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Recent Advances in Solar Cell Technology

Geoffrey A. Landis,* Sheila G. Bailey,† and Michael F. Piszczor Jr.‡
NASA Lewis Research Center, Cleveland, Ohio 44135

The advances in solar cell efficiency, radiation tolerance, and cost over the last decade are reviewed. Potential performance of thin-film solar cells in space are discussed, and the cost and the historical trends in production capability of the photovoltaics industry are considered with respect to the requirements of space power systems. Concentrator cells with conversion efficiency over 30%, and nonconcentrating solar cells with efficiency over 25% are now available, and advanced radiation-tolerant cells and lightweight, thin-film arrays are both being developed. Nonsolar applications of solar cells, including thermophotovoltaics, alpha- and betavoltaics, and laser power receivers, are also discussed.

Introduction

FOR future space solar arrays, improved performance is desired in five solar cell parameters: 1) energy conversion efficiency, 2) weight, 3) tolerance to the space radiation environment, 4) cost, and 5) high-volume cell production and array assembly.

Improvements have been made in each of these parameters; however, not all of these have been achieved in the same cell type. Recent progress is reviewed by Flood and Weinberg.[1]

There are three approaches to large-area photovoltaic arrays in space. The conventional approach, used on all existing satellites, is to make flat-plate arrays from individual crystalline solar cells. The material used on spacecraft in the past is silicon (Si). Silicon is still used for some new satellites, but gallium arsenide (GaAs) solar cells, with improved efficiency, have now widely replaced Si in applications where high efficiency is required. An alternative cell material, indium phosphide (InP), is also under development, but is not yet in use. This cell has a considerably higher tolerance to radiation.

An alternative approach is to use solar concentrators with extremely high efficiency solar cells. Such an approach has yielded the highest conversion efficiencies achieved to date.

A third approach is to use thin-film, integrally connected solar cells, adapting technology that has been developed for use in low-cost terrestrial solar arrays. Thin-film materials used include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide ($CuInSe_2$). This approach has the potential for low weight and low cost, and has been demonstrated to have extremely high tolerance to radiation; but is unlikely to achieve the high efficiency of single-crystal technologies. Thin-film technology has not yet been used in space, although individual solar cells have been tested in space, confirming the high tolerance to radiation.

Research is ongoing to increase the efficiency, lower the cost, and increase the specific power (W/kg) for all three of the approaches discussed.

Single-Crystal Cells

Table 1 summarizes the air-mass zero (AM0) efficiencies achieved in the laboratory of a variety of single junction solar cells, both without concentration (one sun) and concentrator. For many decades, the solar cell technology of choice was the conventional silicon solar cell.[2] Over the last few years, for missions where high efficiency is required, this technology has been supplanted by solar cells made of GaAs, typically produced on germanium substrates, which have higher efficiency and somewhat higher cost than silicon cells. Progress in efficiency of terrestrial solar cells is reviewed.[3]

While currently used Si solar cells only have efficiency of about 14%, over the last decade tremendous advances have been made in Si solar cell efficiency. Advanced Si solar cells have been manufactured with efficiency approaching 21% AM0.[4] These solar cell designs are not yet space qualified, however, and preliminary tests indicate that they are not tolerant of radiation damage.[5] Future ultrathin, light-trapping Si cell designs may be both highly efficient and radiation tolerant.[6]

The state-of-the-art Si space solar cell is a large area (8 × 8) cm cell, 0.2 mm thick, covered with a 0.125-mm-thick ceria-stabilized glass microsheet. This cell, 10-Ω-cm base resistivity, with dual antireflective coating and a back surface field, has an average efficiency of 14.5% at 28°C, beginning of life (BOL). These cells are currently in production for the power system for the International Space Station.[2]

III-V materials have efficiency routinely produced in (small area) laboratory cells in excess of 20%.[7] Larger-area commercial GaAs solar cells are available at 18.5% AM0 efficiency, with higher efficiency available by special order. The desire to reduce cost and breakage has led to the production of III-V cells on germanium (Ge) substrates.[8] The current cost of 5-cm

Table 1 Achieved efficiency of single-crystal solar cells under space (AM0) conditions

Cell type	Cell area, cm^2	Efficiency at 25°C, %
One sun cells		
Conventional Si[a]	64	14.6
Advanced Si	4	20.8
GaAs	4	21.8
InP	4	19.9
Ge	4	9.0
GaInP/GaAs	0.25	25.7, monolithic cascade
GaInP/GaAs/Ge	4	23.3, monolithic cascade
AlGaAs/GaAs	0.5	23.0, monolithic cascade
AlGaAs/GaAs/InGaAsP	0.5	25.2,[b] mechanical stack cascade
Concentrator cells		
GaAs	0.07	24.6, 100X AM0 concentration
GaInP/GaAs	0.25	26.4, 50X AM0 concentration
GaAs/GaSb	0.05	30.5, 100X AM0 concentration

[a]Gridded back-contact commercial space cell. [b]Aperture area.

