Essay   **PHOTOVOLTAIC CONVERSION**

The photovoltaic effect occurs when light is absorbed by a semiconductor. The energy of the photons is transferred to electrons in the valence band of the semiconductor, promoting them into the conduction band and resulting in the formation of electron-hole pairs. Only photons with energies exceeding the band-gap energy of the semiconductor can be effective in this process. If the semiconductor has a small band gap, a large fraction of the incident photons are able to create electron-hole pairs. This yields a large current, but the voltage generated across the solar cell is low. With a large-band-gap semiconductor, the voltage generated is high but the current is low. Analysis has shown that to convert sunlight, in which most of the photons have energies between 1 eV and 3 eV, the optimum band gap for maximum power conversion is approximately 1.5 eV.

In an isolated semiconductor, the excited electron eventually recombines with a hole in the valence band, emitting its excess energy as photons (photoemission) or phonons (heat), and no useful generation of electric energy takes place. To extract the energy of the photoexcited carriers as usable electricity requires the existence of a charge-separating junction such as a *p-n* diode. The passage of the excess charge carriers, known as minority carriers (electrons in the *p*-region, holes in the *n*-region), across the junction prevents electron-hole recombination. Thus a photogenerated electron in *p*-type material has a limited lifetime in the presence of the stable population of holes but an unlimited lifetime after crossing the junction into the *n*-type material (vice versa for holes in *n*-type material).

In the traditional crystalline silicon solar cell, the charge-separating region is formed when the diffusion of specific impurities, or dopants, into a wafer of silicon creates regions of opposite conductivity type. Diffusion of carriers across the transition between the *n*- and *p*-regions — that is, across the junction — occurs until an equilibrium is established in which the electric field created prevents further diffusion of charges. This internal electric field constitutes the charge-separating barrier, which is key to the operation of the solar cell. Electrons created by light in the *p*-type material migrate to the junction and are then swept into the *n*-type region. (An analogous situation exists for holes created on the *n*-type side of the junction.) In an efficient cell, this collection occurs before the electrons recombine with the stable population of holes in the *p*-region. The energy absorbed from the light is thus converted to electrical energy, which can be fed into an external circuit.

Figure 12.2.1a illustrates a diode under illumination and shows the production of electron-hole pairs, which are then separated by the built-in electric field. The I–V behavior of an ideal photodiode is obtained by adding a light-generated current, I_{sc}, to the diode equation presented in Chapter 12:

$$I = I_0[\exp(qV/k_B T) - 1] - I_{sc}$$

where I and V are the external current and voltage, respectively; q is the electronic charge; k_B is Boltzmann's constant; I_{sc} is the short-circuit current; and I_0 is the reverse-saturation current of the diode. The corresponding I–V curve (Fig. 1b) is seen to be that of a diode but displaced along the current axis by the "light-generated current," I_{sc}.

