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Amorphous and Thin-Film Silicon

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ABSTRACT

This paper outlines the key concepts set forth in the Amorphous and Thin-Film Silicon session at the National Center for Photovoltaics and Solar Program Review Meeting held March 26, 2003, in Denver, Colorado. Key elements of discussion centered around benchmarking the NREL/NCPV amorphous and thin-film silicon program, identifying holes in the scientific understanding of these materials and devices, identifying hurdles to large-scale manufacturing, and what direction the program should take for future activities.

1. Introduction

The session was composed of four oral presentations followed by a short panel discussion. The four speakers participated in the panel discussion and presented:

- (a) “Status of Amorphous and Crystalline Thin Film Silicon Solar Cell Activities” by Bolko von Roedern.
- (b) “Status of Hydrogenated Microcrystalline Silicon Solar Cells at United Solar” by Jeff Yang.
- (c) “Thin Silicon-on-Ceramic Solar Cells” by Paul Sims.
- (d) “Amorphous and Microcrystalline Silicon Solar Cells—A Status Review” by Xunming Deng.

Vikram Dalal, David Carlson, Tihu Wang, and Harry Atwater added key thoughts to start off the panel discussion. This paper summarizes these views; it is not a transcription of the session.

2. Benchmarking a-Si and TF-Si Technologies

Crystalline silicon (c-Si) technologies make up over 90% of the photovoltaics (PV) sales worldwide. This is obviously the benchmark to which all other PV technologies must compare. If hydrogenated amorphous silicon (a-Si:H) or other thin-film (TF-Si) technologies are to compete directly with the c-Si standard, they must achieve conversion efficiencies of ~14%. Currently none of these technologies have such performance.

In Table 1 we summarize the status of the various TF-Si technologies. We arrange them in order of grain size from none (amorphous) in the second column to nano-crystalline (nc-Si) to polycrystalline (pc-Si) to multicrystalline (mc-Si) to single crystal (c-Si). The demonstrated efficiencies summarized in Table 1 are best at either extreme and dips at the in-between grain sizes. This is not necessarily a fundamental limit, but may more closely reflect research and development funding.

Table 1: Summary of Current Amorphous and Thin-Film Si Approaches

	a-Si/SiGe	nc-Si	pc-Si			mc-Si *	c-Si *
Grain Size (μm)	Amorphous	< 0.1	0.1-5	0.1-50	10-50	100-1000	Single Crystal
Sub. Temp. (°C)	< 300	< 300	800-1200	< 300	900-1000	1000-1400	1000-1400
Typical Growth Methods	CVD	CVD	CVD	CVD, MIC, low T epitaxy	APIVT	CVD (+ZMR), APIVT, epi	epitaxy + “epi-lift,” “smart-cut”
Rates (μm/m)	0.01-0.1	0.01-0.1	1-3	0.01-0.1	1-10	1-10	1-10
Efficiencies (%)	8-13	3~10	~1	N/A	3~4	~15	~18
Cell Thk. (μm)	0.3-0.7	1-2	5-20	10-20	5-50	10-50	5-50
Cell Type	drift, stacked	diff./drift, stacked	diffusion	diffusion	diffusion	diffusion	diffusion
Pros	very high absorption, E _g tailoring	high absorption, no Ge	existing tech.	low T	low system & process costs	low-cost feedstock	infrastructure, synergy with IC industry
Cons	instable (SWE), poor red collection	post deposition oxidation	low H, small grains	slow, H-limited max. epi thickness	low H, glass or ceramic substrates	2-step processes, ceramic substrates	3-step processes, large area difficult

* = The mc-Si and c-Si technologies in this table are for thin films, supported by substrates, not bulk-Si PV (>200 μm).

The light-green-colored cells in Table 1 indicate favorable aspects of devices grown with a particular grain size, whereas light-red-colored cells indicate unfavorable aspects. If all these materials could produce devices with the same efficiency, obviously those materials grown at low temperatures and thinner cells would be most cost effective. Low-temperature processes are less expensive due to reduced energy demands during manufacturing and less stringent substrate requirements. If they are grown from gases containing hydrogen (e.g., SiH₄) dangling Si bonds are naturally passivated; at higher temperatures, H is driven from the network and requires post-growth passivation steps. Material costs increase with cell thickness. Unfortunately, not all materials produce high-efficiency devices. The bottom line is \$/Watt, so reducing cost is as important as increasing efficiency. Efficiency remains an important issue, however, in minimizing the installed area.

