Chapter 1

SOLAR CELLS AND SUNLIGHT

1.1 INTRODUCTION

Solar cells operate by converting sunlight directly into electricity using the electronic properties of a class of material known as semiconductors. In the following chapters, this elegant energy-conversion process will be examined starting from the basic physical principles of solar cell operation. From this basis, the mathematical equations quantifying the energy transformation are developed. This is followed by a description of the technology used to produce present commercial solar cells, based predominantly on a particular semiconductor, silicon. Improvements in this technology, as well as alternative technologies that hold the promise of significantly lower cost, are then described. Finally, the design of solar cell systems is discussed, ranging from small power supplies for remote-area use to possible future residential and central power-generating plants.

In this chapter, the history of solar cell development is outlined briefly, followed by a review of the properties of the sun and its radiation.

1.2 OUTLINE OF SOLAR CELL DEVELOPMENT

Solar cells depend upon the *photovoltaic effect* for their operation. This effect was reported initially in 1839 by Becquerel, who observed a light-dependent voltage between electrodes immersed in an electrolyte. It was observed in an all-solid-state system in 1876 for the case of selenium. This was followed by the development of photocells based on both this material and cuprous oxide. Although a silicon cell was reported in 1941, it was not until 1954 that the forerunner of present silicon cells was announced. This device represented a major development because it was the first photovoltaic structure that converted light to electricity with reasonable efficiency. These cells found application as power sources in spacecraft as early as 1958. By the early 1960s, the design of cells for space use had stabilized, and over the next decade, this was their major application. Reference 1.1 is a good source of more detailed material up to this stage.

The early 1970s saw an innovative period in silicon cell development, with marked increases in realizable energy-conversion efficiencies. At about the same time, there was a reawakening of interest in terrestrial use of these devices. By the end of the 1970s, the volume of cells produced for terrestrial use had completely outstripped that for space use. This increase in production volume was accompanied by a significant reduction in solar cell costs. The early 1980s saw newer device technologies being evaluated at the pilot production stage, poised to enable further reduction in costs over the coming decade. With such cost reductions, a continual expansion of the range of commercial applications is ensured for this approach to utilizing the sun's energy.

1.3 PHYSICAL SOURCE OF SUNLIGHT

Radiant energy from the sun is vital for life on our planet. It determines the surface temperature of the earth as well as supplying virtually all the energy for natural processes both on its surface and in the atmosphere.

The sun is essentially a sphere of gas heated by a nuclear fusion reaction at its center. Hot bodies emit electromagnetic radiation with a wavelength or spectral distribution determined by the body's temperature. For a perfectly absorbing or "black" body, the spectral distribution of the emitted radiation is given by *Planck's radiation law* (Ref. 1.2). As indicated in Fig. 1.1, this law indicates that as a body is heated, not only does the total energy of the electromagnetic radiation emitted increase, but the wavelength of peak emission decreases. An example of this within most of our ranges of experience is that metal, when heated, glows red and then yellow as it gets hotter.

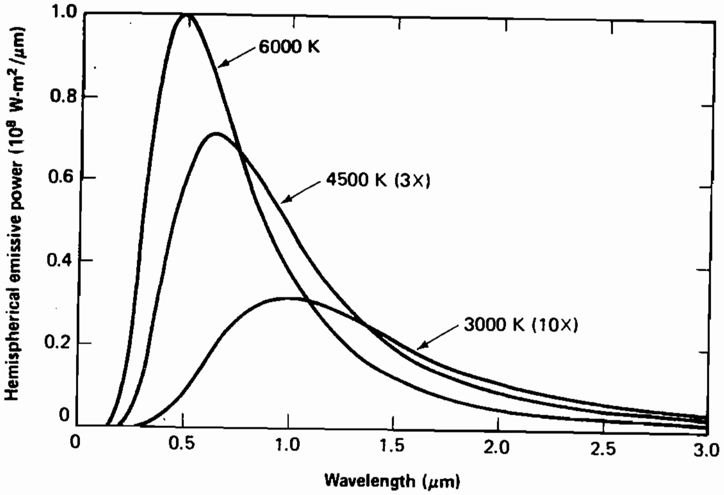


Figure 1.1. Planckian black-body radiation distributions for different black-body temperatures.

Temperatures near the sun's center are estimated to reach a warm 20,000,000 K. However, this is *not* the temperature that determines the characteristic electromagnetic radiation emission from the sun. Most of the intense radiation from the sun's deep interior is absorbed by a layer of negative hydrogen ions near the sun's surface.

