Climate and Trends in Solar Cell Technologies

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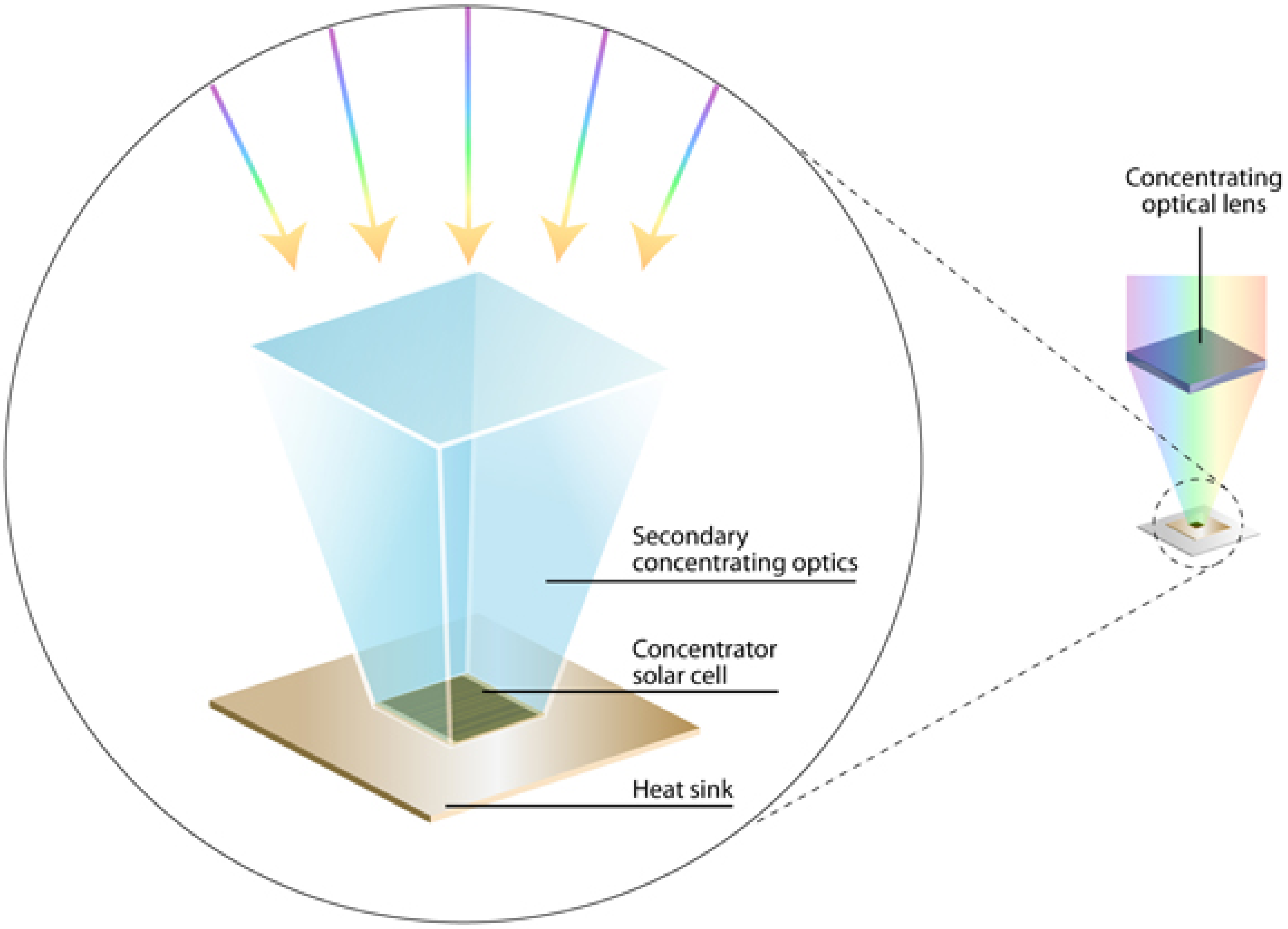
As solar energy systems evolve, there is a tendency amongst investors and industry pundits to look for “the winning technology” that has the highest efficiency and the lowest production cost. However, winning solutions for solar energy are, in fact, as diverse as the earth’s climates. The winner in an equatorial desert bears little similarity to the winner in a >45° latitude. Virtually all the current solar energy technologies have particular virtues that make them appropriate in one location and inappropriate in another.

Broadly speaking, high-efficiency crystalline silicon cells are well suited for cooler, high-latitude environments. Thin films are more cost effective in warmer, brighter climates, while very high-efficiency, high-output concentrator solar cells work in areas with minimal cloud cover, independent of temperature or latitude. Moving forward, there will be dramatic shifts in market shares as these technologies find their correct geographical niches.

