current manufacturing trends for both crystalline Si and the thin-film technologies. I will review how NCPV programs support these technologies and attempt to identify some of the crucial strategic issues as well as those performance issues that can most likely benefit from fundamental R&D efforts and general better understanding.

2. CRYSTALLINE SI-BASED TECHNOLOGIES

As can be seen from Figure 1, traditional crystalline Si wafer based technologies are still in an exponential growth pattern. Interestingly, various manufacturing approaches are used by different companies. These approaches will be briefly presented and discussed.

2.1. Wafers or Substrates

The vast majority of crystalline Si Solar cells are made on wafers produced either from Czochralski single crystals (the largest U.S. manufacturer is Siemens Solar Industries) or from large grain polycrystalline ingots (the second largest U.S. manufacturer, Solarex Corporation, now BP-Solarex). In the past, it has been the philosophy of the U.S. based photovoltaic manufacturers to produce their own wafers in order to have tight control over manufacturing cost and wafer quality. The crystal growth processes appear to have become less critical in recent years. Most economical advantages were derived from changing the wafering technology by going from inner diameter (ID) saws cutting one wafer at a time to wire saws slicing several feet of ingot in one cut. This has resulted in increasing the number of usable wafers obtained per inch of ingot from 25-30 to 40-50 with typical wafer thicknesses at or just under 300 μm. Wire-sawing does in principle allow cutting even thinner wafers. However, these thinner wafers can presently not be handled without enduring excessive breakage in the cell processing and module assembly steps.

Smaller, but not insignificant portions of crystalline Si cells are based on wafers grown as silicon ribbon or as thick silicon films deposited on conducting ceramic substrates. These technologies avoid wafering steps, and in recent years, the performance of Si ribbon cells (ASE Americas, Inc.) has reached levels comparable to wafer Si-based technologies. Thick SiliconFilm™ prototype modules manufactured by AstroPower, Inc. presently reach about two-thirds of the performance of their wafer-based counterparts. It is of interest to note that these various approaches still continue to be developed and used in parallel. Some 15 years ago, when today's manufacturers or their predecessors began to develop the different processes, each had hoped that their preferred method of making the Si substrate would result in a unique cost/performance advantage. To date, it has not become evident which of these approaches is the most cost effective. Some manufacturers in Europe and Japan manufacture cells using wafers purchased in the open market or from dedicated wafer suppliers. It is quite possible that their approach could become the preferred approach if crystalline Si photovoltaic technologies continue to grow to production levels many times larger than today's.

2.2. Cell Processing and Material Quality

All U.S.-based crystalline Si cell manufacturers produce their cells by phosphorus diffusion for the emitter and aluminum alloy for the collector. In order to achieve high throughput, several manufacturers converted from batch-diffusion processes carried out in quartz-tube diffusion furnaces to conveyorized belt furnaces. It has become well accepted now that the Si material can be "upgraded" during the cell processing step. This upgrading may occur automatically as the cell contacts are formed, and is usually referred to as phosphorous and/or aluminum gettering. Optimizing these gettering processes was critical to achieve today's high cell-efficiency levels (typically 12% to >15% cell efficiencies). Some manufacturers use additional process steps such as hydrogenation treatments for defect passivation.

NREL organizes an annual workshop on Crystalline Silicon Solar Cell Materials and Processes.[4] Understanding the gettering and passivation processes is a major focus of these workshops. Researchers who are providing supporting defect or fundamental materials characterization services are now well aware that it is not sufficient to characterize Si substrates in their as-grown state. Characterization has to be repeated in the as-processed states. The interactive nature of defects and impurities is now also well accepted among researchers. Several years ago, it was thought to be important to establish material specifications for solar cell substrates. It is now well accepted that such specification is not as simple as originally thought. The lifetimes or diffusion lengths not only depend on the impurity levels, e.g., the concentration of a lifetime killing metal impurity, but also on the presence of other inactive impurities, such as oxygen or carbon, point or extended defects such as dislocations, structural defects in polycrystalline materials, and gettering and passivation effects. Some years ago, it was argued that structural imperfections might make multicrystalline Si less sensitive to the effects of impurities. It is now generally accepted that the effect of impurities is as critical or perhaps more critical in multicrystalline substrates.