Included in Table 1 are a variety of chemical vapor deposition (CVD) techniques including hot-wire, RF plasma enhanced, very high frequency (VHF), modified VHF, microwave, electron cyclotron resonance, and gas jets. There is also zone-melt recrystallization (ZMR) and metal-induced crystallization combined with CVD and atmospheric pressure iodine vapor transport (APIVT).

To review the status of the performance of specific types of a-Si and TF-Si PV technologies in detail, see the other papers from this session.

3. Key Fundamental Scientific and Technical Issues

3.1 a-Si:H-based materials and devices

Three fundamental material properties limit the large-scale production of a-Si:H as low-cost PV. The Staebler-Wronski effect (SWE, which is the degradation of electronic properties of the material, and thus device performance, with illumination) forces device engineering to minimize the degradation. While there has been considerable world effort in the understanding and elimination of this effect, eliminating it would allow for device engineers to focus on initial, higher efficiency designs that would have 20%–30% higher output power than existing designs that focus on stabilized efficiency.

Because a-Si:H is a wide-bandgap material, a-Si:H PV devices perform poorly in the red portion of the solar spectra. A suitable narrow-bandgap alloy (e.g., a-SiGe:H) has proven elusive. Typically, Ge is added to a-Si:H to narrow the bandgap, however, increasing Ge is deleterious to the structural and opto-electronic properties of these alloys. Multiple cells are stacked in series, each having a different bandgap, to capture as much of the solar spectra as possible. Development of a high-quality, narrow-bandgap alloy (particularly below 1.4 eV) would allow device engineers to utilize designs that would have 15%–25% higher output power than existing designs that lose response below 1.4 eV.

Fundamentally, a-Si:H is a highly defective material with a low hole mobility. It requires H to passivate an intrinsically high concentration of dangling bonds. The

good news is that it can be deposited easily over large areas from gas sources that make H-incorporation an easy part of the growth process. Nevertheless, a “magic” a-Si:H material with high hole mobility would solve many problems.

3.2 Thin-film-Si-based materials and devices

We apply the term TF-Si to represent silicon-based PV devices other than a-Si:H (< 0.7 μm) and wafer-based c-Si (> 200 μm). In general, it applies to nanocrystalline-Si (nc-Si) films that are > 80% crystalline (< 20% a-Si:H). These films have high absorption coefficients and thus require cell thicknesses of only a few microns or less. It also applies to films with larger grain sizes, including polycrystalline-Si (pc-Si) and multicrystalline-Si (mc-Si), which require cell thicknesses of over 5 μm.

Both nc-Si and small-grained pc-Si are receiving much attention worldwide as a replacement to a-SiGe:H alloys as the bottom cell in multijunction devices. It has advantages in being much thinner than wafer-based Si, is grown at lower temperatures, and does not contain Ge, which is usually grown from GeH₄, a relatively expensive and toxic gas. However, because of a lower absorption coefficient, it needs to be much thicker than a-SiGe:H and thus requires longer deposition times. Larger-grained films eliminate the need for tandem structures altogether (lowering cost) and may be able to capture some of the advantages of c-Si, although at the cost of requiring thicker devices and post H-passivation steps.

There are some fundamental questions that must be answered to advance TF-Si technologies. Carriers pass through a complicated structure full of small, flawed crystallites, grain boundaries, and possibly some amorphous tissue. Therefore, it is important to gain an understanding of what factors limit the mobility and lifetime in TF-Si. There must be an assessment the efficacy of grain boundary passivation and the role of various intragranular defects. Experiments and modeling must determine whether the best TF-Si PV devices are going to be “a-Si:H like” or “c-Si like.”

4. Key Hurdles to High-Volume Manufacturing

The most limiting factor to large-scale production of a-Si:H as low-cost PV is relatively low conversion efficiencies relative to other PV technologies. If stable efficiencies close to c-Si were available on the module scale, it would be the dominant—or sole—PV technology. Even at low conversion efficiencies, if the material could be deposited very quickly, it would reduce manufacturing costs by increasing throughput and reducing capital equipment costs (shorter chamber for inline processes.) However, the highest conversion efficiencies are obtained at low deposition rates (Å/s rather than tens or hundreds of Å/s). This is also true for low-temperature processes to deposit TF-Si, and is a particular problem because TF-Si devices need to be thicker than a-Si:H/a-SiGe:H devices. Although some

progress has been made by VHF-CVD and HWCVD in increasing deposition rates, more progress is needed in this area to further reduce manufacturing costs. (Researchers at Julich and Neuchatel are obtaining conversion efficiencies within 10% of their best values at deposition rates of $\sim 10 \text{ \AA}/\text{sec}$.)

