Photovoltaic Materials

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Summary. Solid-state photovoltaic cells are feasible devices for converting solar energy directly to electricity. Recent cost reductions have spurred an incipient industry, but further advances in materials science and technology are needed before photovoltaic cells can compete with other sources for the supply of large amounts of energy. In this article energy loss mechanisms in solid-state photovoltaic cells are examined and related to materials properties. Various systems under development are reviewed which illustrate some key concepts, opportunities, and problems of this most promising emerging technology. Areas where contributions from innovative materials research would have a significant effect are also indicated.

During the last quarter of a century photovoltaic generation of electricity has been proved technically feasible and reliable, and photovoltaic cells became the standard source of power for space vehicles and satellites. Adoption of this technology for widespread terrestrial use has not been feasible, however, since the photovoltaic cells used in space during the 1960's were at least 1000 times too expensive to compete with other methods of electricity generation. The challenges of producing competitive and reliable electrical power in a terrestrial environment have dominated photovoltaic research and development during the past decade and are expected to continue to do so.

Cost has been significantly reduced in the last few years by reducing the manufacturing costs of solar cells substantially identical to those used in space. These cells are produced from sliced wafers of single-crystal silicon, processed by standard methods of semiconductor fabrication and assembled into flat-plate collectors. Since it is generally accepted that this technology will not reach the cost goals required for widespread use, systems based on solar concentrators and thin-film flat plates are also being investigated. In the former, costs are reduced by use of relatively inexpensive materials to concentrate sunlight on a small area of costly but highly efficient cells. The second approach seeks to reduce materials costs to an insignificant level and to use continuous, automated, low-cost fabrication processes akin to those encountered in the printing and photographic industries.

The materials and device properties required to successfully meet these goals are different for each approach and are intimately related to the fabrication process chosen. In this article, we review the materials requirements of typical solid-state photovoltaic cells and how they are related to the constraints and demands imposed by the various configurations under study. A view in greater depth can be obtained from comprehensive review articles and books (*1*).

Operation of Photovoltaic Cells

The key component of a photovoltaic cell is a semiconductor that absorbs light energy by exciting an electron from the valence band to the conduction band and leaving a positive hole behind. The electron and hole so generated eventually recombine, giving up the acquired energy to the lattice as heat or emitting light. In a photovoltaic cell, however, a region of high electric field is provided within the semiconductor, so that most of the photogenerated electrons and holes are separated on reaching this region and thus prevented from recombining. The flow of these charges through an external load produces useful work and in this way completes the process of direct conversion of light to electricity.

Intimate contact of two materials, at least one of which is a semiconductor, produces the high-field region if the chemical potentials of electrons in the two materials are different. Such a structure—a semiconductor junction—can be obtained in various ways in solid-state devices. A *p-n* junction occurs between oppositely doped semiconductors, so that there are excess holes (*p* type) on one side of the junction and excess electrons (*n* type) on the other. The major components of the semiconductors on either side of the junction can be the same (homojunction) or different (heterojunction). Certain metal-semiconductor contacts (Schottky barriers) likewise produce high-field regions in the semiconductor side of the junction. Variations of these structures are achieved when a thin insulating layer is interposed between the two active regions, leading to semiconductor-insulator-semiconductor or metal-insulator-semiconductor configurations. All of these junctions have been used in promising photovoltaic devices, but the materials requirements of each depend on the predominant optical and electronic processes characteristic of that configuration.

Next we focus attention on the mechanisms that limit the efficiency of the charge generation and separation processes described above, and their relation to materials properties. Figure 1 is a schematic view of a solid-state photovoltaic cell.

The current output of solar cells is limited by the number of carriers (electrons and holes) generated by the incident light. Losses inevitably occur when light is prevented from reaching the active semiconductor, and these must be minimized by optimization of front electrode design and reduction of reflection losses. Absorption of light by the active semiconductor requires that the light energy be at least equal to the magnitude of the energy gap separating the valence band from the conduction band of the semiconductor (the band gap). The low-energy fraction of the available solar spectrum is therefore lost without being absorbed, since it falls below the band-gap energy of most semiconductors. A fraction of the light having the proper energy can also be lost if the semiconductor is not thick enough to allow complete light absorption—that is, thinner than the optical absorption length of the semiconductor.