If the outside circuit has zero resistance, a maximum current I_{sc} flows as shown on the I–V curve. As the load resistance rises, a voltage is generated across the cell, and the external current eventually falls to zero at the open-circuit voltage, V_{oc}. In this situation, electrons accumulate on the *n* side of the junction (holes on the *p* side), biasing the junction in the sense opposite that of the built-in field. The maximum voltage the cell can develop corresponds to the forward light-generated current that exactly
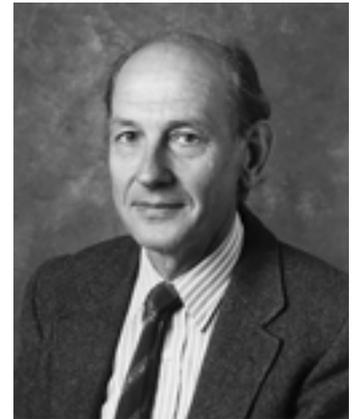
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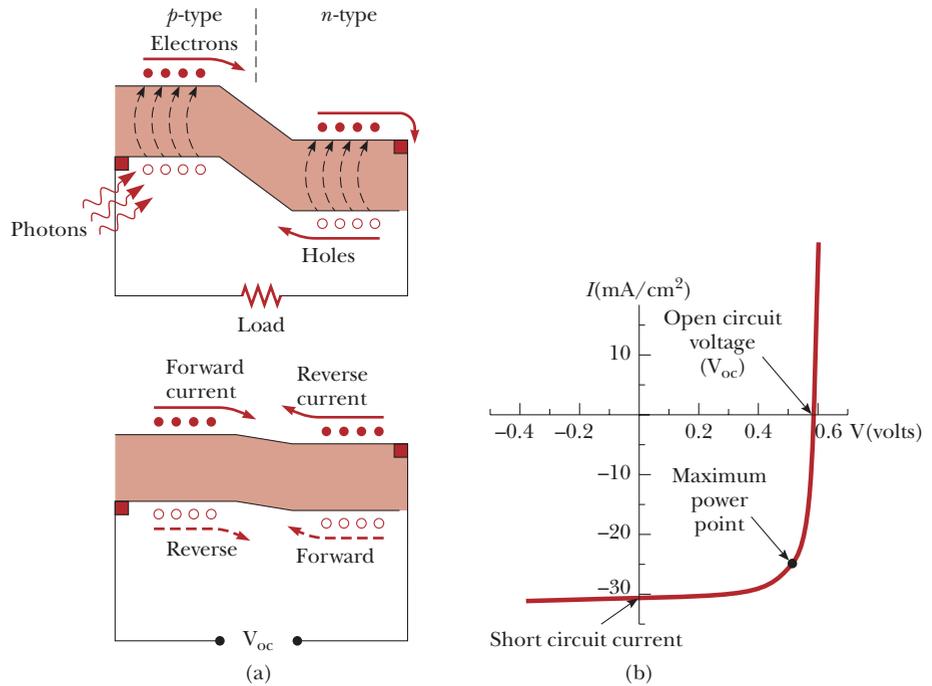
Figure 12.2.1   (a) A p-n junction under illumination, showing, in the upper diagram, the generation and collection of electrons and holes near the short-circuit current point. As the external load increases, charges accumulate in the cell, reducing the height of the charge-separating barrier until at open circuit there is no net current flow. (b) A typical current–voltage curve for a silicon solar cell under 1 kW/m^2 insolation.

matches the reverse current. The maximum power generation occurs where the current–voltage product, $I \times V$, is largest. Under ideal conditions, a single-junction solar cell in direct sunlight should convert about 25% of the incident solar energy to electricity. This figure ignores all the losses that inevitably occur in an actual cell, such as reflection from the front surface and various other electrical and optical losses. The theoretical efficiency limit is increased by operating the cell under concentrated illumination, which can be achieved with mirrors or lenses. Efficiencies of more than 30% are possible from sunlight concentrated a few hundred times, but the concentrating system must track the Sun as it orbits across the sky.

In 1954, the first practical solar cells, which had a structure similar to that shown in Figure 12.2.2, were made from single-crystal wafers of semiconductor-grade silicon. These cells converted about 6% of the total incident sunlight to electrical power; that is, they had an efficiency of 6%. Research Si cells have now attained over 23% efficiency under direct sunlight and almost 30% under sunlight concentrated by a factor of a few hundred times. Commercial cells are moving toward 20% efficiency, yielding multicell modules of about 15% efficiency. Why, then, are solar cells not being used more extensively to generate electricity? To answer this question, we must look more closely at the economics of electricity generation from solar cells.

The most significant costs are the initial capital outlays; operation and maintenance costs are small, and there are no fuel costs. A simple analysis reveals the scale of investment that would be economically competitive. A module rated at 1 kW (that is, able to produce 1 kW of electricity under sunlight of 1 kW/m^2—typical of noon under a clear sky) generates, on average, about 5 kWh/day or about 4.10^4 kWh of electricity over its

Front contact
grid

Antireflective coating

n-type

Junction

p-type

Back contact
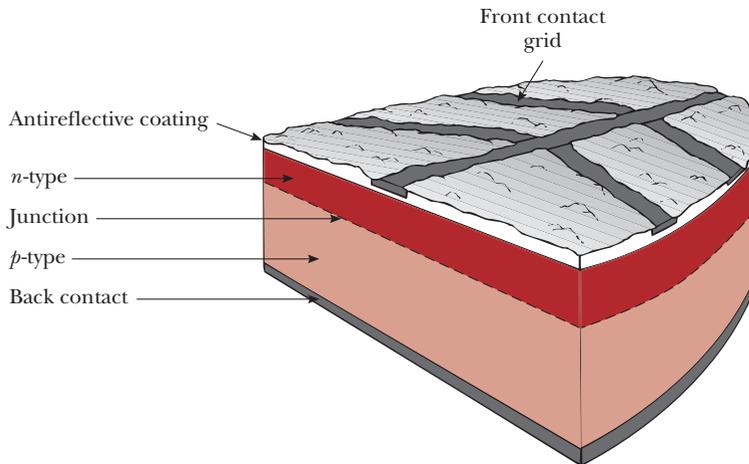
Figure 12.2.2 A schematic drawing of a silicon solar cell. Recent developments include a highly textured front surface to induce light trapping and grids in grooves to reduce the unilluminated area of the cell.