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*Senior Research Associate; currently at Ohio Aerospace Institute, 22800 Cedar Point Road, Brook Park, OH 44142.
†Scientist, Photovoltaics Branch.
‡Electrical Engineer, Photovoltaics Branch. Member AIAA.

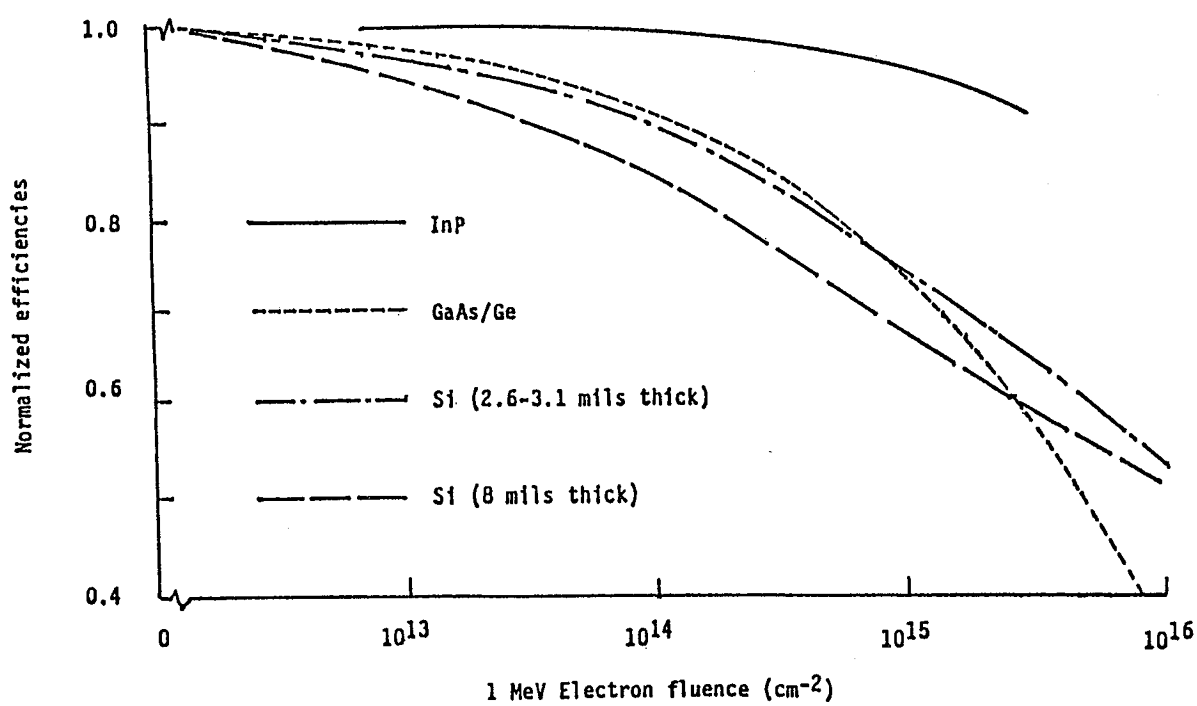

Fig. 1 Degradation caused by the radiation of InP, GaAs, conventional (8 mil) Si, and thin (3 mil) Si solar cells.

semiconductor grade wafers for solar cell production is \$3.00 for Si, \$65.00 for Ge, \$100.00 for GaAs, and \$200.00 for InP. The current costs for a GaAs (on Ge) cell is roughly twice the cost of an Si solar cell of the same area. Cell cost, however, is only a small component of the cost of an array, and in many missions the increased efficiency is more important than the cell cost increase.

