SERI/TP-211-2733
UC Category: 63
DE85012133

Terrestrial Photovoltaic Research and Development

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June 1985

Prepared for the
20th Annual Intersociety Energy
Conversion Engineering
Conference '85--Energy
for the 21st Century
Miami Beach, Florida
18-23 August 1985

Prepared under Task No. 3452.10
FTP No. 522

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

ABSTRACT

Developing practical photovoltaic (PV) devices for the conversion of sunlight into electricity on earth requires R&D to build on the knowledge acquired during the successful space-PV development program. It also requires new generations of materials and structures specifically designed for the terrestrial environment. Silicon ribbon technology has had marked success as an adaption of the single-crystal and polycrystalline silicon technologies. A new generation of terrestrial PV technologies is emerging based on single- and multi-junction thin-film flat plate and concentrator systems. These are the technologies being emphasized in the research program conducted by the Solar Energy Research Institute as part of the U.S. Department of Energy's National Photovoltaics Program. This paper examines the status of silicon ribbons, thin films, and concentrators, as well as their application in various potentially high-performance, cost-competitive structures.

ALTHOUGH PHOTOVOLTAICS (PV) is one of the more successful solar technologies, the transition from laboratory research to practical application is a difficult one. By various measures, the cost of photovoltaic power has fallen two-to-three orders of magnitude over the last 20 years, but solar cells are still not commercially viable in competition with conventional power sources such as oil, natural gas, coal, and nuclear. Sunlight is a diffuse energy source, and solar cells are complex electronic devices. Developing solar arrays of practical dimensions for multi-megawatt energy production makes exceptional demands on our state-of-the-art understanding of electronic materials and their processing. New PV technologies have been conceived and developed specifically for terrestrial use. These terrestrial PV technologies take three main approaches:

- Ribbon silicon
- Thin films
- Concentrators

Ribbon silicon is the adaption of the successful single-crystal and polycrystalline silicon (Si) solar cell technologies which are the mainstay of the current terrestrial PV market. High-performance solar cells are made by growing high-quality continuous Si ribbons at high rates and in large sizes. These ribbons can approach the performance of single-crystal Si cells, but at potentially reduced costs. The key economic advantages of thin film solar cells are their low materials and processing costs. Their difficulty is in achieving high efficiency. Concentrators gain their economic advantage by focusing a large area of sunlight on a small-area solar cell. By replacing the solar cell area by an optical concentrator, cost savings are achieved. These approaches form the basis for the Department of Energy's (DOE) and the Solar Energy Research Institute's (SERI) national program to develop PV technologies with commercial potential. The Program's research goals are ambitious (1). Practical central power application is projected to require module sunlight-to-electric conversion efficiencies of 13%-17% and costs of $40-$75/m^2 for flat-plate technologies; and 23%-29% conversion efficiencies and $90-$160/m^2 costs for concentrators. These goals are current best estimates for PV to be cost-competitive in central power applications in the late 1990's; however, profitable near-term PV markets exist and are already being explored internationally. Circumstances, energy costs, interest rates, and developments in the technology itself will continually refine and update these projections. However, the DOE/SERI goals form the basis for a "best guess" at the kind of overall cost/performance required. The national program is designed to explore avenues for meeting these goals.

SILICON RIBBON

Silicon ribbons can be pulled from a melt by various methods, forming high-quality silicon sheets of practical width and thickness for solar cell fabrication. A number of reviews of silicon ribbon growth have been published in recent years (2-4) which provide a variety of viewpoints on the subject. Of the many approaches to silicon ribbons, two are deemed to be the most promising in view of their advanced stage of development. They are: dendritic-web silicon and edge defined film-fed growth (EFG) of silicon ribbon.