2.3. Si Feedstock Issues

Ironically, Si PV technology was the first one to be affected by feedstock shortage, even though silicon is the most abundant metallic element in the earth's crust. Because it is now established that low levels of critical impurities are important, all PV ingots and ribbons are grown from secondary grade polysilicon manufactured for the electronic wafer manufacturers. Due to rapid expansion of DRAM manufacturing in 1995, a worldwide shortage of polysilicon ensued. Additional polysilicon manufacturing capacity has since been brought on line, alleviating an immediate shortage. The secondary grade polysilicon used (and purchased for <\$20 per kg) by the PV industry continues to remain at 10% to 15% of total polysilicon production (total worldwide production in 1999 will be around 23,000 tons, with typical market prices of \$60 per kg). Based on a conversion of 20 metric tons of Si required for each megawatt of modules, it becomes evident that further accelerated growth of the Si PV industry would require the development of dedicated "solar grade" feedstock; otherwise, growth would be limited to that of the needs of the semiconductor Si industry at approximately 10% annual average growth.[5] While limited R&D efforts are carried out to develop dedicated solar grade feedstocks, no major U.S.- based polysilicon manufacturer is presently involved in commercializing such a product. Any dedicated manufacturing of solar grade polysilicon feedstock has substantial economical risk because the lowest projected manufacturing costs for dedicated solar grade feedstock are slightly higher than the cost of off-grade polysilicon, which will continue to be available from electronic industry suppliers. Demand for polysilicon could also decrease if thin-film PV technologies were to begin an exponential growth pattern and successfully competed with traditional crystalline Si PV markets.

2.4. R&D Opportunities

Crystalline Si PV manufacturing is well established today and the largest manufacturers have manufacturing capacities over 20 MW_p per year. Today, processes are rather well established. R&D efforts supporting this PV technology have to be compatible with the manufacturing environment. There is continued interest by Si-PV manufacturers to better understand how impurities and defects affect device performance and how gettering and passivation can upgrade materials. There is interest in developing quantitative predictive characterization techniques that could predict cell parameters from characterizing ingots and wafers. Manufacturers using multicrystalline substrates are specifically interested in trying to assess expected performance from a characterization of the wafer in the pre-processed state, and also have a strong interest in eliminating areas on multicrystalline wafers that do not respond to upgrading steps. There is also continued interest in viable surface passivation schemes that could be implemented into manufacturing and an improved understanding of such schemes. There is perhaps also some interest in research geared towards module encapsulation and lifetime evaluations of new packaging schemes. To date, no comprehensive R&D programs have been established to address these issues.

3. THIN-FILM TECHNOLOGIES

Although crystalline Si PV manufacturing still experiences an exponential growth pattern in 1999, there can be no doubt that ultimately thin-film technologies should offer the best cost/performance prospects. Thin-film technologies pursued by many of the participating photovoltaic module manufacturers contributing to the PVMaT surveys must have had already some impact on moving future year average projections shown in Figure 2 towards higher volumes and lower cost. The largest US-based manufacturers, Siemens Solar and BP-Solarex, are pursuing the development of all established thin-film options, namely copper indium diselenide (CIS), cadmium telluride (CdTe), and amorphous silicon (a-Si). In addition to these thin-film developments within these established crystalline Si manufacturers, there are several companies focussing on becoming large volume suppliers of thin film modules, United Solar Systems Corporation (a-Si), First Solar (formerly Solar Cells, Inc., CdTe) and Global Solar Energy (CIS). Among these, United Solar and Solarex were the only U.S.-based companies with substantial thin-film (a-Si) sales in 1998. I would like to refer to review articles that describe the technical details[6] and the economical aspects[7] of these technologies. AstroPower is presently manufacturing prototype quantities of SiliconFilm-based cells. These presently are made from thick electronically active layers and attempts to reduce Si usage by simply using thinner layers lead to unacceptable performance loss. In addition, AstroPower is pursuing the development of monolithic interconnection schemes for their present thick Si films as an intermediate measure[8] and pursues other approaches to make high-efficiency thin-film Si devices on low-cost substrates.