The solar cell selected for the next generation of space solar cells is a tandem (cascade) structure using a high-bandgap gallium–indium phosphide (GaInP) top element grown directly on a GaAs bottom layer.[9] The best GaInP/GaAs to date has 25.7% AM0 efficiency,[10] and 4 cm^2 cells are now being manufactured with efficiencies of 21.5%. A program is now under way to bring this cell design to manufacturing readiness, with a target of achieving 22–24% conversion efficiency in mass production. An obvious next step for this material system will be to make an active Ge bottom cell. Such a bottom cell should allow efficiencies to increase to over 30% in the laboratory, and over 25% in production. Currently, three-junction GaInP/GaAs/Ge cells have been produced with efficiency as high as 23.3%,[11] and a significant amount of research on the material system is in progress.

Nearly as high efficiency has been achieved on a three-cell cascade using an AlGaAs/GaAs tandem stack over an InGaAsP bottom cell.[12] However, the mechanically stacked configuration used is extremely complex, and unlikely to be useful for a commercial cell. Without the bottom InGaAsP element, the best efficiency achieved of this combination is 23%.

Missions requiring radiation tolerance have led to the development of InP cells. These cells may be of great significance for commercial satellites in high-radiation orbits.[13] InP solar cells potentially have efficiency equivalent to that of GaAs, with vastly superior tolerance to radiation, as shown in Fig. 1.[1] (Note that 10^{15} e^-/cm^2 corresponds to approximately 10–15 years in geosynchronous orbit with typical shielding thicknesses.) InP solar cells tested on the LIPS satellite have shown no degradation after five years in space. A difficulty with InP is the cost of the material. Several methods of growing InP on low-cost substrates are currently under development. InP solar cells are not yet being manufactured commercially, although several thousand InP solar cells were produced by the Japanese to power a lunar orbiter on the Japanese Space Agency scientific satellite MUSES-A.

Growth of InP on Si and GaAs are efforts to develop a less expensive InP cell by using a lower-cost substrate. Efforts are also in progress to remove the thin InP solar cell structure from a reusable substrate by mechanical techniques[14] or preferentially etched epitaxial liftoff.[15] Both of these techniques also apply to other III-V structures and hold great promise for future crystalline thin-film solar cells.

Concentrator Arrays

In missions requiring a minimum array area and a high degree of protection for the photovoltaic device, concentrator arrays provide a promising alternative to planar structures. The advantages of the concentrator systems rely on minimizing the cell area and replacing it with high-efficiency, light-concentrating optics. For a given temperature, properly designed photovoltaic devices are more efficient under concentration. Since cell area is significantly reduced (typically by a factor of 15–100, depending upon the system concept), it is also much easier to protect the cell from the natural radiation environment. Thus, the capability exists to design relatively lightweight arrays that survive in extremely harsh radiation orbits. There is also significant potential for cost reduction based on reducing the total amount of semiconductor area and replacing it with relatively low-cost optics.

Concentrator systems require more precise tracking of the sun than flat-plate systems, which produce significant power even when pointed off-sun by 45 deg or more. The precision required is typically on the order of a few degrees and is highly dependent upon the specific design, the desired cell concentration ratio, and whether the primary concentrator is a line or point-focus design. For example, the two-axis pointing requirements for the minidome Fresnel concentrator utilizing an optical secondary, are ± 3.5 deg.[16] Although more restrictive than a flat-plate array, this is still an order of magnitude less stringent than the pointing required by solar dynamic concentrating systems, and well within the capability of modern tracking systems.

Photovoltaic concentrator concepts were looked at a number of years ago for civilian missions. During the 1980s that work transitioned into military programs where the emphasis was survivability from man-made threats. While many concepts were proposed, most of the work centered on systems using line-focus and point-focus reflective optics. Changes in the world political structure eventually eliminated those programs, or changed their emphasis to high-performance/low-cost systems. Much of the recent work on concentrator systems has centered on the use of domed-refractive optics.[16] The refractive concentrator system uses a domed lens design that has high optical efficiency and is extremely insensitive to shape errors and thermal distortions. A point-focus version of this concept is currently flying on the photovoltaic array space power plus diagnostics (PASP Plus) flight experiment. Results to date have shown no significant performance degradation of the lens or cells.[17] A design using a linear refractive element is now being developed for flight. The line-focus design eases the requirement for precise tracking to a single axis and is much simpler to manufacture than domed systems, which implies reduced array costs.[18]