lifetime of, say, 20 years. In America, this can be worth as little as $1000 or more than $5000, depending on the location and the type of user. About half of the initial investment will be for costs other than the modules, which must therefore be available for a few hundred dollars per kilowatt-hour. More sophisticated analyses that take inflation and carrying charges into account yield similar order-of-magnitude estimates. Although the first cells produced for space use cost about $1 million/kW, extensive technical and manufacturing progress coupled with much less stringent specifications for terrestrial use have brought the present price down to about $3000 to $5000/kW in large quantities. Is it likely that a further reduction in order of magnitude can be achieved? To answer this question, we must return to the physics of solar cell operation.

The rate at which sunlight is absorbed by a semiconductor of thickness t and absorption coefficient α is

$$F = e^{-\alpha t}$$

where F is the fraction of radiation absorbed by the semiconductor. The absorption coefficient α, measured in cm^{-1}, varies with the wavelength of the light. It is very low for photon energies below the semiconductor band gap and rises as photon energies increase. Crystalline Si has a relatively low absorption coefficient, between 10^2 and 10^4 cm^{-1}, which means that a thickness of about 200 μm is necessary to absorb most of the sunlight. The carriers generated by the photons must then be able to travel about that far to reach the charge-separating junction before recombination occurs, requiring, in turn, a long minority lifetime.

Efficient carrier collection in the traditional crystalline Si cell requires very pure and perfect material, and bringing the price of Si cells down by a further factor of 10 cannot be assured, although ongoing developments may yield substantial reductions. These developments include methods to produce large-area, thin sheets directly from a silicon melt to avoid the wafering step used with single crystals. Large-grained polycrystalline material, which is less expensive than single crystals, is also in use. Another promising approach is to texture the front and/or rear surface of the cell so that light undergoes multiple reflections within the cell and can become totally trapped. This approach lengthens the light path for a given cell thickness without increasing the distance that carriers must travel and has yielded ~15% efficient cells that are as thin as 50 μm.

There are many semiconducting compounds in addition to the semiconducting elements of Group IV, Si and Ge. The essential properties that a material must possess to be a candidate for a low-cost solar cell are an appropriate band gap—say, between 1.0 and 1.7 eV—and a very high absorption coefficient. The latter makes it possible to use very thin layers, which in turn relaxes the limitations on purity and perfection, as short collection distances (short carrier lifetimes) now apply. Any compound is a potential semiconductor if the ratio of valence electrons to atoms, e/a, is 4, as is the case for the Group IV elements.

Among the classes of semiconducting compounds are the II-VI (that is, a compound AB where A is from Group II and B from Group VI), III-V, and I-III-VI$_2$ families. At present, solar cells based on members of each of these groups are being developed with the expectation that a combination of higher efficiency and lower cost will result.

Representative of the III-V compounds are GaAs and InP, which in single-crystal form have yielded solar cells of about 30% efficiency. As a general rule, the III-V compounds have excellent carrier properties, and indeed there is a major effort to develop them for high-speed integrated circuits and the like, but their properties are seriously degraded in thin-film form, and single crystals may have to be used to maintain performance. If this should continue to be the case, it may be necessary to use a concentrating system in which an optical assembly focuses the energy from a large aperture onto a much smaller solar cell, thus reducing the total area of solar cell needed for a given output. (See the recommended reading.)

The II-VI compounds are represented by CdTe, which has an ideal band gap of about 1.5 eV and which has yielded solar cells of about 16% efficiency. Techniques for forming large areas of thin film are under development, including electroplating, various types of vapor deposition, and a spray pyrolysis process.

The I-III-VI$_2$ material that is receiving the most attention is CuInSe$_2$. It has a rather low band gap of 1.0 eV, but (as we shall discuss shortly) that may be an advantage for two-junction or tandem cells. Research groups have demonstrated efficiencies of well over 10%, and recently 15% has been reported. Indicative of the sophistication now being practiced is the use of Cu(GaIn)Se$_2$, in which the band gap can be controlled through the Ga:In ratio. All investigators have confirmed a very high degree of stability for these cells, which is particularly important for thin-film cells that in the past have often exhibited unacceptably short usable lifetimes.