The losses most sensitive to materials quality and device structure are those incurred when photogenerated electrons and holes recombine before they are separated in the high-field region. Figure 2 shows energy band diagrams of a *p-n* homojunction solar cell under three conditions. These diagrams present the elec-

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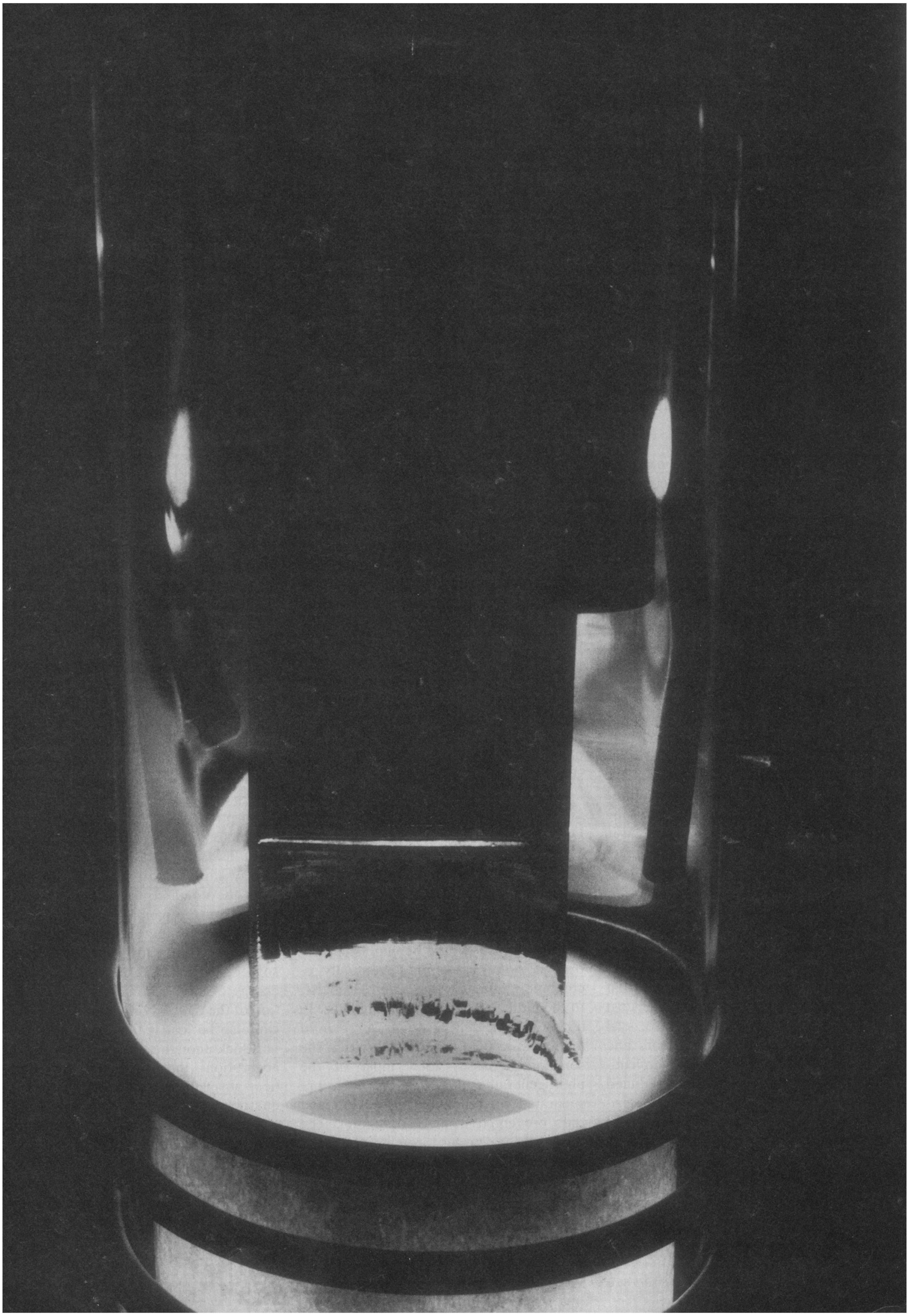