Early cell-development work designed to support the first concentrator systems centered on single-junction GaAs cells. The best laboratory GaAs concentrator cells have reached AM0 efficiencies approaching 25% at concentrations of 100 suns.[19] However, it was not long before higher-efficiency multijunction devices were being considered, in which a lower bandgap solar cell is placed underneath an infrared (IR)-transparent higher bandgap cell. A mechanically stacked gallium arsenide/gallium antimonide cell[20] has achieved efficiency in excess of 30%.[21] (Note that the cell efficiency of 30.5% does not account for optical losses in the concentration system, projected to be about 15% for current lenses without antireflective coatings.) Adaptation of the recently developed planar GaInP/GaAs monolithic devices to concentrator designs is also starting. While the type of cell chosen is highly dependent upon the mission requirements and total system cost, concentrator arrays offer an opportunity for faster implementation of newer, higher efficiency photovoltaic devices and allow these devices to become cost competitive with current photovoltaic array systems.

While concentrator arrays have yet to be flown as a primary power source, significant interest is being shown by commercial and government users because of the potential for increased performance at lower cost. Other benefits, such as reduced momentum control and plasma interaction effects, offer advantages at the spacecraft system level. Data from the PASP-Plus flight experiment indicate that concentrator arrays have minimal interactions with the space plasma, even when biased to high voltages. Thus, concentrator arrays may make high-voltage arrays practical. Despite these advantages, flight data are needed to address concerns regarding pointing and tracking, lens material survivability, and long-term system performance.

Thin-Film Solar Cells

An alternative to the conventional single-crystal solar cell is the thin-film solar cell. Thin-film solar cells are made from thin (1–5 μm) semiconductor layers deposited on an inert substrate or superstrate material. The semiconductors have a high-absorption constant; the high-absorption constant allows essentially complete absorption of the light within the first micron or so of the material. Recently, thin-film solar cells have been the topic of a considerable research effort for low-cost terrestrial electricity production. Initial research efforts focused on a-Si; recently, copper indium selenide ($CuInSe_2$) and CdTe have shown extremely good progress. Figure 2 shows progress in efficiency of $CuInSe_2$ and CdTe cells.

For technologically well-developed materials, such as Si and GaAs, achieved efficiencies are very close to the theoretical predicted limits. For thin-film materials, achieved efficiencies fall well below these values. There are two reasons for this disparity. First, Si and GaAs have received the benefit of extensive materials development for the electronics industry and are technologically very well understood materials; thin-film materials have been comparatively little researched. Second, because thin-film materials are polycrystalline or amorphous, there are additional sources of efficiency loss because of the effects of structural disorder and grain boundaries. It is not known whether the ultimate efficiencies of these materials can ever approach those of the single crystals.

In general, all of the thin-film solar cell types have exceptionally high radiation tolerance compared to conventional single-crystal cells. A review of radiation damage effects in thin-film cells can be found in Ref. 22; later data can be found in Refs. 23 and 24.

Advantages of thin-film solar cells are: high radiation tolerance; high specific power (potentially in the kilowatt/kilogram range); large-area arrays with integral series interconnections; the potential for thin, flexible blankets; and low cost. Disadvantages are, lower efficiency, lack of spacecraft experience, and the fact that they are not currently produced in volume on lightweight substrates.

Reviews of thin-film solar cell research for terrestrial applications can be found in Refs. 25 and 26. Reviews of applications for space can be found in Refs. 27–29.

Experimental measurements on thin film solar cells are typically quoted for a solar spectrum filtered by passage through the atmosphere (air mass 1.5, or AM1.5 spectrum). Very few measurements have been made of cells under the space (AM0) spectrum. Efficiency measured under space sunlight is lower than that under terrestrial sunlight because most of the added energy available in space is in the IR and uv regions, to which solar cells are generally not very responsive. The conversion