This article gives a brief overview of the current technological players — crystalline wafers, thin-films, and multijunction concentrator cells — and the factors that will guide their applications. Then, we discuss a technology on the horizon: high-efficiency crystalline thin film deposited onto inexpensive substrates to provide cost-effective, high-output solar panels. The proliferation of this type of panel will eclipse climactic barriers — the same technology will work appropriately in full-sun, high-temperature deserts and low-light-intensity, high-latitude environments.



Concentrated Photovoltaic (CPV) Solar-Energy Generation

Crystalline Wafers

Crystalline silicon (Si) wafers, still the most popular material for solar cells, dominate the photovoltaic landscape with 75-90% of the entire market. Thoroughly proven in the marketplace, they are reliable due to their simple, large-area p-n junction design. Crystalline Si's relatively high efficiency has, however, a negative correlation with temperature. The hotter it gets, the less electricity it produces. Most crystalline Si solar cells decline in efficiency by 0.50%/°C. Thus, it is particularly suitable for cooler climates.

Monocrystalline Si wafers, cut from grown cylindrical ingots, make the most productive cells, with efficiencies ranging from 20-24%. The crystal lattice is continuous and there are no grain boundaries. Polycrystalline Si wafers are cut from cast, square ingots. Due to the presence of grain boundaries, they achieve about half the efficiency of single-crystal cells.

Monocrystalline cells are the most costly from a manufacturing standpoint. The raw material is expensive and there are a limited number of manufacturers. With rectangular wafers cut from cylindrical ingots, there is a substantial waste of refined Si. Improved manufacturing techniques are making wafers thinner and larger, and optimized gridlines are obscuring less surface area, improving efficiencies. Techniques for roughening the surface area, including building pyramidal structures, increase the effective surface area as well. Si ink technologies can also incrementally improve cell efficiency.

Polycrystalline Si is much less expensive to produce; wafers are cut from large, rectangular blocks produced by carefully cooling and solidifying molten Si. In the market, there is a definite trend towards polycrystalline products as technological advances lessen the effects of grain boundaries. SunPower, the world's largest producer of Si solar cells, has set records with its monocrystalline technology, recently achieving 24.2% efficiency. However, SunPower is increasingly investing in its polycrystalline product lines, anticipating the need to meet skyrocketing demands with lower-cost manufacturing solutions.

Thin Films
Thin-film photovoltaic solutions are gaining ground quickly and are expected to capture up to 30% of solar panel market share by 2013 . Production costs are significantly less than with crystalline products for a variety of reasons: deposition processes use a fraction of the raw material as wafers, the raw material need not be grown or cast, and there is no sawing or waste from unused portions.

The growing usage of thin-film cells also results from their better efficiency at higher temperatures when compared to crystalline Si cells. Whereas crystalline cells lose efficiency at about half a percent per degree centigrade, thin film decreases in efficiency at lower rates depending on the type of material. This makes thin-film solutions particularly appropriate in warmer, sunnier geographies.

Amorphous Si
Non-crystalline, amorphous Si (a-Si) was the first material widely used for thin-film solar panels and nearly six gigawatts of panel production are being built or have been announced worldwide . a-Si panels currently range in efficiency from 6-9 percent, and in 2009, Oerlikon announced test panels that can reach 11 percent using a semi-multijunction technology. However, the market factors for a-Si are oppressive, as marked by Applied Materials' discontinuance of its SunFab line of a-Si panel manufacturing equipment. A major factor in the decision was competitive pressure from crystalline Si technologies as the price of polycrystalline silicon continues to drop.

Indeed, the acquisition of OptiSolar, which used a-SI technologies, by FirstSolar, which uses cadmium telluride technologies, was seen by many as a real-estate deal — OptiSolar owned extensive desert (sunny) lands, and FirstSolar did little if anything with OptiSolar's a-Si technologies.

Cadmium telluride
Highly absorbtive cadmium telluride (CdTe) is a well-established crystalline thin-film material that lends itself to low-cost manufacturing techniques. It is typically bonded with cadmium sulfide (CdS) to create a heterojunction interface to increase efficiency. First Solar, the leading developer and manufacturer of CdTe-based solar panels, produced 1,011 MW of panels in 2009 and has lowered its manufacturing costs to $0.76/W with improvements in throughput, material cost reductions, and foreign exchange rates. Notably, FirstSolar has implemented procedures to recover

100% of the highly toxic cadmium in both manufacturing and panel recycling. This is a hugely important factor for success with green-oriented governments.