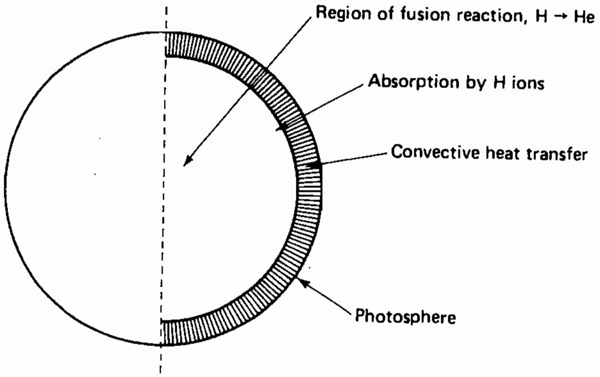


Figure 1.2. Principal features of the sun.

These ions act as continuous absorbers over a great range of wavelengths. The accumulation of heat in this layer sets up convective currents that transport the excess energy through the optical barrier (Fig. 1.2). Once through most of this layer, the energy is reradiated into the relatively transparent gases above. The sharply defined level where convective transport gives way to radiation is known as the *photosphere*. Temperatures within the photosphere are much cooler than at the sun's interior but are still a very high 6000 K. The photosphere radiates an essentially continuous spectrum of electromagnetic radiation closely approximating that expected from a black body at this temperature.

1.4 THE SOLAR CONSTANT

The radiant power per unit area perpendicular to the direction of the sun outside the earth's atmosphere but at the mean earth-sun distance is essentially constant. This radiation intensity is referred to as the *solar constant* or, alternatively, *air mass zero* (AM0) *radiation*, for reasons that will soon become apparent.

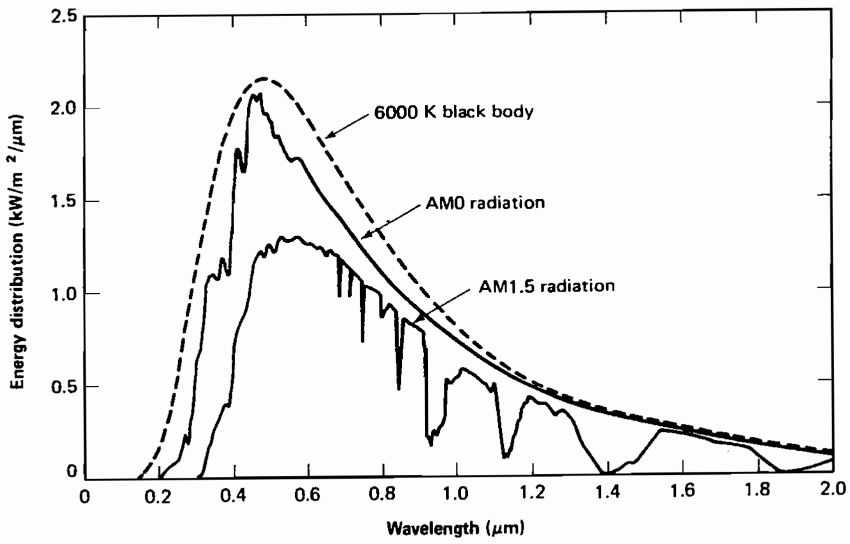


Figure 1.3. Spectral distribution of sunlight. Shown are the cases of AM0 and AM1.5 radiation together with the radiation distribution expected from the sun if it were a black body at 6000 K.

The presently accepted value of the solar constant in photovoltaic work is 1.353 kW/m^2. This value has been determined by taking a weighted average of measurements made by equipment mounted on balloons, high-altitude aircraft, and spacecraft (Ref. 1.3). As indicated by the two uppermost curves in Fig. 1.3, the spectral distribution of AM0 radiation differs from that of an ideal black body. This is due to such effects as differing transmissivity of the sun's atmosphere at different wavelengths. Currently accepted values for this distribution are tabulated in Ref. 1.3. A knowledge of the exact distribution of the energy content in sunlight is important in solar cell work because these cells respond differently to different wavelengths of light.

1.5 SOLAR INTENSITY AT THE EARTH'S SURFACE

Sunlight is attenuated by at least 30% during its passage through the earth's atmosphere. Causes of such attenuation are (Ref. 1.4):

1. Rayleigh scattering or scattering by molecules in the atmosphere. This mechanism attenuates sunlight at all wavelengths but is most effective at short wavelengths.
2. Scattering by aerosols and dust particles.
3. Absorption by the atmosphere and its constituent gases—oxygen, ozone, water vapor, and carbon dioxide, in particular.

A typical spectral distribution of sunlight reaching the earth's surface is shown by the lower curve of Fig. 1.3, which also indicates the absorption bands associated with molecular absorption.