The reason for the interest in all of the preceding compounds is their high absorptivity, which means that very thin layers, as little as 1 μm thick, will completely absorb the useful solar spectrum. The carriers generated by the light then need only travel equally short distances to the junction, and relatively impure and imperfect materials, such as polycrystalline thin films, can be used successfully.

In parallel with the development of polycrystalline materials have been extensive investigation and application of amorphous materials based on an alloy of Si and H, conventionally designated a-Si:H. Thin films of this material are deposited by creating a plasma in a gas containing the two elements, most frequently SiH$_4$. The resulting solid contains tetrahedrally bonded Si but in a disordered, noncrystalline array. The hydrogen appears to heal any unsatisfied SiSi bonds, eliminating energy states that would otherwise introduce electronic states in the band gap. The hydrogenated a-Si can therefore be doped, in contrast to a hydrogen-free amorphous silicon.

Progress in the science and technology of amorphous thin films has been remarkable; in about a decade, a-Si:H solar cells developed from a laboratory curiosity into a familiar component in solar-powered calculators. Panels with areas of 1 m^2 and greater are now entering the market for various uses, such as battery charging and so on. Intense research is focused on the light-induced decay in conversion efficiency, the Staebler–Wronski effect, which is currently the major limitation on widespread use of a-Si:H modules.

Scientifically and technically, the field of photovoltaic conversion remains exciting and challenging. New materials are being developed, and more efficient configurations are being reduced to practice. In place of one cell to harvest the entire solar spectrum, stacked and tandem structures are appearing. In these systems, the top cell removes the high-energy photons, allowing the longer wavelengths (lower-energy photons) to be efficiently harvested in a second or even third cell and thus creating the photovoltaic equivalent of a multistage turbine. The a-Si:H makes an attractive top cell, as its band gap of about 1.6 eV efficiently uses the short-wavelength light while transmitting the longer wavelengths into a bottom cell. Polycrystalline $CuInSe_2$ is available as a material for the bottom cell, as its band gap, 1.0 eV, is close to the ideal value for a two-junction device. Multijunction a-Si:H cells are also being developed with the use of amorphous Si alloys containing C, Ge, or Sn to give various band gaps. A stack of thin cells has been shown to be more resistant to the Staebler–Wronski effect than a single thick cell.

Interest in the nonpolluting use of fossil fuels is encouraging development of an intriguing variant on traditional solar cells known as thermophotovoltaics (TPV). The ideal incident radiation for a given band gap would be at a single wavelength with an energy just above the gap. Such radiation cannot be derived from burning a fuel, but a spectrum optimally centered at the best wavelength can be generated from a heated radiator. The fuel can then be burned under ideal conditions and electricity generated by TPV. One application would be a hybrid fossil fuel electric car that has the advantages of readily portable fuel and electric motive power.

The present world production of solar cells, about 60 MW, is only 0.01% of the conventional electrical generating capacity installed in America alone. However, the electric utilities are showing growing interest in dispersed generation, which relieves the load on the distribution system and can aid demand-side management.

The costs of nuclear energy and traditional fossil fuels, such as oil, gas, and coal, control the economic incentive to develop alternative sources of electricity for use in the developed nations. However, growing concern about the greenhouse effect and acid rain appears likely to motivate more rapid utilization of photovoltaics and other renewable energy resources.

Solar cells are ideally suited for remote locations and Third World areas without grid systems, where the only alternatives are diesel generators and expendable batteries. Under such conditions it is already economical to use solar cells. For example, the American Coast Guard's remote buoys all use solar cells. Space satellites, such as those used to distribute TV signals, continue to be powered entirely by solar cells.

In spite of uncertainty about the rate of growth of electricity generation, particularly in developing nations, there can be no doubt that solar cells will make a very significant contribution and will continue to attract both scientific and commercial interest.

Suggestions for Further Reading

E. Cook, *Man, Energy, Society*, New York, W. H. Freeman, 1976.
P. D. Maycock and E. N. Stirewalt, *Photovoltaics*, Philadelphia, Brick House, 1981.
M. A. Green, *Solar Cells*, Englewood Cliffs, NJ, Prentice-Hall, 1983.