Denritic-web silicon growth, developed by Westinghouse Electric Corp. (5), is the only ribbon process that currently produces an effectively single-crystal silicon sheet. In this process, two single-crystal silicon dendrites, formed from a single-crystal seed, are propagated downward in the [211] crystalline direction into a supercooled melt at the rate of ribbon withdrawal. A liquid silicon film forms between the two dendrites, which are both part of the same single crystal. This film freezes a few millimeters above the melt with the same single-crystal structures as possessed by the growing dendrites. For stable growth, a set of twin planes forms in the plane of the web surface, but buried in the interior of the web. The web surfaces are both (111) crystallographic planes, as shown in Figure 1. Typically, ribbon widths of 5 to 6 cm are grown at a linear rate of 1 to 1.5 cm/min with a thickness of 150 microns. Solar cell efficiencies of over 16% have been reported.

Mobil Solar Energy Corp. has been developing the EFG ribbon process for more than 10 years (6). The EFG ribbon process is the only commercial ribbon process at this time. Mobil Solar is manufacturing and supplying EFG modules at nearly 200 kW per year. The EFG process depends on a silicon-wetted graphite capillary die, as shown in Figure 2. This die is immersed in the silicon melt, which is typically contained in a graphite crucible. To start ribbon growth, a seed ribbon crystal is brought into contact with the top of the wetted die and vertical withdrawal is begun. Ribbons of 10 cm width are routinely pulled in multiple-die growth systems. Mobil Solar has also developed a variant of the EFG process that has become the preferred production approach. In this process, a nine-sided silicon tube (or nonagon) is grown using a single, closed-form nine-sided die (7). Currently, nonagons 5 cm on a side are pulled in length of over 5 m; typical thickness is 250 to 300 microns at a growth rate of 2 to 2.5 cm/min. Solar cell efficiencies for EFG ribbon are typically 11%, with highest efficiencies reported to be 14%.

Single-crystal silicon has demonstrated consistent progress in achieving high efficiencies. Recently, Green (8) produced a 19%-efficient silicon device using high quality float-zone silicon. Important future research in ribbon growth will concern continued improvement in sheet quality and cell performance to reach the level demonstrated by Green. This will require better understanding and control of grain boundaries, defects and impurities, and passivation of defects. Further, economic issues such as thin ribbons, long continuous ribbon growth, melt-replenishment, and ribbon yield will have to be addressed if ribbon silicon is to meet the DOE goals for performance and cost. A key problem to be resolved, to improve ribbon throughput and yield, is the effects of thermal stresses/strains on ribbon quality.

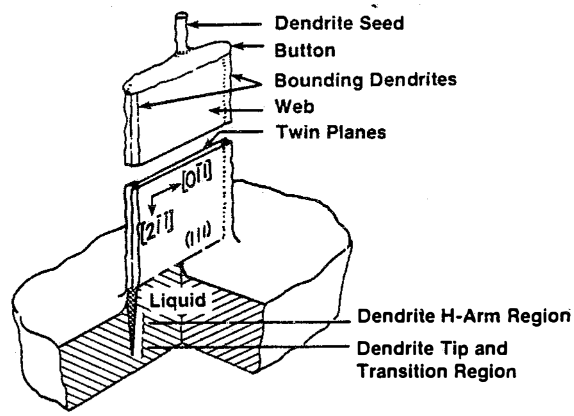


Figure 1. Westinghouse Electric Corp. Dendritic-Web Process

THIN FILM SOLAR CELLS

Thin film solar cells exploit the optical properties of direct bandgap semiconductors. Such semiconductors can absorb most of the sunlight available for conversion in about a micron of thickness. This contrasts with crystalline silicon (an indirect bandgap semiconductor) which requires an optical path length of

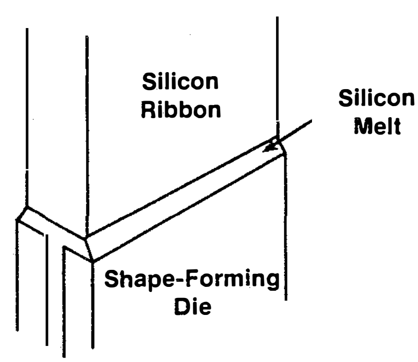


Figure 2. Mobil Solar Energy Corp. Edge-Defined Film-Fed Growth Process

about 20 microns for the same sunlight absorption. There are a large number of semiconductors that have a direct bandgap, and the history of thin film research and development has been the selection and investigation of these materials. In the last few years, a handful have emerged as the leading contenders: amorphous silicon, copper indium diselenide, cadmium telluride, and gallium arsenide. The state-of-the-art performance of these materials is given in Table 1.

