CHAPTER 9.7
SOLAR CELLS*

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INTRODUCTION

A solar cell is a semiconductor electric-junction device that absorbs the radiant energy of sunlight and converts it directly and efficiently into electric energy. Solar cells may be used individually as light detectors, e.g., in cameras, or connected in series and parallel to obtain the required values of current and voltage for electric-power generation.

Most solar cells are made from single-crystal silicon and have been to expensive for generating electricity, except for space satellites and remote areas where low-cost conventional power sources are unavailable. Recent research has emphasized lowering solar-cell cost by improving performance and by reducing materials and manufacturing costs. One approach is to use optical concentrators such as mirrors or fresnel lenses to focus the sunlight onto solar cells of smaller area. Other approaches replace the high-cost single-crystal silicon with thin films of amorphous or polycrystalline silicon, gallium arsenide, cadmium sulfide, or other compounds.

SOLAR RADIATION

The intensity and quality of sunlight is dramatically different outside the earth's atmosphere and on the surface of the earth, as shown in Fig. 9.7.1. The number of photons at each energy is reduced on entering the earth's atmosphere because of reflection, scattering, or absorption by water vapor and other gases. Thus, while the solar energy at normal incidence outside the earth's atmosphere is 1.36 kW/m^2, on the surface of the earth at noontime on a clear day the intensity is about 1 kW/m^2.

PRINCIPLES OF OPERATION

The conversion of sunlight into electric energy in a solar cell involves three major processes: (1) absorption of the sunlight in the semiconductor material; (2) generation and separation of free positive and negative charges which move to different regions of the solar cell, creating a voltage in it; and (3) transfer of these separated charges through electric terminals to the outside application in the form of electric current.

In the first step, the absorption of sunlight by a solar cell depends on the intensity and quality of the sunlight, the amount of light reflected from the front surface of the solar cell, the semiconductor bandgap energy,

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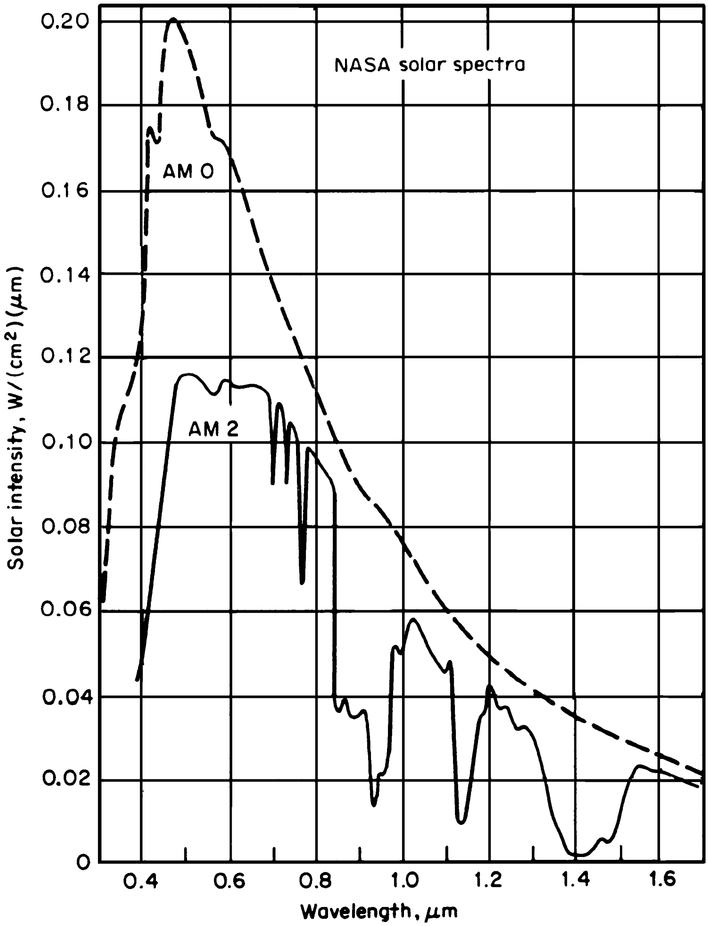

FIGURE 9.7.1 Variation of solar intensity with wavelength of photons for air mass O (AMO) outside the earth's atmosphere and for AM2, a typical spectrum on the surface of the earth.

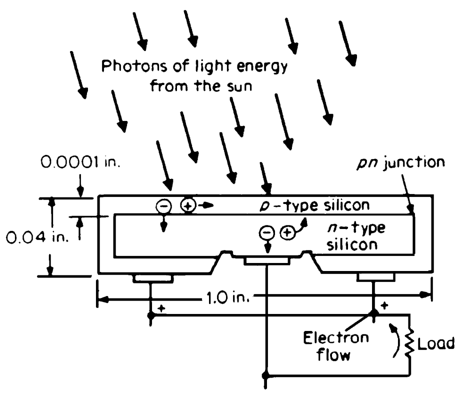

FIGURE 9.7.2 Cross-sectional view of a silicon *pn*-junction solar cell, illustrating the creation of electron pairs by photons of energy from the sun.