There are two major advantages for thin film based devices: (a) lower material usage of expensive semiconductor materials and (b) the feasibility to monolithically manufacture large area modules without the need to assemble them by interconnecting large numbers of cells discretely using soldering techniques. On the other hand, there are several factors why thin-film products have not exceeded the volumes shown in Figure 1. Firstly, 6 – 9 MW of the annual quantities of the a-Si and CdTe products constitute small solar cells used in the fabrication of solar powered devices such as calculators. (For such applications, thin-film cells are used almost exclusively.) The market volume for such has been somewhat constant over recent years but can lead the uninformed reader to conclude that sales volume has been stagnant for many years. Significant quantities (>1 MW per manufacturer per year) of a-Si modules for power applications were only shipped since 1998. Secondly, it has taken much longer much longer than expected to take a prototype fabrication processes into manufacturing and simultaneously achieve good performance, good reliability, and high yield. Thirdly, some of the crystalline Si manufacturers are now operating >20 MW_p production lines with more and more automated assembly lines resulting in economy of scale manufacturing cost reductions.

3.1. The Established Thin Films

At this point in time, amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS) thin film PV technologies have near-term commercialization potential. Amorphous silicon is commercially available now. Commercial CIS modules were recently introduced by Siemens Solar. Substantial numbers of precommercial CdTe modules have been deployed by Solar Cells Inc. (now First Solar). Although a-Si and CIS are now produced in plants with limited manufacturing capacity (<10 MW_p/year), First Solar has announced plans to quickly transition CdTe manufacturing to the ≥20 MW_p/year level.

I believe that the potential of these technologies can be gauged by reviewing verified cell and module "champion" data shown in Figure 3 and Table 1. The cell data shown in Figure 3 suggest that CI(G)S cells have the potential to achieve performance levels comparable to diffused Si wafer based cells. CdTe cells have the next best potential, and amorphous silicon cells the least potential. One should note that earlier review papers reported better performance for the a-Si technology. However, because of an intrinsic light-induced degradation mechanism, a-Si solar cell performance has to be derated to reflect "stabilized" performance levels.

Company	**Device**	**Size (cm^2)**	**Efficiency**	**Power**	**Date**
United Solar	**a-Si triple junction**	**9276**	**7.6% (stabilized)**	**70.8 W**	**9/97**
First Solar	**CdTe/CdS**	**6728**	**9.1%**	**61.3 W**	**6/96**
Solarex	**a-Si dual junction**	**7417**	**7.6% (stabilized)**	**56 W**	**9/96**
Siemens Solar	**CdS/CIS-alloy**	**3651**	**12.1%**	**44.3 W**	**3/99**
BP Solar	**CdS/CdTe**	**4540**	**8.4%**	**38.2 W**	
United Solar	**a-Si triple**	**4519**	**7.9% (stabilized)**	**35.7 W**	**6/97**
Golden Photon	**CdS/CdTe**	**3366**	**9.2%**	**31 W**	**4/97**
ECD	**a-Si triple**	**3906**	**7.8% (stabilized)**	**30.6 W**	