Table 1. Best Single-Junction Thin-Film Solar Cells

Material	Best Efficiencies (Small areas)	Largest Areas (over 5% Efficiency)	Major Research Groups
Amorphous Silicon	10% - 11%	3700 cm^2	Over 10 Japanese, 6 U.S.
Copper Indium Diselenide	10% - 11%	91 cm^2	ARCO Solar, Boeing SERI, IEC
Cadmium Telluride	10% - 11%	4800 cm^2	Matsushita, Kodak, Monosolar, ARCO Solar
Gallium Arsenide	9% - 10% (poly)	9 cm^2	Southern Methodist University
	19% (CLEFT)*	1 cm^2	MIT Lincoln Labs

*Cleavage of Lateral Epitaxial Films for Transfer

The materials in Table 1 are the most mature and successful of the new thin-film technologies developed during the last decade. Of them, amorphous silicon has had the most support, including an especially large research effort in Japan. Its attractions are the success of large-area deposition using glow-discharge methods; relatively high efficiencies; an apparent familiarity based on experience with other silicon technologies; and amenability to several structures (see Cascade Cells, below). Amorphous silicon has progressed rapidly since research began in about 1975. Both small-area efficiency and cell size have shown consistent improvements (Fig. 3). Amorphous silicon's major disadvantage is degradation caused by illumination. Material optimization and the selection of proper cell designs appear to have reduced long-term degradation to manageable proportions (under 20%), and ARCO Solar's recent 1-ft^2 amorphous silicon panel is guaranteed for one year. A great deal of research effort is being devoted to the solution of this degradation problem in amorphous silicon (9).

Another class of thin-film material with a potential for low cost are the polycrystalline thin-film semiconductors. Two of the most successful direct-gap polycrystalline semiconductors are copper indium diselenide ($CuInSe_2$) and cadmium telluride (CdTe). $CuInSe_2$ has been developed almost exclusively in the United States, initially under the DOE/SERI program. Its advantages are relatively high efficiency; initial success in scaling-up to larger areas; and a demonstrated stability over long durations under illumination. Its major disadvantages are its narrow scientific base (few research participants and a relatively small research effort to date) and the need to scale-up its fabrication to commercial areas of 1000 cm^2 and more. The major research efforts currently underway in $CuInSe_2$ are to improve its efficiency and to develop a potentially low-cost commercial fabrication method. The material's efficiency is hampered by a lower-than-expected open-circuit