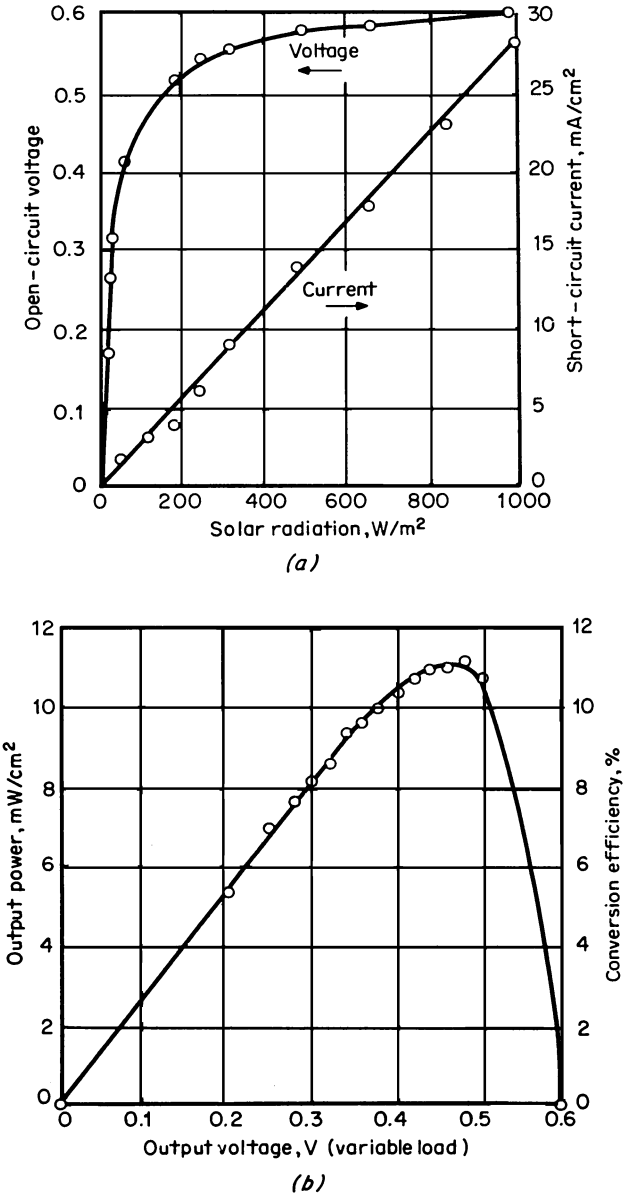

FIGURE 9.7.3 Electrical characteristics of silicon *pn*-junction solar cell at operating temperature of 17°C; (*a*) variation of open-circuit voltage and short-circuit current with light intensity; (*b*) variation in power output as load is varied from short to open circuit.

which is the minimum light (photon) energy the material absorbs, and the layer thickness. Some materials, e.g., silicon, require tens of micrometers thickness to absorb most of the sunlight, while others, e.g., gallium arsenide, cadmium telluride, and copper sulfide, require only a few micrometers.

When light is absorbed in the semiconductor, a negatively charged electron and positively charged hole are created. The heart of the solar cell is the electric junction which separates these electrons and holes from each other after they are created by the light. An electric junction can be formed by the contact of (1) a metal to a semiconductor (a Schottky barrier); (2) a liquid to a semiconductor (a photoelectrochemical cell); or (3) two semiconductor regions (a *pn* junction).

The fundamental principles of the electric junction can be illustrated with the silicon *pn* junction. Pure silicon, to which a trace amount of a column V element such as phosphorus has been added, is an *n*-type semiconductor where electric current is carried by free electrons. Each phosphorus atom contributes one free electron, leaving behind the phosphorus atom bound to the crystal structure with a unit positive charge. Similarly, pure silicon to which a trace amount of a column III element such as boron has been added is a *p*-type semiconductor, where the electric current is carried by free holes. Each boron atom contributes one hole, leaving behind the boron atom with a unit negative charge. The interface between the *p*- and *n*-type silicon is called the *pn* junction. The fixed charges at the interface owing to the bound boron and phosphorus atoms create a permanent-dipole charge layer with a high electric field. When photons of light energy from the sun produce electron-hole pairs near the junction, the built-in electric field forces the holes to the *p* side and the electrons to the *n* side, as illustrated in Fig. 9.7.2. This displacement of free charges results in a voltage difference between the two regions of the crystal, the *p* region being plus and the *n* region minus. When a load is connected at the terminals, an electron current flows in the direction shown by the arrow and useful electric power is available at the load.

SOLAR-CELL CHARACTERISTICS

The electrical characteristics of a typical silicon *pn*-junction solar cell are shown in Fig. 9.7.3. Figure 9.7.3*a* shows open-circuit voltage and short-circuit current as a function of light intensity from total darkness to full sunlight (1000 W/m^2). The short-circuit current is directly proportional to light intensity and amounts to 28 mA/cm^2 at full sunlight. The open-circuit voltage rises sharply under weak light and saturates at about 0.6 V for radiation between 200 and 1000 W/cm^2. The variation in power output from the solar cell irradiated by full sunlight as its load is varied from short circuit to open circuit is shown in Fig. 9.7.3*b*. The maximum power output is about 11 mW/cm^2 at an output voltage of 0.45 V.

Under these operating conditions, the overall conversion efficiency from solar to electric energy is 11 percent. The output power as well as the output current is proportional to the irradiated surface area, whereas the output voltage can be increased by connecting cells in series, as in a chemical storage battery. Experimental samples of silicon solar cells have been produced which operate at efficiencies up to 18 percent, but commercial cell efficiency is around 10 to 12 percent under normal operating conditions.

Using optical concentration to intensify the light incident on the solar cell, efficiencies above 20 percent have been achieved with silicon cells and above 25 percent with gallium arsenide cells. New concepts to split the solar spectrum and illuminate two optimized solar cells of different bandgaps have achieved efficiencies above 28 percent with expected efficiencies of 35 percent. Thin-film solar cells currently between 4 and 9 percent efficiency are expected in low-cost arrays to be above 10 percent.

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