Table 1: Verified efficiencies for the best thin-film modules

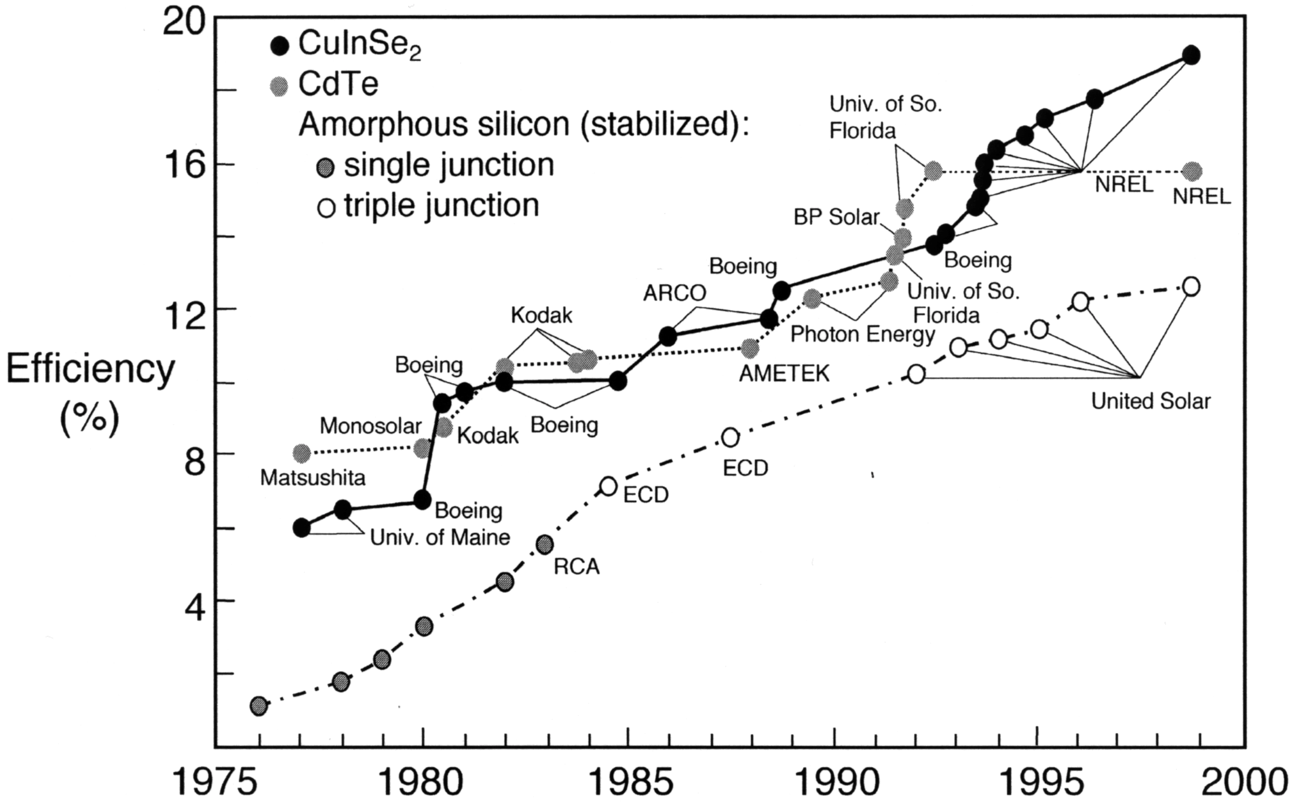

Fig 3: Verified champion solar cell efficiencies of the three established thin film technologies (data compiled by NREL Thin Film Partnership)

In order to manufacture a commercial product, equally important as champion performance of small area cells or one-of-a-kind prototype modules is the requirement to manufacture large area modules with high yield. The data shown in Table 1 suggest that at the module level, presently there is perhaps less of a difference. Manufacturing issues have taken much longer than expected to be resolved. For example, 8%-9% efficient CIS prototype modules were made by ARCO Solar (predecessor of Siemens Solar) in 1988. The quick commercialization failed because of insurmountable manufacturing yield problems.[9] It is of interest to note that some of the problems causing yield reductions reported in reference 9 were actually not solved. Rather, different processing approaches developed circumvented some of the problems identified earlier altogether. However, this can serve as an example that it may take over 10 years to begin commercial production after establishing a viable prototype product.

Table 2 provides some rationale why the NREL Thin Film Partnership Program continues to provide support to 4 technologies instead of "picking a winner." For the sake of completeness, this table contains a line for thin crystalline Si films. Pacific Solar in Australia has announced to commercialize this product, but as of today no performance data have been published for any type of prototype device. I presently would consider this to be a next generation technology.

Technology	**"potential"**	**"risk"**	**Number of entities Commercial (pre-commercial)**		**(pre) commercial module efficiencies**
Amorphous silicon	low	low	3	(1)	5 – 7%
Cadmium telluride	medium	medium		(2)	(5 – 8%)
CIS	high	high	1	(1)	~10%
Si-Film (thick)	? (medium)	low		(1)	(6-9%)
Si film (thin)	unknown	very high	-	-	-

In the following, I wish to briefly review the most salient features of each of these thin film technologies.