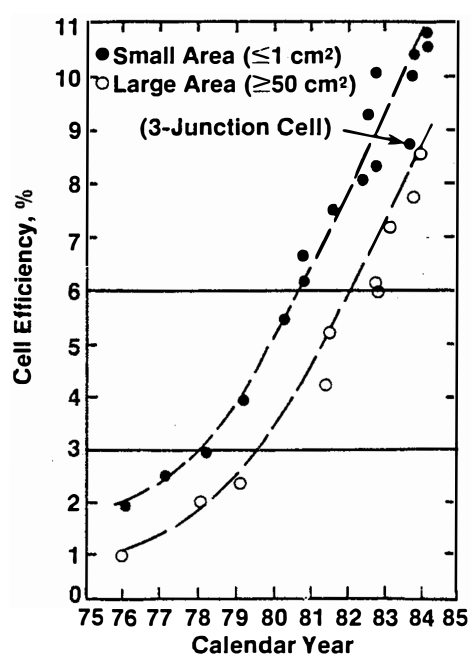
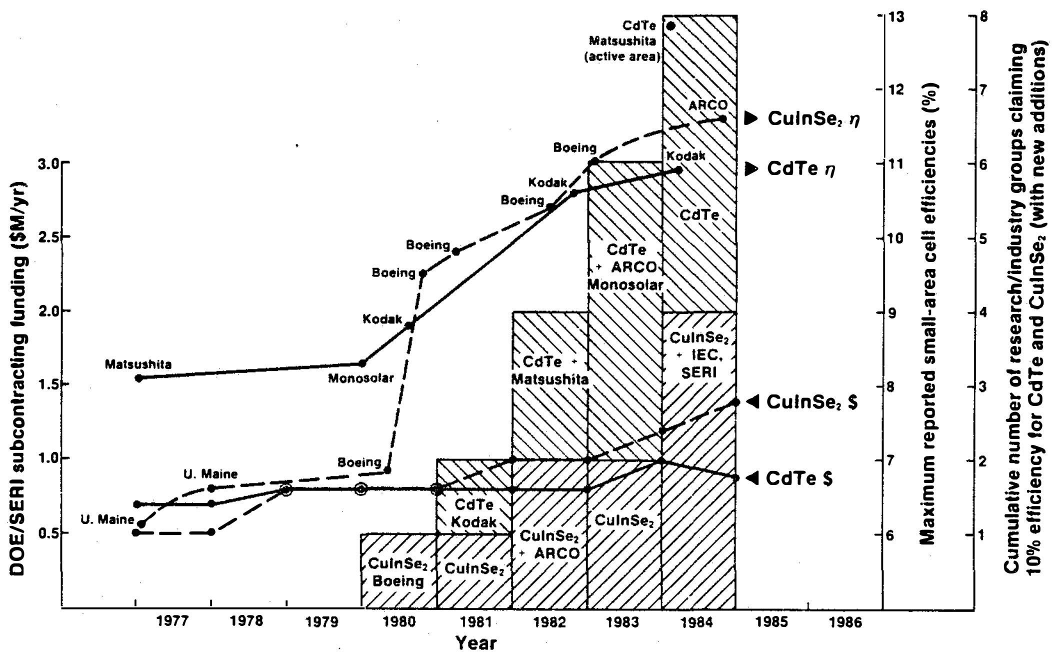


Figure 3. Efficiency of a-Si p-i-n Solar Cells Prepared by Glow Discharge

voltage (under 450 mV). Other materials demonstrate voltages about two-thirds their energy gap, which for $CuInSe_2$ would be about 650 mV. Attaining this voltage would produce $CuInSe_2$ cells with efficiencies well over 15%.

CdTe has a longer history than $CuInSe_2$ as a PV material. Its commercialization is led by a very successful effort by Matsushita in Japan. The advantages of CdTe are its good efficiency; its deposition in very large areas; and the success of a number of potentially low-cost methods for its fabrication. Stability may be a problem with CdTe, especially at the electric contact to the p-CdTe. However, Matsushita recently reported that their modules had demonstrated no observable degradation after 400 days exposure outdoors. The major research areas being investigated are the optimization and stability of the p-CdTe contact and the potential control of conductivity through heat-treatments and extrinsic doping. Figures 4 and 5 summarize the history and present status of the $CuInSe_2$ and CdTe technologies.