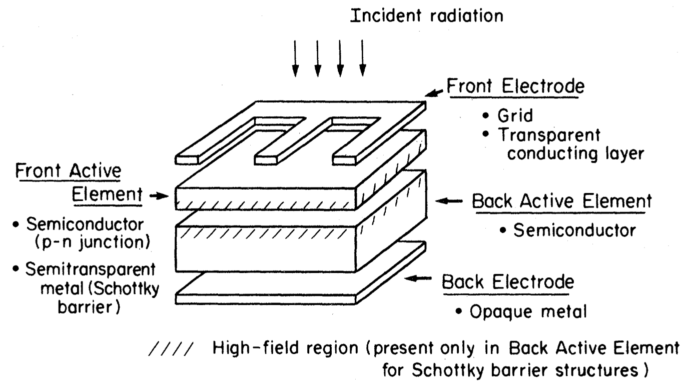

Fig. 1. Schematic exploded view of a generalized solid-state photovoltaic cell.

tron energy as a function of depth into the cell. Solid lines indicate the energy at the edges of the conduction and valence bands, and the dashed line indicates the Fermi level—that is, the chemical potential of the electrons in the semiconductor. Figure 2A illustrates the condition when the terminals of an illuminated cell are directly connected to each other (short circuit) and shows the most important recombination paths. Bulk recombination of carriers (process 1) takes place away from surfaces and interfaces and generally occurs at impurity sites and structural defects in the semiconductor. Minimizing bulk recombination is important for efficient cell operation, since many carriers are generated outside the narrow high-field region and must diffuse to it in order to be separated. The diffusion length is the distance photogenerated carriers diffuse without recombination and ideally is long enough to allow all such carriers to reach the high-field region. Weakly absorbing materials therefore require longer diffusion lengths for efficient carrier collection.

Unique electronic states arise in the vicinity of compositional and structural discontinuities in solids. These states often act as effective recombination centers; consequently, surfaces and interfaces are critical regions in photovoltaic devices. Recombination at the front (illuminated) surface (process 2) is a loss mechanism particularly important in *p-n* homojunction cells, where many carriers are generated in the front active element (Fig. 1). In these cells the effect of front-surface recombination can be reduced by decreasing the thickness of the front active element or by "passivating" the surface by chemical treatments or addition of a compatible, transparent semiconductor layer in front of the cell (heterostructure). In heterojunction cells, the front active element can be made of a semiconductor with a wide band gap, which will absorb only the small fraction of the incident radiation of energy larger than the band gap. In this way most carriers are generated in the back active element and thus are not susceptible to front-surface recombination.

Recombination at the back surface (process 3) becomes important when the thickness of the back active element is comparable to both the optical absorption length of the semiconductor and the carrier diffusion length. In this case a significant number of carriers are generated near the back surface, where the recombination rate is high. The effect of back-surface recombination can be reduced by using a back-surface-field structure, in which the region of the back active element adjacent to the electrode is heavily doped. This produces a field that effectively confines the photocarriers to the bulk of the back active element and keeps them away from the electrode.

Defects arising at the interface between two dissimilar materials provide another important recombination path. Interface recombination (process 4) is an important loss mechanism in heterojunctions and Schottky barriers, and is reduced by matching certain key properties of the materials involved, such as lattice parameter, thermal expansion, energy of the conduction and valence band edges, and so on. A critical interface is also found at the grain boundaries of polycrystalline materials. Recombination at these centers is a crucial loss mechanism in many low-cost, thin-film devices.

Up to now we have considered loss mechanisms that primarily affect the number of photogenerated carriers delivered by the photovoltaic cell, and thus its current output under short-circuit conditions. We now focus on the voltage appearing across the terminals of an illuminated cell connected to a resistive load. Figure 2B shows the energy band diagram under this operating condition. A semiconductor junction has the electrical characteristics of a diode—that is, significant current flows only for one polarity of applied voltage. This forward polarity is precisely the one appearing across an illuminated solar cell connected to a load. The current thus produced, the diode current, flows in the direction opposite to the photogenerated current discussed above. The net current flow is therefore reduced from that under short-