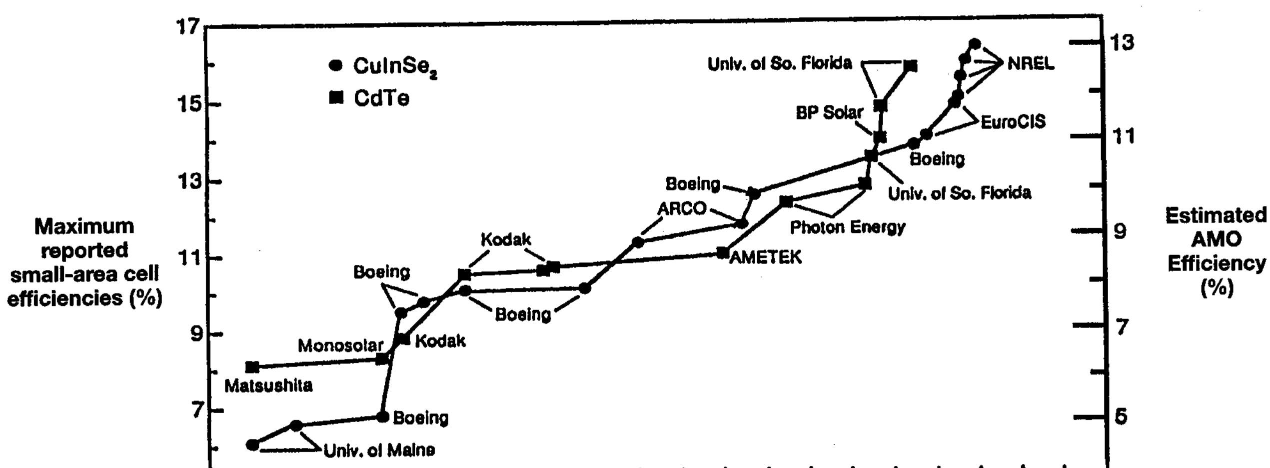

Fig. 2 Historical improvement in the efficiency of $CuInSe_2$ and CdTe thin-film solar cells.

factor from AM1.5 to AM0 efficiency is typically a decrease in efficiency by 15 to 20% for cells with bandgaps in the range of interest, varying with the spectral response of the solar cell in question. For an amorphous Si cell, for example, conversion of AM1.5 efficiency to AM0 is by a multiplicative factor of 0.80.[30] For a copper indium gallium selenide ($CuInGaSe_2$) cell, an efficiency of 11.1% AM1.5 was measured as 10.0% AM0,[31] resulting in a multiplicative factor of 0.90. In Fig. 2, we used a multiplicative factor of 0.8 to convert measured AM1.5 efficiency to estimated AM0 efficiency.

While thin-film technologies have not yet been demonstrated in space, there is a very large (by space standards) manufacturing base on the Earth. Amorphous silicon production is currently at a level of tens of megawatts per year. Commercial production of $CuInSe_2$ modules has been slower than expected; however, a factory for production of $CuInSe_2$ arrays at the level of hundreds of kilowatts to megawatts per year has been announced, and two companies commercially produce CdTe at the level of a hundred kilowatts per year, with increases in capacity expected.[32]

The active thickness of thin-film cells are typically a few microns, compared to several hundred microns thickness required for conventional Si solar cells. The technology could potentially be extremely lightweight, if the cells can be deposited on lightweight substrates (or superstrates). However, current technology development programs are directed at glass substrates, inexpensive and rugged, but not lightweight. There is only a small research effort on alternative, lightweight substrates. Four-cm^2 $CuInSe_2$ cells have been produced on 50-μm-thick flexible glass substrates.[33] Kapur and Basol[34] have reported small-area $CuInSe_2$ cells of efficiency as high as 9% (AM1.5, corresponding to about 7% AM0 efficiency) fabricated on thin molybdenum foils. Technology to manufacture a-Si solar cells on lightweight thin substrates has been demonstrated by several organizations,[35-37] and one company even produces a-Si solar cells on flexible substrates as a commercial product with a specific power corresponding to about 220 W/kg at AM0.

Flexible substrate a-Si arrays are not being made with space-qualified materials, and to date only a very small amount of testing has been done under space conditions. There is some interest in lightweight, high specific-power a-Si arrays for space.[38]

Future high-efficiency thin-film arrays could be produced in multibandgap cascade structures. This could potentially allow efficiencies of 15–20%, with the lightweight and high-radiation tolerance characteristic of thin-film cells.[28,29] The best a-Si solar arrays often use a cascade structure, because this allows thinner subcells and decreases the amount of light-induced degradation. The lower cell elements typically use amorphous Si–Ge, an alloy with a lower bandgap than a-Si.[39] The best demonstrated thin-film cascade[40] uses an a-Si top cell on a $CuInSe_2$ bottom cell, with an efficiency of 12.5% AM0 (estimated from AM1.5 measurement). In this cell the two elements are deposited on separate substrates, and the two elements coupled with transparent encapsulant. For higher specific power, it would be desirable to eliminate the intermediate layer by depositing the a-Si cell directly on the $CuInSe_2$. In the seven years since this reported result, little work has been done on multibandgap cascade thin-film cells, despite significant improvements in efficiency of the individual cells. However, the potential efficiency improvement of cascade cells is so large that it is unlikely that the approach will not be taken up again in the future.