Gallium arsenide (GaAs) is a direct gap material with a great deal of success in PV. Single-crystal GaAs cells have demonstrated the highest efficiencies (over 22%) of any single-junction solar cells (10). Single-crystal GaAs and its alloys are of great interest for concentrator structures (see below). For large-area, flat-plate applications, GaAs must be made inexpensively. Two approaches are being taken: the growth of polycrystalline GaAs and the growth of single-crystal GaAs on reusable substrates. These methods converge in the sense that research efforts to grow polycrystalline GaAs on low-cost substrates attempt to recrystallize or otherwise enlarge the GaAs grains so that the cells perform more like their high-efficiency single-crystal analog. Polycrystalline GaAs cells are particularly sensitive to grain boundary problems. Passivation of grain boundaries, or minimizing their number, are avenues for improving polycrystalline GaAs solar cells. Approaching the problem from the other direction, several groups have attempted to grow nearly single-crystal GaAs by low-cost methods. MIT/Lincoln Laboratories grows GaAs on a single-crystal structure of patterned GaAs. The resulting single-crystal GaAs film can easily be cleaved from the substrate. The peeled GaAs film can be used to make a high-efficiency cell, while the patterned GaAs substrate can be re-used as a substrate for another peeled film. The process is called CLEFT by MIT, and has resulted in very efficient cells (see Table 1). The major research problems are to assure the continued usability of the expensive single-crystal GaAs substrate, and to assure the ultimate economics of the peeled film process for large areas. Another group (United Technologies) is growing single-crystal GaAs on single-crystal sodium chloride. This novel approach may result in single-crystal GaAs grown on a potentially low-cost, discardable substrate.



*The efficiencies recorded here are reported in the literature or at public meetings. They do not necessarily represent measurements done under standard conditions.

Figure 4. Polycrystalline Thin-Film Cell Efficiencies (Reported) and DOE/SERI Funding Chronology

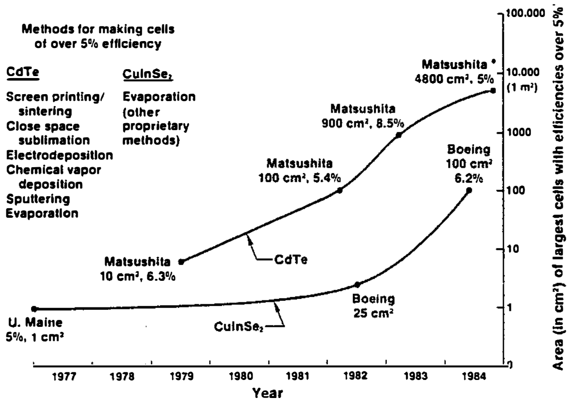


Figure 5. Large-Area Polycrystalline Thin-Film CdTe and $CuInSe_2$ Cells

CASCADE CELLS--Each of the four most promising thin-film technologies has the potential to attain the low-cost, moderate-efficiency goals of the DOE PV Program. They are also capable of success in near-term markets other than central power production. A great deal of technological progress is being made by companies exploiting the small-power markets. Perhaps the most important development arising from the maturation of the thin-film technologies is the possibility of combining them in new, more complex, but potentially more efficient PV structures called "cascade cells." The amorphous silicon technology pioneered the use of all-thin-film flat-plate cascade cells. It was found that thin amorphous silicon cells are more stable than thicker ones. To take advantage of this, two-junction amorphous silicon cells are made in which two thin cells are physically stacked on top of each other with a tunneling contact connecting them electronically. The light passing through the top cell produces current in the bottom cell, and the combination can be as efficient, but more stable than, a thicker single-junction cell. However, the potentially most important advantage of the cascade design is that it can be made with two different materials that use the solar spectrum more effectively than either alone. Usually, a higher bandgap cell is stacked on a lower bandgap cell, and the bottom cell uses the sunlight that passes through the top cell. Progress in thin-film technologies allows their combination into two-junction cascade cells that are more efficient than any of them separately. Some thin-film cascade cells of current or potential interest are shown in Table 2.

Developing the variety of combinations in Table 2 will make exceptional demands on the technology base already developed in thin films, but the promise is flat-plate solar cells of low-to-moderate cost and of efficiencies over 20%. The subject of flat-plate cascade cells is too broad to detail here, but the central research issues concerning their development are:

1. Selecting optimal structures (two- or four-terminal) based on economics and performance.
2. Developing optimal combinations of top/bottom cell materials.
3. Developing or optimizing transparent electronic interconnection or separation of top and bottom cells.
4. Minimizing photon losses in the top cell.