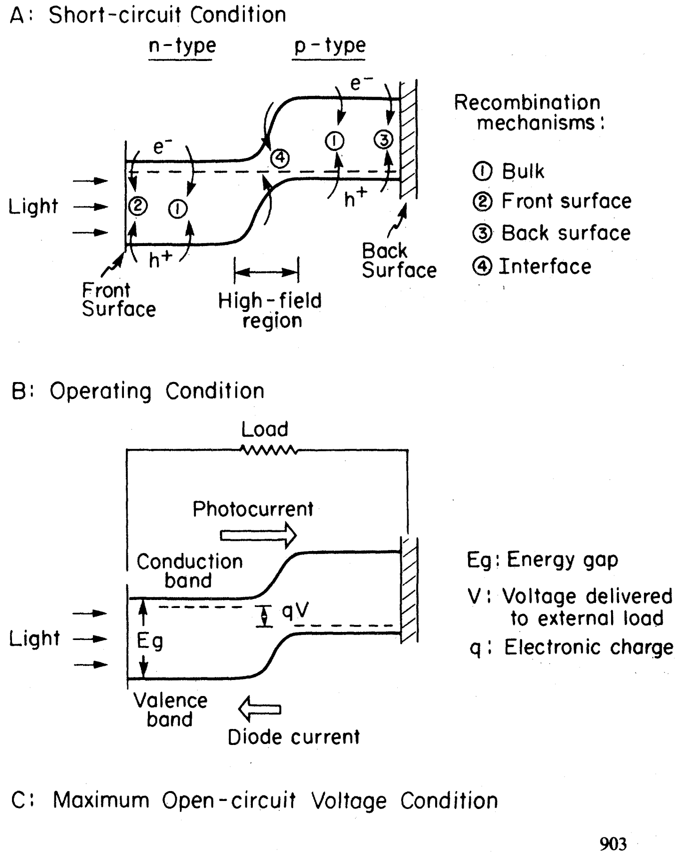

Fig. 2. Electron energy diagram of a *p-n* homojunction photovoltaic cell: (A) short-circuit condition, (B) operating condition, and (C) maximum open-circuit voltage condition. Electrons and holes are denoted e^- and h^+, respectively.

circuit conditions by the magnitude of this diode current, and becomes zero when the external load resistance becomes infinite. This is called the open-circuit condition, and the voltage measured under this condition is the one at which the diode current exactly balances out the photocurrent. High open-circuit voltages, therefore, are obtained for small diode currents.

The magnitude of the diode current for a given voltage bias depends on the current-carrying mechanisms across the junction. The minimum diode current, and thus the maximum open-circuit voltage, occurs when current is carried only by diffusion of energetic carriers over the top of the potential barrier at the junction. Voltage of forward polarity reduces the height of this barrier and increases the diode current. If this voltage is large enough, the barrier vanishes and the diode current can balance any photocurrent level produced by the cell. This condition, therefore, defines the maximum open-circuit voltage of a photovoltaic cell; it is illustrated in Fig. 2C for a homojunction. Inspection of this energy band diagram shows that the maximum open-circuit voltage achievable is slightly smaller than the band gap of the semiconductor, and consequently the use of large-band-gap semiconductors produces high voltages. Such semiconductors, however, produce small currents because they can absorb less radiation. Another consequence of the voltage-output limitation is the occurrence of significant energy losses from the high-energy portion of the solar spectrum. Since the maximum cell voltage is smaller than the band gap, carriers generated by light of energy larger than the band gap can deliver to the load only a fraction of the absorbed energy. The excess energy is dissipated as heat. These factors limit the choice of useful semiconductors to those having band gaps in the range 1.0 to 2.0 electron volts, and favor those with values near 1.5 electron volts (*2*).

In practice, because the diode current due to diffusion increases exponentially with temperature and additional mechanisms are present for generating diode current, the current-balancing condition at room temperature occurs at lower voltages than that illustrated in Fig. 2C. The prime route to enhanced solar cell performance, therefore, is minimization of the diode current. In particular, note that all the recombination channels mentioned earlier also provide routes for diode current flow. Bulk, interfacial, and surface defects thus decrease not only the current but also the voltage output of the cell.

The power delivered by a solar cell to a load is equal to the product of the current and the voltage across the cell. A typical current-voltage curve for a solar cell is illustrated in Fig. 3. The shape of the curve reflects the voltage dependence of the diode current, since the photogenerated current is nearly independent of voltage. The power delivered by the cell is strongly dependent on the load. When the load is zero (short circuit) or infinite (open circuit), the power output is zero. Between these two extremes the power reaches a maximum at some finite load resistance. The efficiency of a solar cell is usually reported as the ratio of maximum electrical power output to total incident solar energy.