The degree of attenuation is highly variable. The most important parameter determining the total incident power under clear conditions is the length of the light path through the atmosphere. This is shortest when the sun is directly overhead. The ratio of any actual path length to this minimum value is known as the *optical air mass*. When the sun is directly overhead, the optical air mass is unity and the radiation is described as *air mass one* (AM1) *radiation*. When the sun is an angle θ to overhead, the air mass is given by

$$\text{Air mass} = \frac{1}{\cos\theta} \qquad (1.1)$$

Hence, when the sun is 60° off overhead, the radiation is AM2. The easiest way to estimate the air mass is to measure the length of the shadow s cast by a vertical structure of height h. Then

$$\text{Air mass} = \sqrt{1 + \left(\frac{s}{h}\right)^2} \tag{1.2}$$

With increasing air mass but with other atmospheric variables constant, the energy reaching the earth is attenuated at all wavelengths, with attenuation in the vicinity of the absorption bands of Fig. 1.3 becoming even more severe.

Hence, as opposed to the situation outside the earth's atmosphere, terrestrial sunlight varies greatly both in intensity and spectral composition. To allow meaningful comparison between the performances of different solar cells tested at different locations, a terrestrial standard has to be defined and measurements referred to this standard. Although the situation is in a state of flux, the most widely used terrestrial standard at the time of writing is the AM1.5 distribution of Table 1.1, also plotted as the terrestrial curve in Fig. 1.3. In the photovoltaic program of the U.S. government, this distribution, essentially scaled up so that the total power density content is 1 kW/m^2, was incorporated as a standard in 1977 (Ref. 1.5). The latter power density is close to the maximum received at the earth's surface.

1.6 DIRECT AND DIFFUSE RADIATION

The composition of terrestrial sunlight is further complicated by the fact that, as well as the component of radiation directly from the sun, atmospheric scattering gives rise to a significant indirect or *diffuse* component. Even in clear, cloudless skies, the diffuse component can account for 10 to 20% of the total radiation received by a horizontal surface during the day.

For less sunny days, the percentage of radiation on a horizontal surface that is diffuse generally increases. From observed data (Ref. 1.6), the following statistical trends can be discerned. For days on which there is a notable lack of sunshine, most of the radiation will be diffuse. This will be true, in general, for days on which the total radiation received is up to one-third that which would be received on a clear, sunny day at the same time of the year. For days between the sunny and cloudy extremes mentioned above, where about one-half of clear-day radiation is received, about 50% of this generally will be diffuse. Poor weather will not only cause some

Table 1.1 SOLAR SPECTRUM—AIR MASS 1.5*

Wave-length (μm)	W/(m^2 - μm)	*Wave-length* (μm)	W/(m^2 - μm)	*Wave-length* (μm)	W/(m^2 - μm)	*Wave-length* (μm)	W/(m^2 - μm)	*Wave-length* (μm)	W/(m^2 - μm)
0.295	0	0.595	1262.61	0.870	843.02	1.276	344.11	2.388	31.93
0.305	1.32	0.605	1261.79	0.875	835.10	1.288	345.69	2.415	28.10
0.315	20.96	0.615	1255.43	0.8875	817.12	1.314	284.24	2.453	24.96
0.325	113.48	0.625	1240.19	0.900	807.83	1.335	175.28	2.494	15.82
0.335	182.23	0.635	1243.79	0.9075	793.87	1.384	2.42	2.537	2.59
0.345	234.43	0.645	1233.96	0.915	778.97	1.432	30.06		
0.355	286.01	0.655	1188.32	0.925	217.12	1.457	67.14		
0.365	355.88	0.665	1228.40	0.930	163.72	1.472	59.89		
0.375	386.80	0.675	1210.08	0.940	249.12	1.542	240.85		
0.385	381.78	0.685	1200.72	0.950	231.30	1.572	226.14		
0.395	492.18	0.695	1181.24	0.955	255.61	1.599	220.46		
0.405	751.72	0.6983	973.53	0.965	279.69	1.608	211.76		
0.415	822.45	0.700	1173.31	0.975	529.64	1.626	211.26		
0.425	842.26	0.710	1152.70	0.985	496.64	1.644	201.85		
0.435	890.55	0.720	1133.83	1.018	585.03	1.650	199.68		
0.445	1077.07	0.7277	974.30	1.082	486.20	1.676	180.50		
0.455	1162.43	0.730	1110.93	1.094	448.74	1.732	161.59		
0.465	1180.61	0.740	1086.44	1.098	486.72	1.782	136.65		
0.475	1212.72	0.750	1070.44	1.101	500.57	1.862	2.01		
0.485	1180.43	0.7621	733.08	1.128	100.86	1.955	39.43		
0.495	1253.83	0.770	1036.01	1.131	116.87	2.008	72.58		
0.505	1242.28	0.780	1018.42	1.137	108.68	2.014	80.01		
0.515	1211.01	0.790	1003.58	1.144	155.44	2.057	72.57		
0.525	1244.87	0.800	988.11	1.147	139.19	2.124	70.29		
0.535	1299.51	0.8059	860.28	1.178	374.29	2.156	64.76		
0.545	1273.47	0.825	932.74	1.189	383.37	2.201	68.29		
0.555	1276.14	0.830	923.87	1.193	424.85	2.266	62.52		
0.565	1277.74	0.835	914.95	1.222	382.57	2.320	57.03		
0.575	1292.51	0.8465	407.11	1.236	383.81	2.338	53.57		
0.585	1284.55	0.860	857.46	1.264	323.88	2.356	50.01		

*Total energy content = 832 W/m^2.
Source: Ref. 1.5.

regions of the world to receive low levels of solar radiation but will also cause a significant proportion of it to be diffuse.