The potential practical efficiencies given in Table 2 are based on a simple model of 4-terminal cascade cells in which the total effi-

Table 2. Two-Junction Thin-Film Cascade Cells

Top Cell	Bandgap (eV)	Bottom Cell	Bandgap (eV)	Approximate Highest Theoretical Efficiency **	Near-Term Efficiency Using Currently Available Technology	Potential Practical Efficiency
α-Si[†]	1.75	$CuInSe_2$	1.0	$\eta(\alpha\text{-Si}) + 0.5\ \eta(CuInSe_2)$	16.5%	20% - 25%
α-Si	1.75	xSi*	1.1	$\eta(\alpha\text{-Si}) + .45\ \eta(xSi)$	20%*	20% - 25%*
CdTe	1.5	$CuInSe_2$	1.0	$\eta(CdTe) + .45\ \eta(CuInSe_2)$	16%	20% - 25%
GaAs (CLEFT)	1.4	xSi*	1.1	$\eta(GaAs) + .35\ \eta(xSi)$	27%*	25% - 30%*
GaAs (CLEFT)	1.4	$CuInSe_2$	1.0	$\eta(GaAs) + .4\ \eta(CuInSe_2)$	23.4%	25% - 30%
α-Si	1.75	α-SiGe	1.3-1.5	$\eta(\alpha\text{-Si}) + .35\ \eta(\alpha\text{-SiGe})$	15%	18% - 20%
GaAs-alloy (P or Al)	1.75	$CuInSe_2$ or xSi*	1-1.1	$\eta(\text{GaAs-alloy}) + .45\ \eta(\text{Si or } CuInSe_2)$	—	25% - 30%*
CdTe-alloy	1.75	$Hg_xCd_{1-x}Te$	1.2-1.3	$\eta(\text{CdTe-alloy}) + .45\ \eta(Hg_xCd_{1-x}Te)$	—	20% - 25%
$CuGaSe_2$	1.7	$CuInSe_2$	1.0	$\eta(CuGaSe_2) + .5\ \eta(CuInSe_2)$	—	20% - 25%
α-Si	1.75	$Hg_xCd_{1-x}Te$	1.2-1.3	$\eta(\alpha\text{-Si}) + .4\ \eta(Hg_xCd_{1-x}Te)$	15%	20% - 25%

[†]Amorphous silicon

*Hybrid cell with crystalline Si(xSi); not all-thin-film.

**Non-current matching; 4-terminal; based on the AM1.5 efficiency (η) of the top cell plus the AM1.5 efficiency of the bottom cell multiplied by the fraction of photons it sees with without a top cell over it.

ciency is the top cell's efficiency plus a fraction of the bottom cell's efficiency corresponding to the expected fraction of light it would "see" compared to what it sees without a cell above it. All of the technologies listed in the table are deemed to be capable of meeting the cost/performance goals of the DOE PV Program (1), with no clear winner seen among the options. It is conceivable, in fact, that additional cascade cell combinations will emerge as the research base of new materials expands.

The thin-film technologies are strong contenders for the ultimate commercialization of PV. As single-junction devices, they are easy and potentially inexpensive to make and may ultimately approach the performance of their single-crystal analogs. As two-junction devices, their major drawback (efficiency) is lessened, while their cost remains potentially low. Developing these or even more complex thin-film structures (e.g., three or more junctions, graded bandgap cells, etc.) will ultimately guarantee that solar cells provide a significant contribution to our terrestrial electric generating capacity.