3.1.1. Amorphous Silicon

This is the oldest of the thin-film technologies. In the mid 1980s, it was expected that this technology would quickly become the dominant PV technology. Specifically, the photovoltaic programs in the U.S. and in Japan then focused large portions of their resources on this technology. The deposition technology was quickly scaled to large areas, and monolithic modules were manufactured for the first time in 1984. Based on the rapid progress made with small area solar cells from 1980 to 1988, projections were made that within 10 years, 12 – 15% commercial module efficiencies could be achieved. Although it was well known then that amorphous silicon performance degrades upon light exposure ("Staebler-Wronski effect"), initially it was hoped that this degradation could be significantly reduced or eliminated. Since about 1991, the U.S. program switched to using stabilized performance as the yardstick to measure improvements of this technology. Since then, it has become evident that there is a great need to enhance stabilized device performance. It is now generally accepted that light-induced degradation is intrinsic to the a-Si:H system, e.g., not caused by impurities. It has also been learned how to somewhat minimize the degradation, both by making the amorphous semiconductor layers more stable as well as by using multijunction device structures to minimize the effects of the degradation mechanism. Compared to other thin-film technologies, a-Si has benefited from comprehensive fundamental R&D efforts, as well as from a-Si uses in non-photovoltaic large-area thin-film semiconductor applications (displays, sensors). United Solar and Solarex have manufacturing plants rated at 5 and 10 MW_p annual capacity, and these companies each have manufactured about 2 MW of modules in 1998. Energy Photovoltaics (EPV) is manufacturing a-Si modules now, but is also looking into CIS technology as their next generation product. Iowa Thin Film Technologies serves niche markets with lightweight a-Si panels deposited on polyimide foil.

To date, the most critical issues for this photovoltaic technology are:

- Improving stabilized device performance. Efforts to prepare amorphous semiconductor layers with improved stabilized properties to date have had only a limited impact on resulting in improved stabilized devices. It is still hoped for that a breakthrough could be achieved to synthesize a stable material with properties at least as good as those of today's unstable films in their "initial" (as prepared or annealed) state. Another approach is to optimize the cell design to minimize the impact of degradation. For example, a-Si technology has developed schemes capable of using very thin (usually <250 nm thick) semiconductor layers, using light-trapping schemes to insure complete absorption of the incoming sunlight.

- Increasing deposition rates. a-Si solar modules are deposited by plasma-enhanced chemical vapor deposition, requiring relative expensive vacuum systems. Presently, the throughput of the existing manufacturing lines could be enhanced if the deposition rates (typically 0.1 to 0.3 nm/sec) could be increased without loss of stabilized device performance.

- Understanding of fundamental mechanisms that are limiting device performance. For example, the highest open-circuit voltages achieved to date are only 1.00 V with absorber bandgaps of 1.7eV. In crystalline Si or GaAs cells, open circuit voltages >60% of the corresponding absorber bandgap energy can be achieved. For reasons that are not well understood, this is not the case for a-Si and other thin-film solar cells.

Amorphous silicon continues to be a viable PV technology. It can be deposited on glass or flexible substrates. The latter approach lends itself to manufacture interesting products such as photovoltaic roofing materials. Present commercial product provides low to modest efficiencies. The ultimate fate of this technology will depend on whether higher stabilized performance levels can be obtained using low-cost manufacturing approaches and by the performance levels realized by competing thin-film technologies.

3.1.2. Cadmium telluride

This technology is presently being developed by two companies in the U.S. First Solar focuses on developing a very high throughput manufacturing process, with the long-term goal of manufacturing photovoltaic modules by applying all layers in the device as a coating operation attached to a float-glass line[10,11] First Solar has been able to develop a very rapid vapor transport deposition (VDT) process requiring only seconds to deposit the semiconductor layers.[11] At this point in time, other processing steps like the $CdCl_2$ anneal step required for CdTe device fabrication[12] still require processing times on the order of several minutes. First Solar has announced to set up a factory with a minimum 20 MW manufacturing capacity in the near future. They expect their first product to be 0.6 m by 1.2 m in size with a rating of 50 W. Substantial numbers of prototype modules meeting these specifications have been installed.