The light weight of thin-film materials allows new designs for solar power satellites. Landis and Cull[41] have proposed using an extremely light thin-film solar cell to reduce the mass of a solar power satellite by integrating the solar cells with a solid-state transmitter. Such a technique could potentially decrease the mass of a solar power satellite by a factor of 10 to 100. This approach requires considerable additional study before it will be ready for engineering design.

Cost and Production Readiness

Despite revolutionary decreases in the cost of terrestrial solar cells, solar arrays for space applications have not decreased in cost significantly over the past 20 years. Space solar arrays currently cost on the order of \$1000/W, whereas terrestrial array costs are as low as \$2/(peak) W, with costs of under \$1/W quoted as actual manufacturing costs for the generation of manufacturing plants currently under construction, assuming that the demand exists to run these plants at full capacity.

Space array costs are high because there is only a weak incentive to try to reduce them. Even at \$1000/W, for example, the 6-kW array of an Intelsat-VI satellite represents only a small portion of the \$250,000,000 cost of building and launching the satellite.

Some of the cost difference between terrestrial and space arrays is because of the fact that space arrays use more efficient cells, have more stringent weight requirements, and have many more inspection steps to assure reliability. Custom array design and fabrication costs for a particular mission also drive up costs; such costs could be reduced if many arrays can be fabricated according to a single template. Space power systems are also subject to far more stringent requirements than terrestrial systems, including the requirement to survive repeated deep thermal cycling (a typical cycle might be -150 to $+80$°C), radiation, and uv exposure, to withstand launch vibration and acoustic loads, and to have highly reliable deployment mechanisms. A significant portion of the cost of a satellite solar array is the cost of interconnecting the cells. Two-by 4-cm cells are still in use on satellite arrays, considerably smaller than the 10 cm^2 and larger cells used in terrestrial arrays. In this respect, the solar arrays for the space station, using 8×8 cm cells and a rear-side printed-circuit interconnect, are a considerable advance. Use of thin-film cells, with the interconnections made on large-area sheets during cell manufacture, could also considerably reduce this expense.

Over the last 10 years, the terrestrial photovoltaic industry has made great advances in production capability, with single-crystal Si, polycrystalline Si, and a-Si all having well over a megawatt per year of production capability, and with several factories recently announced to produce both CdTe and copper indium selenide. Figure 3 shows the historical trend of world shipments of photovoltaic-generating capacity. While the production capability is growing, the cumulative production of solar panels over the last 25 years only totals slightly over 500 MWp, roughly the power capacity of a single nuclear electric plant. Note also that solar cell production quantities are quoted in terms of peak megawatts, the power produced with the sun directly overhead. Actual power production on the Earth's surface is lower because of night and cloud coverage. On the same graph, the world usage of solar cells for space, well under 1 MW/year, would not even be visible.

Several new production plants have been announced for completion in the near future, and production capacity is expected to continue to grow. Capacity by the year 2000 should be over 100 MWp of new photovoltaic generating capability per year.

Nonsolar Use of Solar Cells

A nonsolar area of interest for photovoltaic space power systems is the development of thermophotovoltaic (TPV) cells based on solar cell technology. In a TPV cell, IR radiation emitted from a heat source is converted into electricity by a photovoltaic cell. This can be used, for example, as a conversion mechanism for radioisotope power systems. Another proposed use is to heat the emitter with concentrated solar energy. Such a system has two potential advantages over conversion of the solar energy directly by the solar cell: first, it allows the possibility of energy storage in the form of heat, eliminating