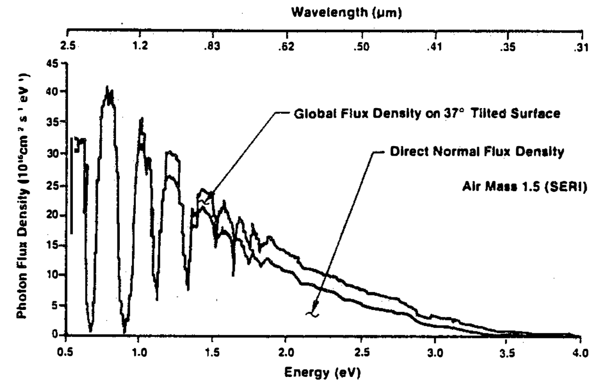


Figure 6. Comparison of Global and Direct Solar Spectra. Flat-plate technologies can use the global spectrum; concentrators cannot use diffuse sunlight, so their energy output depends on the direct spectrum.

CONCENTRATOR CELLS

Most solar cells actually improve in sunlight-to-electricity conversion efficiency if a high concentration of sunlight is focused on them. In fact, the highest single-junction solar cell efficiency (26%) ever measured is for a GaAs cell made by Varian and measured under 385 suns of concentrated sunlight (11). Recently, a single-junction Si concentrator cell, with a novel device structure, was measured to be 22% efficient under 138 suns (11). Concentrator cells exploit the improvement of some cells under focused sunlight. Their main economic advantage comes from the fact that a large area of relatively inexpensive optical-focusing mechanism can focus sunlight on a small-area solar cell. Therefore the optical element can replace the high cost of making large areas of high-quality, but expensive, solar cells. The solar cells used in concentrators are expensive; they are usually single-crystal devices grown by costly methods. The cells may be single junction or cascade, grown epitaxially on a single-crystal substrate. One requirement for all concentrators is that they must track the sun to focus its rays on the solar cell. Diffuse sunlight, reflected from clouds or from the sky, cannot be focused by the lens and is not available for concentration; a cloudy day produces little output. Figure 6 shows standard "direct" and "global" spectra; the latter contains diffuse sunlight and is available to all flat-plates. The loss of diffuse sunlight (about 20% of the total) and obscuration by clouds are drawbacks to the concentrator approach. However, all PV technologies have system related losses (tracking vs. nontracking, tilt angle, spectral variations, temperature), and specific analyses are needed to clearly show if any are favored or eliminated thereby.

Concentrator systems based on single-junction Si cells are commercially available today, and several large installations (up to a few megawatts) are in place. Laboratory prototypes of 1000-suns concentrators using GaAs cells have been fabricated. In addition to improving the single-junction GaAs and Si cell efficiencies, the current research emphasis is on high efficiency concentrator cells using the cascade-cell approach. Materials of current interest for the top cell include AlGaAs and GaAsP, while bottom-cell materials include Si, GaInAs and GaAsSb. One of the successes of the SERI-supported concentrator program was the report by Varian of a 21.5% efficient single-junction GaInAs low-bandgap cell at 175-320 suns concentration. GaInAs, with a bandgap near 1.1 eV, provides concentrator systems with a potentially attractive bottom cell for GaAs-alloy top cells. Research is underway on various combinations of top and bottom cell materials. The cells may be mechanically stacked, or grown monolithically with a lattice-grading layer. Two-, three- and four-terminal designs are being considered. The major thrust in the research is the improvement of material properties to simultaneously achieve high efficiencies in both the top and bottom cells. Research breakthroughs will also be required in putting top and bottom cells together, both from the standpoint of avoiding damage during processing and of meeting the performance requirements of transparent interconnects between cells. It is expected that the research will result in the achievement of greater than 30% efficient concentrator cells.

CONCLUSIONS

The greatest progress over the last few years in photovoltaics has been the maturation of new technologies specifically designed for terrestrial electric power generation. Future progress should result from exploiting these new technologies and their combinations. By properly supporting research involving these terrestrial PV technologies, solar cells with high efficiencies and reasonable costs can be developed and can eventually make a significant contribution to electric power production.

ACKNOWLEDGMENTS

This work was supported by the U.S. DOE under Prime Contract No. DE-AC02-83H10093. The authors would like to thank E. Sabisky, A. Hermann, and J. Benner of the Solar Energy Research Institute for useful discussions.

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