Since cell efficiency depends not only on the values of short-circuit current and open-circuit voltage but also on the shape of the current-voltage curve, it is important to optimize this shape. A quantitative description is given by a parameter called the fill factor, which is defined as the ratio of the maximum output power to the product of short-circuit current and open-circuit voltage. The fill factor depends on diode current mechanisms, but more important, it is influenced by electrode design, contact fabrication, and electrical shorts across the active elements. These effects can be described in terms of an added series resistance between the cell and the load or a shunt resistance across the cell terminals. The former must be minimized and the latter maximized for optimum cell operation. The front electrode and front active element are particularly important in this regard. To maximize the amount of solar radiation reaching the active elements, the front electrode is either a transparent continuous layer or a fine grid structure with minimum shading. Electrode light transmission is usually improved at the expense of increased resistance, leading to a reduction of the fill factor. Increasing the conductivity of the transparent electrode or the front active element, therefore, improves device performance.

The fill factor is also improved by lowering the electrode-semiconductor contact resistance. Semiconductor contact technology, therefore, is by no means trivial, especially where novel semiconductors are involved. Low fill factors also result from materials having very short diffusion lengths or very large interfacial recombination rates. In these cases the photocurrent, normally voltage-insensitive, becomes voltage-dependent and reduces the current output of the cell under load, lowering the overall efficiency.

Equally important to cell efficiency is cell stability over many years of exposure to sunlight and other environmental stresses. Identification of the causes of cell degradation and achievement of adequate lifetime are central issues in photovoltaic research, especially when new materials show encouraging performance.

Silicon

Single-crystal silicon solar cells are the most advanced of all photovoltaic devices. Nearly all the commercial cells sold to date have been silicon cells. This dominance has resulted from the availability of techniques for growing the large, defect-free, silicon single crystals required by the electronics industry. Strictly speaking, silicon does not have the most desirable physical properties for a solar cell device. Its band gap of 1.1 eV is not optimum, and its optical absorption is rather weak; thus active silicon layers must be thicker than 100 micrometers to adequately absorb the solar radiation. This demands carrier diffusion lengths of the same magnitude. High-quality single-crystal silicon with a moderate resistivity (about 1 to 10 ohm-centimeters) and an adequate diffusion length is readily available, and *p-n* homojunction cells with efficiencies higher than 10 percent have been routinely reported since the late 1950's (*3*). Progress during the past decade demonstrates that silicon can be fabricated into devices with efficiencies approaching 19 percent (*4*). Refinements in technology are expected to increase this value.

Improvements in device design account for most of the progress during the decade. Front-surface recombination losses were significantly reduced by decreasing the thickness of the front silicon layer (*5*), thus reducing the number of carriers generated in the front layer and subject to recombination there. Passivation of the front surface with transparent thin layers, such as SnO_2, also helped to reduce the front-surface recombination loss (*6*). Current gains from increased light absorption were achieved by using textured surfaces and antireflection coatings, which virtually eliminate light reflection at the front surface (*7*). Adoption of a back-surface-field structure decreased back-surface recombination, resulting in reduced diode current and increased voltage output (*8*).

The real challenge in producing solar cells for terrestrial applications is to reduce the overall cost so that they can compete economically with other energy sources. The present high cost of silicon cells includes significant contributions from all fabrication steps—preparing high-purity raw materials, growing single crystals, slicing and polishing the single crystals into thin wafers, fabricating devices, and packaging. Efforts are being made to reduce costs in all these areas. High-capacity, efficient processes for less costly silicon production and purification are being explored, and cells of 15 percent efficiency have recently been fabricated on slices of cut polycrystalline silicon ingots (*9*). Several processes have provided essentially single-crystal silicon ribbons directly from the melt. These processes can potentially reduce the silicon cell manufacturing costs by eliminating the bulk crystal growth and slicing steps. Cell efficiencies around 15 percent have been obtained with ribbons made by a dendritic web process (*10*). The next steps in ribbon-growth processes are improving the material quality and increasing the throughput. Alternative methods of junction formation are being investigated; metal-insulator-semiconductor configurations and ion implantation show promise of achieving high-efficiency cells at reduced fabrication costs.

