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Photovoltaic research progresses rapidly from the lab to the market.

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power from the sun

The field of photovoltaics (PV)—the direct conversion of sunlight to electricity—has evolved at an incredible pace over the past several decades. PV was recognized as an important source of space power in the 1950s, and terrestrial PV development began in response to the 1970s oil crises. Over the past 30 years, PV researchers have developed new materials, devices, and fabrication approaches, improved device efficiency and reliability, and lowered module and system costs.

Concern for the environment, as well as global efforts to seek indigenous sources of energy, drives the investment in PV research and deployment. Today, PV is a several-billion-dollar industry worldwide, with more than 520 MW of PV modules shipped in 2002. In total, nearly 2 GW of PV systems are installed worldwide, generating clean electricity from sunlight. These include large, multi-megawatt installations feeding into the utility grid, kilowatt rooftop systems supplying power to a home or business, and single 50- or 100-W PV modules on homes in developing countries.

technology basics

Solar cells are semiconductor devices that produce electricity from sunlight via the photovoltaic effect. When sunlight strikes the cell, photons with energy above the semiconductor bandgap impart enough energy to create electron-hole pairs. A junction between dissimilarly doped semiconductor layers sets up a potential barrier in the cell, which separates the light-generated charge carriers. This separation induces a fixed electric current and voltage in the device. The electricity is collected and transported by metallic contacts on the top and bottom surfaces of the cell.

Applicable semiconductor materials include conventional silicon (Si), gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium diselenide (CIS), and hydrogenated amorphous silicon. There are significant differences between the best performance and the theoretically predicted value for each material; closing these gaps is the subject of ongoing research (see figure 1).

In the case of a single-junction device, the efficiency of the solar cell, the ratio of the power produced, and the incident light power are limited. Photons with energies below the bandgap of the material produce only heat. Excess energy above that needed to generate electron-hole pairs also produces heat. A multijunction device, in which two or more solar cells are stacked on top of each other, can exploit different portions of the solar spectrum. For example, a four-junction device with bandgaps of 1.8, 1.4, 1.0, and 0.7 electron volts (eV) results in a theoretical efficiency of more than 52%. The multijunction approach, however, presents significant challenges in both materials preparation and device design.

crystalline silicon

The conventional technology that supports more than 85% of today's PV market is based on wafers of crystalline Si. Production capacities are expected to more than double in the next three to five years, and the products are proven and accepted in the markets. Single-crystal ingots are pulled from the melt, or polycrystalline ingots are cast in a crucible that is consumed in the process. Technical advances include the growth of ingots as big as 300 kg, the growth of multiple ingots with melt replenishment, and the reduction of consumable materials and energy costs. Significant R&D effort has been focused on reducing defects, improving doping, and automating the growth process. Still, for single-crystal Si, the best commercial module efficiencies are only about 15%.

Si ribbon and sheet technologies, which avoid the cost and material losses associated with slicing ingots, are the first of the new PV technologies to be commercialized. About 6% of today's PV modules are made using these methods. Most notable are the edge-defined, film-fed growth process, the string ribbon process, and the Si-film process (growth of a high-speed, continuous Si sheet of a variety of substrates). Cell and module efficiencies are similar to those for polycrystalline Si wafers from ingots—about 12% at best—with somewhat lower efficiencies for the small-grained sheet materials.

Ongoing research in crystalline Si aims to improve the throughput and yield of the growth processes (especially the ribbon and sheet technologies), develop techniques for making and using low-cost Si feedstock, understand the roles of defects and impurities and minimize their impact on cell performance, develop low-cost processes for high-efficiency cells, and improve all parts of the manufacturing process with in-situ diagnostics and automation. Ongoing incremental improvements will probably reduce manufacturing costs and increase module performance,