BP Solar is presently making a CdTe module manufacturing plant operational in California, using electrodeposition as the process for laying down the CdTe. This deposition process is much slower than VDT, but does not require vacuum deposition equipment. BP Solar uses large electrodeposition tanks that are holding many modules at a time and that are low-cost equipment. Both First Solar and BP Solar have indicated that they would manufacture substantial quantities of modules by 2000. If these companies meet their respective goals, they would have an initial commercial product that in performance would be comparable to the best commercial a-Si modules. It is argued that the manufacturing cost per Watt would be lower than for multijunction a-Si, because the manufacturing process requires less investment into deposition equipment.

To date, the most critical issues for this photovoltaic technology are:

- Device Stability. While there are very encouraging "proof of concept" data available on modules deployed for a few years outdoors,[10] tests using only modestly accelerated exposure conditions (e.g., exposure to 1-sun light at a module temperature of 100 °C) typically show some performance degradation. This degradation is linked to the processing of the devices and does not appear to be intrinsic.[13] Understanding the underlying mechanisms is a major focus of the NREL Thin-Film Partnership CdTe program.

- Cd perception. The fact that this product contains a toxic element was unfortunately highlighted by supporters of competing PV technologies. Detailed studies have shown that the amount of Cd expected to be released into the atmosphere during the lifetime of a CdTe-based PV plant is actually smaller than the amounts released by a coal-fired power plant generating the same amount of energy. This issue remains an emotional and regulatory concern (some countries may ban Cd-containing consumer products). In a collaborative effort between NREL and Brookhaven National Laboratory, safety and health aspects for the manufacturing, use and final disposal or recycling of photovoltaic modules are evaluated. This project also assesses the impact of using photovoltaic technologies, such as reduced greenhouse gas emissions, on the environment.[14] First Solar has already implemented a viable recycling approach at its facilities.[15]
- Advanced performance. The commercial product would greatly benefit from enhanced understanding of mechanisms limiting device parameters such as voltage. Contact preparation for these cells presently is presently more an art than science. The ability to understand and control device degradation observed under accelerating conditions would greatly benefit this technology.

CdTe is a promising photovoltaic technology presently pursued by two U.S. based companies and one company in Germany. It promises to deliver near term modest efficiencies with further improvements possible as demonstrated in small area cells. Even at modest efficiency levels (~8%) present projections are that lower manufacturing cost per Watt can be obtained than for crystalline Si products, mainly because manufacturing equipment is not very capital intensive and VDT deposition rates are high.

3.1.3 Copper Indium Diselenide

A commercial product with an approximately 10% efficiency has recently been introduced by Siemens Solar. A second U.S. company, Global Solar Energy, is focusing on developing a roll-to-roll manufacturing process on polyimide or stainless steel foils. Global Solar is hoping to have commercial product available soon. These companies manufacture their modules using vacuum deposition (co-evaporation or sputtering) of metal or metal-selenide precursors followed by a selenization step to for a single-phase $Cu(In,Ga)Se_2$ compound. Siemens Solar actually uses a pentenary $Cu(In,Ga)(S,Se)_2$ absorber. Alloying Ga to the absorber increases the bandgap and open circuit voltage of the devices. The champion performance as those shown in Fig. 3 are obtained with Ga/In ratios on the order of 20 – 30% and absorber bandgaps of 1.1 to 1.3 eV. Sulfur incorporation has a similar effect on the absorber bandgap. While it is possible to prepare alloys with higher Ga or S content, it is consistently observed that there is reduced carrier collection and consequently deterioration of device performance as the absorber bandgap is increased to values >1.3 eV.[16] Two smaller companies (ISET and UNISUN) are developing CIS based PV technology using non-vacuum (nanoparticle powder) deposition processes for the absorber formation.[17,18]

To date, the most critical issues for this photovoltaic technology are:

- Large area manufacturability issues. It took Siemens Solar about 10 years to establish processing schemes robust enough to obtain a high efficiency product with high yield. While yield issues are clearly process dependent, i.e., may be more problematic for some deposition approaches than for others, there is a substantial risk that other developers of CIS-based modules have to tackle a substantial hurdle.