Polycrystalline thin films of silicon deposited on low-cost substrates promise further cost reductions and higher throughput than the ribbon processes. An efficiency approaching 10 percent was recently reported (*11*) for films prepared on lower-purity silicon bulk substrates, but deposition onto other substrates produces cells with much lower efficiencies. The current output of thin-film silicon cells is much lower than that of single-crystal cells, even though the voltage output is comparable. It is believed that grain boundaries provide efficient recombination centers, where a large fraction of photogenerated carriers are lost. Methods for increasing grain size or passivating grain boundaries are being investigated.

Gallium Arsenide

Gallium arsenide has a much higher optical absorption than silicon, and its ~ 1.4 eV band gap is nearly an ideal match for the solar spectrum. The high optical absorption reduces the thickness of material required for adequate light absorption to a few micrometers, and hence reduces the required photocarrier diffusion length to ~ 2 μm, compared to $\geq$ 100 μm for silicon.

However, GaAs has a set of dominant loss mechanisms which, until the early 1970's, limited the efficiency of single-crystal GaAs cells to about 12 percent (*12*). For example, as a compound semiconductor, GaAs is more prone to imperfections than silicon, making it more difficult to obtain the crystal and material quality required for even modest carrier diffusion lengths. Moreover, in homojunctions the high optical absorption of GaAs produces a large fraction of photocarriers in the front side of the junction, thus increasing front-surface recombination losses. This enhanced carrier recombination reduces both current and voltage and accounts for the disappointing performance of early GaAs cells.

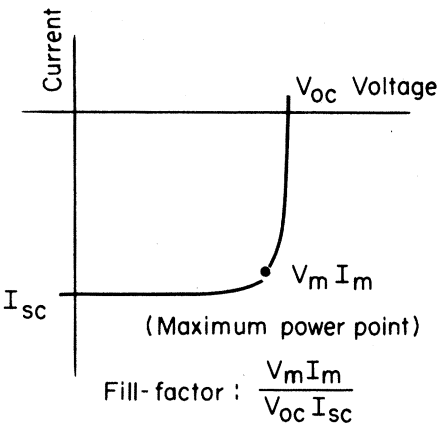

Fig. 3. Current-voltage characteristics of a photovoltaic cell.

Advances in materials and device technology have solved many of these problems. Improvements in liquid- and vapor-phase growth techniques have produced GaAs layers with diffusion lengths adequate for high-efficiency cells. These layers are grown epitaxially on low-quality single-crystal substrates, yielding a high-quality single-crystal region where carrier generation, separation, and collection take place. Front-surface recombination losses have been practically eliminated by use of a so-called heterostructure, where *p*-GaAlAs, which has a wider band gap and low optical absorption, is grown over the *p* layer of a *p-n* junction GaAs single-crystal cell. An efficiency of 22 percent has been achieved in such devices (*13*). Other approaches that have been effective in reducing front-surface recombination and improving cell efficiency include the use of metal-insulator-semiconductor structures (*14*), AlAs/*p*-GaAs (*15*) heterojunctions, shallow homojunctions (*16*), and heterostructures where InGaP (*17*) replaces GaAlAs.

Although GaAs cells are very efficient, fabrication costs and unavailability of materials have limited their use. Two approaches have been used to address these problems. The first uses solar concentrators in which sunlight incident over a large area is optically concentrated onto a small-area solar cell. The electric current produced is roughly proportional to the concentration ratio, which can be very high. Electrode design and contact quality are of prime importance in order to minimize series-resistance losses. Well-designed systems with efficiencies of ~ 22 percent at a concentration ratio of 900 have been reported (*18*).

The second approach employs thin-film technology. A recent report describes a 21 percent efficient, shallow homojunction GaAs cell, which was fabricated with 4 μm of GaAs epitaxially grown onto a single-crystal Ge substrate (*16*). This demonstrates that highly efficient cells can be made with single-crystal, thin-film GaAs. Polycrystalline thin-film GaAs cells on various substrates, however, have efficiencies of only 5 to 6 percent without antireflection coatings (*19*). High photocurrents are usually obtainable but voltage outputs are low—just the opposite of the situation with thin-film Si cells. Since the techniques for growing thin films are similar to those for making high-efficiency epitaxial layer cells, it appears that the poorer performance of polycrystalline cells must result from grain boundaries.

Cadmium Sulfide/Copper Sulfide

Thin-film Cu_2S/CdS cells have followed a different development path and thus have faced different problems. These cells were discovered in 1954, and by the early 1960's the basic structure and manufacturing techniques for a 5 percent efficient thin-film cell were established (*20*). An understanding of the properties of the cell materials and the device operation, however, took longer to develop and even today is incomplete. The cell preparation process summarized below illustrates some unique features of this cell.