Nonetheless, CdTe films are highly resistive electrically, and although their manufacturing costs are being optimized, they may fail to meet the challenge of less-resistive copper indium gallium selenide/sulfide (CuInGaS, or CIGS) coatings.

Copper indium gallium selenide/sulfide (CIGS)
With hundreds of millions of dollars spent on researching optimal materials for solar panels, CIGS is emerging as a premier thin-film material and might indeed come to dominate the solar PV marketplace. Lab efficiencies have reached nearly 20% and this level of performance, if achievable in production panels, means CIGS thin-film panels will directly compete with the capabilities of monocrystalline Si-based solar cells. However, as yet production panels have not come close to matching the efficiencies obtained in lab environments.

An important factor in the growing success of CIGS solar cells has been the implementation of manufacturing techniques used in hard-disk media and high-speed flex-circuit printing industries. These techniques, using contiguous foils and sheet materials for substrates, are moving in the direction of the crystalline thin film on inexpensive substrate technology described later in this article.

Multijunction Concentrator Solar Cells
Multijunction concentrator solar cells are the heart of high-efficiency, concentrated photovoltaic (CPV) solar-energy solutions. CPV installations consist of arrays of concentrating optics that focus and concentrate sunlight—up to 1500x suns—onto the cells. For sunlight-intense regions such as deserts and other arid, dry climates where normal direct irradiation (NDI) is greater than 1800 kWh/m2/year, CPV solar energy is the most attractive energy solution.

Because they capture and convert much broader light frequencies than other designs, these three-junction cells, typically made of gallium indium phosphide (GaInP), gallium arsenide (GaAs), and germanium (Ge) pn junctions, can achieve efficiencies greater than 40%. The technology is on track to reach as high as 50% efficiency by 2020.

A very important factor — these multijunction cells do not lose efficiency at higher temperatures.

The raw materials for these types of cells are expensive, but the vast majority of the surface area deployed in a CPV installation is used by concentrating optics, not cells. Indeed, the amount of required cell material is 500x less than that used in crystalline solutions. However, the total cost of CPV precludes usage in lower-light climates where they would sit idle for significant proportions of time.

Currently, CPV solutions make up less than 1% of the solar energy market. However, the technology substantially outperforms all other techniques in appropriate climates and it is likely to be the dominant solar energy implementation in deserts and bright, sunny climates within ten years.

The Future — Crystalline Thin Film on Non-Crystalline Substrates

The challenge in cost-effectively manufacturing non-amorphous, crystalline thin films is how to grow crystals on non-crystalline, inexpensive matrices. In other words, combining the high efficiency of crystalline cells with the low cost of thin films.

These high-efficiency III-V crystals — structures such as GaAs, indium gallium arsenide (InGaAs), InGaP, and indium gallium nitride (InGaNi), are currently used for multi-junction concentrator solar cells such as those used in the CPV applications previously described.

These crystals are typically grown on a Ge matrix. Ge needs support and thus sits on an Si substrate. Ge just seems to work as a matrix, fooling the III-V compounds into believing that, during a chemical vapor deposition (CVD) process, the matrix is a familiar crystal lattice structure. Of course, a solid or bulk Ge substrate could be used, but Ge is expensive. Si is less so, but it is still a cost and its presence adds manufacturing complexity.

The next generation of these types of cells will forego the Si base substrate and, instead, make use of Ge-coated non-crystalline substrates such as metal or plastic foil or glass. Such a Ge-coated substrate will then undergo atomic-layer epitaxy that deposits alternating monolayers of III-V compounds. A major challenge remains to form the Ge-coated surface without detrimental defects such as unwanted grain boundaries.

Ultimately, a way will be found to forego the Ge matrix as well. In one possible scenario, seed crystals instead of Ge will be attached to the inexpensive substrate and then an epitaxial process will feed the crystal growth. The fundamental technologies for all these processes have been known since the ‘80s, but the development of appropriate manufacturing (rather than laboratory) techniques have kept them theoretical. Now, however, the technologies are getting significant attention in academic and research environments and, as the ultimate proof of concept, are being adopted commercially by several companies currently operating in stealth mode.

These developments suggest an exciting runway. Within the next decade, we will see the development of cost-effective thin-film solar panels that will reach efficiencies up to 30% — a factor 2-3x that of current thin-film panels. The effectiveness and cost of these new panels will enable the use of the same basic panel designs over all climactic environments, eliminating the need for different technologies for different light levels. The global ubiquity of these panels will drive costs even lower by enabling the highest-volume manufacturing rates.

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