- Potential shortages of In and Ga raw materials. If CIS technology turns out to be the lowest-cost photovoltaic option, there is a concern that a shortage of In and Ga may limit its growth. This is not a concern for production levels of a few thousand MW per year. Certainly, this issue should not be taken as a reason not to rapidly develop this promising technology now. It could support a near and intermediate term viable industry for at least 15 years even under the most optimistic PV growth scenarios.

- Advanced performance. The commercial product would greatly benefit from enhanced understanding of mechanisms limiting device parameters such as voltage. Device optimization presently is more an art than science. Often, it is found that device efficiency is not strongly dependent on crystallite size, crystallite orientation, or chemical composition.

CIS is a very promising photovoltaic technology presently pursued by several companies at various levels ranging from the development of new deposition processes to commercial manufacturing. It promises to deliver near-term efficiencies close to crystalline Si. Further improvements are likely and CIS can be expected to be the first thin-film device expected to pass the 20% efficiency mark. Manufacturing issues are somewhat complex and difficult to establish. However, there are no indications that these issues could not be resolved.

3.2. Next-Generation Thin-Films

Here I want to discuss briefly results on next generation thin-film cells of technologies that to date have achieved at least reasonable cell results. Some are being considered for early commercialization, but to date no prototype large area modules have been demonstrated.

3.2.1 Thin crystalline Si cells

There is a significant interest in developing various approaches towards manufacturing thin-film crystalline Si films on low-cost substrates into monolithic modules. There are formidable challenges to accomplish these goals, and to date there is no convincing prototype devices with promising properties for low-cost, high volume manufacturing. First, one should ask the question why thin Si films have become the object of so much attention? Crystalline Si clearly is not the ideal material for a solar cell: it possesses an indirect bandgap that is too small to absorb the solar spectrum in a single-junction cell. Secondly, Si is a sensitive material that is easily degraded by many metallic impurities. Si is also quite sensitive to oxidation, and requires high temperatures to grow or recrystallize reasonable large crystallites. This will probably impose significant limitations on substrate materials onto which crystalline Si films with high electronic quality can be deposited. One driver for advocating use of thin Si films may be somewhat self-serving. Si is the most widely researched semiconductor material. Could it be that the Si research community is looking for a technology where its expertise can be used? Only the future will tell if the vast Si expertise will allow the design of an efficient thin-film Si based solar cell that outperforms cells made from other polycrystalline materials.

In the following, I wish to review some thin Si approaches in the order of increasing crystallite sizes. It has not been established which combinations of crystallite sizes and absorber thicknesses may give the best results. For a true thin film advantage, ultimately it will be required to deposit films onto insulating substrates so that they can be monolithically interconnected. There are also approaches of using single crystalline Si thin layers such as lift-off processes.[19] I believe that such processes have little future. The greater manufacturing cost reductions for PV modules are derived from manufacturing large area monolithic modules, rather than from minimizing the usage of a low cost material such as Si. The lift-off approaches appear to complicate rather than simplify handling during manufacturing; this is contrary to current industry developments that clearly look for simplified handling and fewer processing steps.

- Micro- or nano-crystalline cells have been demonstrated. It is well known that certain deposition conditions used for amorphous silicon film deposition can lead to the deposition of microcrystalline films even for substrate temperatures below 200 °C. These microcrystalline materials consist of small crystallites (10 – 100 nm). The best device results to date have been obtained at the University of Neuchatel. However, these cells typically have low voltages limiting their efficiency to about 8%. This is not high enough for single-junction thin-film cells, but it has been suggested to use the microcrystalline cell as a bottom cell in conjunction with an a-Si top cell ("micromorph" cells).[20] The deposition techniques and conditions of the microcrystalline device are very much compatible with amorphous silicon methods. The microcrystalline cells have been shown not to degrade upon light-soaking.

- Recrystallized polycrystalline Si films on glass substrates have larger crystallite sizes. To date, efficiencies of 10%-11% have been achieved for single-junction cells.[21] Again, these efficiency levels are lower than state-of-the-art multijunction all amorphous Si based cells.

- Epitaxially prepared thin-film cells on crystalline Si substrates to date have reached the highest performance, demonstrating in principle that 15 % efficiency are possible using thin crystalline Si absorbers.[22] It is not clear how this approach can easily result in a low-cost, monolithically integrated device. It has been proposed to use large-grain polysilicon ribbon made from metallurgical grade Si or large grain recrystallized films on low-cost substrates as substrates for such epitaxial growth techniques.