Fabrication normally begins with a conductive substrate onto which a layer of CdS 20 to 30 μm thick is vacuum-evaporated. The Cu_2S layer is prepared by dipping the CdS-coated substrate into a hot, aqueous solution of CuCl. A fine-grid collecting electrode is then applied to the Cu_2S layer. In most cells illumination is from the Cu_2S side; it is generally agreed that Cu_2S absorbs most of the light and is the locus of most photocarrier generation.

Cuprous sulfide prepared by methods other than that outlined above usually yields much poorer results. One exception is a dry process in which a thin layer of CuCl is evaporated onto the CdS layer; this is followed by a heat treatment which, in an ion-exchange reaction, converts the thin surface layer of CdS into Cu_2S (*21*). Most workers believe that Cu_2S formation occurs through interdiffusion of Cu and Cd without disturbing the sulfur sublattice. Although this so-called topotaxial process (*21*) produces fewer interfacial defects than other methods, interfacial recombination still plays a major role in limiting cell efficiency (*22*).

The Cu_2S layer is normally heavily doped and the carrier diffusion length is extremely small ($\sim 0.2\ \mu m$). As a result, the Cu_2S layer in the more efficient cells must be extremely thin (0.1 to 0.3 μm) in order to reduce bulk recombination losses. In spite of the high optical absorption coefficient of Cu_2S, the thin layer does not absorb enough light in one pass to account for the high current observed in the best cells. The unexpectedly high current results primarily from an increase in the area of light-absorbing Cu_2S to several times the area of the cell. This is accomplished by using an etched, textured CdS surface and forming Cu_2S along CdS grain boundaries. Reflection by the substrate of transmitted light back to the Cu_2S also increases current output.

Current gains obtained in this way are accompanied by voltage losses due to differences between junction and cell areas. Since the diode current increases linearly with junction area while the photogenerated current is determined by cell area, a cell with a textured surface has a larger diode current than a planar cell for a given photogenerated current, and hence a lower open-circuit voltage. If penetration of Cu_2S along grain boundaries reaches the back electrode, the cell is shorted. To avoid this problem, relatively thick CdS layers (20 to 30 μm) must be used, which increases materials and fabrication costs.

In spite of these difficult materials limitations, an efficiency of 9.15 percent has been obtained by optimizing the collecting grid structure and reducing light reflection losses from the front surface (*23*). Further improvements may require more drastic modifications in cell design. One approach is to replace CdS with $Cd_xZn_{1-x}S$, giving a better match with Cu_2S in energy of the conduction band edge and lattice parameter. This increases the voltage, but the efficiency is not improved because the current output is lower (*24*).

Cell degradation has seriously affected the performance of Cu_2S/CdS cells, and encapsulation has been necessary to increase their lifetime. Stoichiometric changes due to oxidation of the Cu_2S layer are believed to be primarily responsible for the deterioration.

Amorphous Silicon

In addition to the polycrystalline thin films discussed earlier, silicon can be prepared in the form of thin amorphous films. Because of the differences in structure, amorphous thin films have many physical properties that are distinctly different from those of their crystalline counterparts. Optical absorption is much stronger in amorphous films, since lack of crystal symmetry relaxes the selection rules governing the optical transitions; amorphous films are also free of the grain boundaries that plague polycrystalline silicon thin films. Both characteristics make amorphous silicon (a-Si) films attractive candidates for low-cost solar cells. The key limitations of conventional a-Si are its high density of structural defects and, more important, its unsatisfied chemical bonds, which introduce electronic states within the energy gap. Since the density of these states is high (10^{17} to 10^{20} per cubic centimeter per electron volt), they essentially dominate all electronic processes by providing a large number of recombination sites and preventing any observable doping effects; thus conventional a-Si is totally unsuitable for device applications.

It was recently discovered, however, that the density of the gap states is greatly reduced in a-Si films prepared by glow discharge of silane (SiH_4) (*25*) or reactive sputtering of silicon in a hydrogen-containing ambient (*26*). These films respond to *p*- and *n*-type doping, thus allowing the preparation of a-Si solar cells having either *p-n*, Schottky barrier, or metal-insulator-semiconductor structures (*27*). An efficiency of 5.5 percent has been reported (*28*), although most cells are in the 2 to 3 percent range.