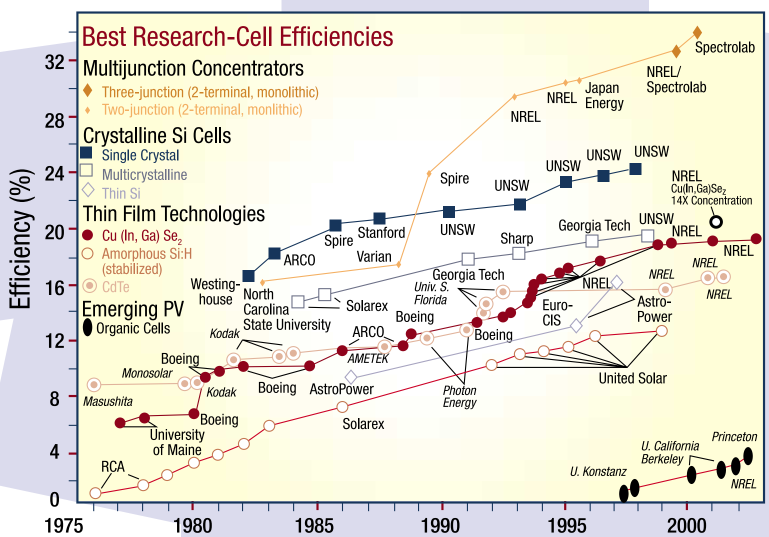

Figure 1 Solar-cell efficiencies have improved since 1976. All these cell efficiencies have been confirmed and were measured under standard reporting conditions.

keeping these technologies as the mainstay of PV markets for years to come.

thin-film technologies

Thin-film PVs are attractive because they use less material and can be manufactured on a large scale using less energy than bulk PV cells. The major approaches are based on amorphous Si, CdTe, CIS, and related alloys.

Ongoing improvements in amorphous Si cells have benefited from increased understanding of amorphous materials microstructure, its relationship to gas-phase chemistries, and the roles of hydrogen and impurities. By engineering layer thicknesses and using multijunction cell structures, developers can minimize the inherent light-induced instability of amorphous Si. Such cells have acted as sources for low-power consumer products such as calculators for more than a decade. More recently, they have found use in building-integrated applications such as flexible roofing shingles and semitransparent modules for windows or skylights. To increase market penetration, manufacturers must improve module efficiencies—currently in the 5% to 7% range for commercial products—and reduce production costs by increasing film deposition rates.

CdTe has a nearly ideal bandgap for a single-junction device (see figure 2). Efficient CdTe solar cells have been made by a variety of potentially scalable and low-cost processes. The record cell is a 16.5%-efficient device, whereas the best commercial-size module is 11% efficient. Most commercial products, however, are in the 7% to 9% range. Understanding the scale-up of the deposition processes and controlling film

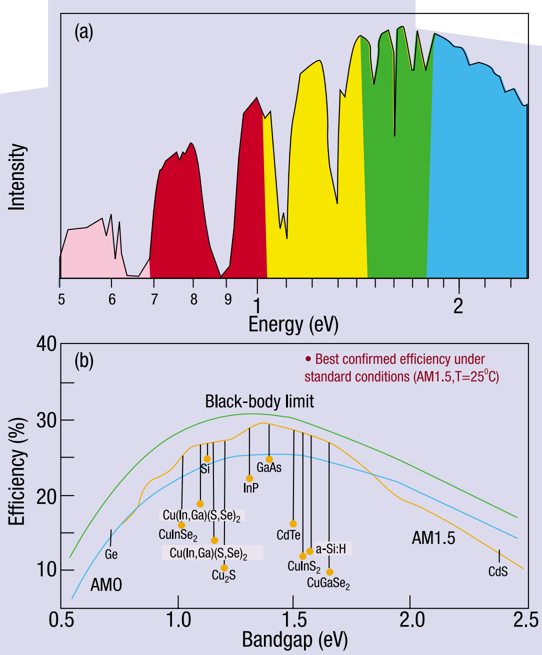

Figure 2 A four-junction device with bandgaps of 1.8, 1.4, 1.0, and 0.7 eV uses the portions of the solar spectrum indicated by the colors shown on this plot of intensity versus energy (top) and can achieve better than 52% efficiency. The plot of efficiency versus bandgap for various single-junction solar cells illustrates the gap between the current record laboratory efficiencies and those predicted under global sunlight conditions (bottom). The blackbody limit is included for reference.

properties is key to closing the efficiency gap. Other research focuses include improvements in areas like contact stability, chemical and heat treatments of the films, transparent conducting oxides at the top surface of the cell, and packaging for long-term outdoor reliability. Although there are concerns and misconceptions about the environmental, safety, and health effects of Cd, extensive studies indicate that all safety issues can be handled at a very modest cost, including the recycling of Cd from old modules.