Many other approaches for thin-film Si solar cells have been proposed.[23] A general observation is that all low-cost micro-and polycrystalline cells made on low-cost substrates suffer from low open-circuit voltages. In the form of single junction devices, they cannot beat the performance of state-of-the-art multijunction a-Si devices, let alone the performance of CIS and CdTe. It is not clear what is causing these limitations in device performance and whether these limitations should be considered fundamental. Except for niche markets such as low-cost building integrated photovoltaic products, it appears that thin films will have to provide module efficiencies comparable to established Si wafer based technologies. If one restricts technologies to using Si, it could well be the case that high open-circuit voltages and efficiencies may be much more easily achievable on thin (less than 100 μm thick) self-supporting silicon ribbon not requiring the use of foreign substrates.[24,25]

3.2.2 Dye-Sensitized Nanocrystalline Devices

Another potential next generation solar cell technology are devices based on dye-sensitized titanium dioxide, sometimes referred to as a Grätzel cell after their inventor and promoter M. Grätzel. To date, these cells have achieved conversion efficiencies of about 10%.[26] While it has been suggested that the 15% efficiency level could be achievable, the exact potential for further improving this type of device is presently unknown. A major drawback to this device is the use of a liquid electrolyte that presently prevents the use of standard thin-film monolithic interconnection schemes. Some sealing concepts to isolate individual cells have been explored. Another option is to replace liquid electrolyte contacts with gel or solid state electrolytes. To date, only insignificant photovoltaic action has been obtained with the latter electrolytes. Like in the case of other cell technologies, the factors limiting device performance and the ultimate performance potential for this type of device are poorly understood. By choosing appropriate dyes, semitransparent or colored devices can be fabricated which could find a use in building integrated photovoltaic applications.

4. RESEARCH CHALLENGES FOR PHOTOVOLTAIC DEVICES

In the discussions of various cell technologies above, there are many examples where mechanisms limiting device performance or the ultimate potential of a certain device schemes are ‘poorly understood’. I suggest that it will be important to develop new concepts to better understand solar cells. The traditional approach of semiconductor physics, characterization of materials in terms of their chemistry (impurities) and structural properties (crystallographic and defect characterizations) may no longer be the most efficient approach to improve our understanding of solar cell devices. Traditionally, characterization of defects, defect complexes and impurities in various types of Si wafers is considered to be very important. The question is whether such focus is warranted given the fact that various single and multicrystalline cell approaches have now been able to result in commercial product with rather similar performance. The fact that often solar cell optimization appears to be more of an art rather than a science may suggest that that the artists (or alchemist) knows something that the scientist is presently unaware of.

I suggest a few general areas that I believe could warrant the redirection of current resources for more efficient R&D.

- Research supporting solar cell development should develop intelligent principles to understand why device optimization is interactive in nature. Interactive processing is well acknowledged in device optimization. Establishing intelligent principles explaining and guiding these interactive optimization requirements appears to be more fruitful than merely characterizing each individual type of material imperfection and attempting to add up all losses to account for less than ideal device performance. The latter approach drives device optimization too much in the direction of striving for perfection in each layer used in a cell. In reality, a higher degree of material perfection may not cause any significant improvement in device performance or may lead to reduced device performance. Such intelligent principles could be developed using statistical device optimization processes or fuzzy logic.[27]

- In the near future, the search for next generation solar cell candidates should be guided by the performance achieved in prototype devices rather than by conducting lengthy material characterization and optimization studies. One should not forget that present promising cell candidates, for example a-Si or Grätzel type cells, would not have been predicted to be suitable candidates by "conventional wisdom."

- There is a great benefit to be derived from a much better quantitative understanding of the device limiting factors. Until such understanding is developed , our research programs will continue to have to find a compromise between viable technological approaches that lend themselves to high through-put, low-cost manufacturing and esoteric device preparation approaches that presently may not be supported because of they are considered unpractical. With better understanding, esoteric approaches would become much more acceptable to guiding solar cell technologies.

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