Most amorphous and TF-Si research and development has been done on “one-of-a-kind” systems. Each company and research team has had a relatively unique process, device design, and system configuration. The integrated-circuit manufacturers had the luxury of being able to team together large resources and make industry-standard specifications for equipment manufacturers to achieve. This combined effort, along with vast amounts of development funding, allowed for the industry to work together around common platforms, allowing each company to specialize in the individual device design without having to solve the all the process problems internally. Historically, the PV industry has neither worked together in such a unified approach, nor have they had the resources to lead such an effort. However, to move beyond the current manufacturing capacity, the PV industry will need to work synergistically with each other and with other industry. The a-Si and TF-Si technologies, especially, will need to exploit already developed experience bases such as the thin-film transistor industry for flat-panel display manufacturing. This industry has done an excellent job at tool development, and has a steeper learning curve than the PV community.

One of the important lessons learned from recent events in the thin-film PV industry is that development of the semiconductor is just one part of a complicated product that has some extreme performance, reliability, and longevity requirements. There is a need for improved reliability of modules, encapsulants, and balance-of-system components. Like the semiconductor growth, standardization of products, packages, and services will further reduce installed costs. The designation of a manufacturing center of excellence may help pull together disjointed and missing knowledge of high-throughput Si processes.

Technology advances occur either through evolution (slow steady progress) or revolution (breakthroughs). Evolutionary progress typically exceeds revolutionary, albeit less visibly. This has certainly been true with a-Si and TF-Si PV. However, more progress is needed. Research on improving optical confinement, improving p-layers (for improving the blue response), improving material properties (e.g., diffusion lengths) and developing of new heterojunctions (e.g., nc-SiC:H/n-Si:H) may provide evolutionary progress. Research on nanophotonic approaches to increase absorption, development of superlattices to boost the quantum efficiency, and attempts to create efficient carrier doubling for high-energy photons could lead to revolutionary progress.

Synergies with the bulk-Si (c-Si) and thin-film industries should also be exploited. Already, Sanyo’s

HIT cell is being called “the winner right now” [Dan Shugar, PowerLight, this conference]. This technology uses very thin layers of a-Si:H with c-Si wafers, lowering the barrier between bulk and thin-film processes, and providing an opportunity for each community to learn from the other. Further studies on these combined technologies may even bring new device physics knowledge.

5. Conclusions

Although we have focused on several of the “issues” with a-Si and TF-Si PV technologies, they have many big advantages versus other thin films (CdTe and CuInSe₂) and bulk c-Si. For example, being the lowest substrate temperature process of the PV technologies, there is less energy consumption during manufacturing. Low substrate temperatures also increase the number of substrates that can be used, including architectural glass and plastics. This is exceedingly important to the building-integrated PV (BIPV) market. Architects are very concerned with the aesthetics of their buildings, and PV systems that “look good” are most easily manufactured using a-Si and TF-Si technologies. BIPV is a large market that may eventually account for $\sim 50\%$ of the total area of installed PV. In the short term, BIPV is a significant market for a-Si and TF-Si technologies, even while efficiencies remain significantly lower than c-Si.

Currently, c-Si technologies are achieving economies of scale to allow them to be cost competitive (even advantageous) to a-Si and TF-Si technologies, in spite of the energy intensive process and device thickness in excess of $200 \mu\text{m}$. However, if PV is to go from the MW manufacturing capacity to the GW scale, such thick devices will lose that advantage and thin-film Si will be the logical choice: thin to reduce the cost of the bulk semiconductor and Si because of its abundance over exotic materials used in other thin-film technologies. Concepts of combining module and support structure costs with the cost of other structures (e.g., roofs, sound barriers, walls) will be necessary to drive down systems costs once the semiconductor costs are pushed down to the bare minimum. In addition, for very large-scale power generation, energy payback issues may turn out to be an important factor in the equation. That is, the time it takes to recover the energy of production from PV energy generation. Currently a-Si:H PV wins in this category over wafer-based c-Si (1.5 years to 5 years).

There is both a short-term and a large market for these technologies (e.g., BIPV) and a very promising future.

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