From virtual obscurity as a semiconductor material, CIS has shown remarkable progress in efficiencies, with 19.2% achieved recently for a CIS device that includes gallium (Ga). Manufacturers have fabricated commercial-size modules with greater than 13% efficiency, and early commercial products are 9% to 11% efficient. Research centers on the effects of alloying with materials like Ga and sulfur, replacing the cadmium-sulfide window layer with Cd-free layers such as zinc sulfide and zinc oxide, and the use of non-glass substrates. Researchers also seek to understand the deposition techniques, process chemistries, and related film and device properties in order to scale up manufacturing and reduce cost. Improving the packaging of the modules for outdoor reliability is also important.

Thin-film polycrystalline Si deposited on low-cost substrates combines the inherent advantages of Si (abundance and device stability) and thin films (low material use and cell interconnection during film deposition). Some progress has been made in cell and module efficiencies and in engineering device structures to capture more sunlight in a thin layer.

Overall, the prospects for thin-film technologies are good. A number of industry players exist worldwide, mostly in a first-time manufacturing and commercialization phase. Many of the thin-film products are well suited to niche, higher-value markets such as building-integrated products or high-voltage/low-current applications for consumer products. The real promise of thin films will be realized in large-scale manufacturing of efficient and reliable products. Success will bring about competition with crystalline Si in the coming decade.

concentrators and high-efficiency devices

One means for improving PV efficiency is through concentrators, which are systems of lenses or reflectors that focus sunlight on the collecting area of solar cells. Key elements of these systems include economical concentrating optics, mounting, and tracking systems. Researchers have previously demonstrated large-scale manufacturability of all components, such as 27%-efficient Si cells that operate with light intensities up to 400 times the normal sea-level sunlight (400 suns) and 28%-efficient GaAs cells (up to 1000 suns). Manufacturers routinely produce concentrator systems that incorporate point-focus Fresnel lenses (up to 400 suns). Module efficiencies of up to 20% have been demonstrated using commercially made, 25%-efficient Si solar cells.

Multijunction, III-V-semiconductor-based solar cells can be used with concentrators. A pair of terrestrial devices based on gallium-indium-phosphide/GaAs/germanium triple-junction structures has achieved 32.2% efficiency under 600 suns and 34% under 200 suns. This cell captures the blue and green portions of the spectrum efficiently, but Ge is not the ideal third junction. Several multijunction candidates incorporate III-V materials such as gallium indium arsenide nitride because researchers can adjust the bandgap of these materials. The research involved, however, is complex. One can reasonably project that 40%-efficient solar cells capable of operating under concentrations as high as 1000 suns will be achieved in this decade.

In addition to these very high-efficiency multijunction structures with concentrators, some research groups are focusing on other PV systems that go beyond optimizing current approaches. Researchers of next-generation technologies mostly aim at higher conversion efficiencies and/or lower costs than today's technologies could achieve. Other researchers are exploring nonconventional PV technologies that could quickly overtake today's best technologies.

Several research projects, including multijunction structures with novel concentrators or multijunction thin films, might double the efficiencies of today's modules. The Graetzel cell, a dye-sensitized titanium-oxide device, has the potential for very low-cost processing. Interest in plastic solar cells is growing, spurred by the rapid successes in organic light-emitting diodes. Quantum dots, nanostructures, thermophotovoltaics, and defect-layer solar cells are other areas of research. By mid-century, photovoltaics will undoubtedly be much different from the technologies of today, governed by new physics, new materials, new processing, and ingenious device engineering. **oe**

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