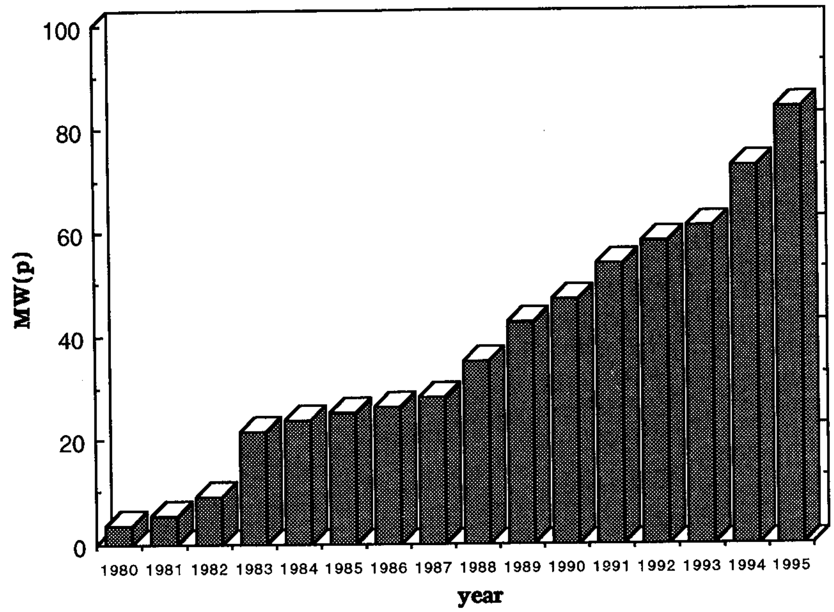

Fig. 3 Worldwide solar cell shipments from 1980 to 1995. Includes solar cell applications in consumer electronics (watches, calculators) as well as utility, remote power, and space applications.

the requirement for batteries, and second, it allows the use of recycling unused energy (i.e., photons of wavelength too long or too short to be efficiently converted) by reflecting them back to the source, resulting in higher efficiency.

In principle, any heat source could be used for TPV conversion. In practice, 1000–1500°C emitters are used. Lower temperatures tend to put out too little optical power to convert efficiently, typically in extremely long wavelengths, while higher temperature emission surfaces are difficult to maintain without degradation.

Since IR sources emit radiation at wavelengths considerably longer than those emitted by the sun, at roughly 6000 K emission temperature, TPV cells require lower bandgap semiconductors than solar cells for optimum conversion efficiency. Thermophotovoltaic converters have made significant advances recently,[42,43] primarily because of the development of GaSb and InGaAs solar cells originally designed as the low-bandgap elements of tandem cells for solar conversion. Ge and InGaAsSb solar cells are also being developed for TPV applications.

Another technology that is beginning to see application to TPV cells is the selective emitter.[43] A selective is a heat source, or a coating applied to a heat source, that emits IR only in a narrow, well-defined band of wavelengths. A solar cell is then chosen that has peak conversion efficiency at this band. Use of a selective emitter can significantly reduce the amount of energy emitted in wavelength ranges to which the solar cell is not responsive, greatly increasing the performance.

Thermophotovoltaic conversion has been proposed, for example, as an advanced power system for the proposed Pluto Fast Flyby mission, to convert power from general-purpose heat source (GPHS) $^{238}PuO_2$ bricks operating at 1200°C. The proposed system requires larger radiator fins than a thermoelectric generator, because of the lower operating temperature of photovoltaic elements, but by increasing the conversion efficiency to 26%, has a system-level increase in specific power by a factor of 2.[44]

Development of TPV cells may extend the range of usefulness of solar cell technology to the outer planets, and to other missions where solar illumination is weak or unavailable.

Photovoltaic cells may also be operated directly from radiation from nuclear sources. Cells can be operated from electron or alpha-particle emission, for example, and are referred to as betavoltaic and alphavoltaic cells, respectively.[45,46]

Finally, solar cells can be used as receivers of laser radiation for beamed power systems.[47] Solar cells are somewhat more efficient operating under laser illumination of the optimally chosen wavelength than under the solar spectrum; in most examples, this roughly doubles the efficiency.[48] A wide variety of applications of laser power beaming are possible.[49]

Conclusions

Significant advances have been made in solar cell efficiency over the last few years, and solar arrays for future missions are expeced to be significantly different than the silicon arrays that have dominated the satellite power industry since 1958. Concentrator cells with conversion efficiency over 30%, and nonconcentrating solar cells with efficiency over 25% are now available. Advanced radiation-tolerant InP solar cells have efficiences approaching 20%, although they are not yet ready for commercial production. In addition, thin-film arrays are being developed that could be extremely radiation tolerant, low-cost, and lightweight, although not highly efficient. Solar cells also have possible nonsolar applications in space, including use as converters for thermal, alpha, beta, and laser power sources.

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