The low efficiency of these cells is evidently due to diffusion lengths so small that only carriers generated within the high-field region near the junction are collected. Since the high-field region is narrow, only a fraction of the incident light is absorbed and the current output of the cells is low. The high-field region can be broadened by placing a relatively insulating a-Si layer between the *p* and *n* regions (*28*). Major improvements in cell efficiency, however, require significantly longer diffusion lengths.

The short diffusion length observed in these materials is apparently related to the band-gap states, which, even in the best a-Si materials, have a much higher density than in crystalline silicon. It has been shown that the reduction in gap states in these new a-Si materials is due to the incorporation of a large amount of hydrogen, as much as 50 atomic percent, during the deposition process (*29*). The mechanism by which hydrogen incorporation affects the density of gap states is complicated and not well understood. Hydrogen could satisfy all dangling bonds, but this does not seem to account for the large amounts of hydrogen incorporated into these films—roughly 100 times the amount of gap states identified by electron spin resonance spectroscopy (*30*). Infrared spectroscopy shows the existence of SiH, SiH_2, and SiH_3 bonds, and the distribution of hydrogen among these bonds depends strongly on the method and conditions of preparation. Once the role of hydrogen in a-Si is better understood, a further reduction of gap states is likely. Simultaneous incorporation of fluorine and hydrogen into a-Si reduces the gap states even further (*31*), and beneficial effects of oxygen have also been reported (*32*). It seems likely that the quality of a-Si will continue to improve with further chemical modification.

Other Semiconductors

Solar cells have been prepared with many other semiconductors, but efficiencies have been poor, even though many semiconductors have nearly optimum band gaps and are good light absorbers. Part of the difficulty is that little is known about the properties of most of these semiconductors. Materials of good quality are not available, and junction- and contact-forming techniques have not been established. This is especially true for thin-film cells, in which grain boundaries and film-substrate interactions complicate matters further. A few materials, however, show promise.

Indium phosphide is a III-V semiconductor, as is GaAs, but its materials technology is much less advanced. Heterojunction cells made with CdS films evaporated onto single-crystal InP have efficiencies of about 15 percent, although the efficiency of analogous thin-film cells is less than 6 percent (*33*). Cadmium telluride is another compound that has the appropriate band gap and very high optical absorption, and it can be prepared in *p* and *n* types. Effective use of this material, however, seems hindered by materials technology, and the best efficiency reported for single-crystal cells is about

12 percent (*34*). This material can be readily prepared in thin-film form, and efficiencies as high as 8.7 percent have been observed in thin-film CdS/CdTe heterojunction cells (*35*). An interesting ternary material, $CuInSe_2$, produces heterojunction cells with CdS yielding 12 and 6 percent efficiencies in the single-crystal (*36*) and thin-film (*37*) forms, respectively.

Conclusions

Photovoltaic solar energy conversion has been considered from the viewpoint of materials, with particular emphasis on cell efficiencies. Promising solar cells are obtainable from a variety of materials, provided cell design and fabrication processes are matched with key materials properties. A weakly light-absorbing material such as silicon is useful because current fabrication procedures yield nearly perfect materials with very large diffusion lengths. Strongly absorbing materials such as GaAs yield efficient devices because surface recombination is effectively reduced by proper device design and improved crystal-growth techniques. Heterojunction Cu_2S/CdS cells with moderate efficiencies, in spite of their thin-film polycrystalline format and mismatch at the interface, are fabricated by processes that minimize interface defects and enhance light capture. Finally, noncrystalline silicon shows promise, as a result of chemical modifications that remove defects inherent in amorphous systems.

Photovoltaic research and development is a relatively young, rapidly moving discipline, but the simultaneous achievement of adequate cell efficiency, low materials and fabrication costs, and long-term stability are yet to be demonstrated. Some existing systems are promising, but further advances must be made in materials properties and in automated, large-volume, cost-effective manufacturing processes before photovoltaic conversion can compete with conventional sources for large-scale electrical power generation.

The rapid growth of innovative research and the beginning of significant industrial production of photovoltaic systems are positive and encouraging. We look forward with optimism to a decade in which this most desirable process of energy conversion may come to fruition and help meet the world's changing energy needs.

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