Diffuse sunlight generally has a different spectral composition from direct sunlight. Generally, it will be richer in the shorter or "blue" wavelengths, giving rise to further variability in the spectral composition of light received by a solar cell system. Uncertainty in the distribution of diffuse radiation from different directions in the sky introduces other uncertainties when calculating radiation levels on inclined surfaces from data generally recorded on horizontal surfaces. A common assumption is that diffuse light is isotropic (uniform in all directions), although the region of the sky surrounding the sun is the most intense source of this radiation.

Photovoltaic systems based on concentrated sunlight can generally only accept rays spanning a limited range of angles. Hence, they usually have to track the sun to utilize the direct component of sunlight, with the diffuse component wasted. This tends to offset the advantage gained by such tracking systems of intercepting maximum power density by always being normal to the sun's rays.

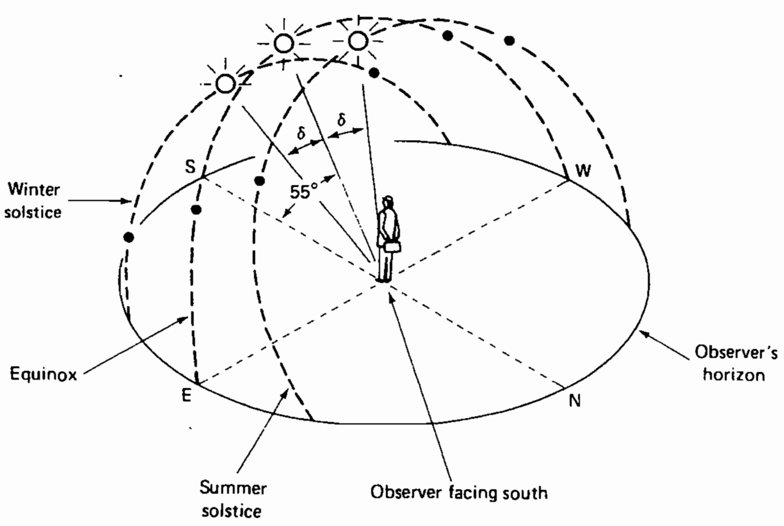
1.7 APPARENT MOTION OF THE SUN

The earth spins daily on an imaginary axis orientated in a fixed direction relative to the plane of the earth's yearly orbit about the sun. The angle this direction makes with the orbital plane is the solar declination (23°27′). Perhaps less familiar are the details of the apparent motion of the sun relative to a fixed observer on earth resulting from the relationship described above.

This apparent motion is indicated in Fig. 1.4 for an observer at latitude 35° north. On any given day, the plane of the sun's apparent orbit lies at an angle equal to the latitude from the observer's vertical. At the equinoxes (March 21 and September 23), the sun rises due east and sets due west, so that the altitude of the sun at solar noon on these days equals 90° minus the latitude. At the summer and winter solstices (June 21 and December 22, respectively, for the northern hemisphere, the opposite for the southern), the altitude at solar noon has increased or decreased by the declination of the earth (23°27′).

1.8 SOLAR INSOLATION DATA

The ideal situation for the design of photovoltaic systems would be when there were detailed records of the solar insolation at the site selected for installation. Not only would data on the direct and diffuse components of light be desirable, but data on corresponding ambient temperatures as well as wind speed and direction could be used to advantage. Although there are stations at various locations around the world that do monitor all these parameters, present economies favor the use of photovoltaic systems in remote regions of the world where it is unlikely that such information is available.



δ = declination of the earth = 23°27′

Figure 1.4. Apparent motion of the sun relative to a fixed observer at latitude 35° in the northern hemisphere. The path of the sun is shown at the equinoxes and the summer and winter solstices. The position of the sun is shown at solar noon on each of these days. The shaded circles represent the sun's position 3 h before and after solar noon.

The available insolation at a given location depends not only on gross geographical features such as latitude, altitude, climatic classification, and prevailing vegetation, but it also depends strongly upon local geographical features. Although unable to incorporate the latter features, maps of solar insolation distribution are available for different parts of the world. These have usually been prepared by combining measured insolation data with data estimated from a large network of stations around the world monitoring hours of sunshine.

The information most generally available is the average daily total or *global radiation* on a horizontal surface. A widely used source

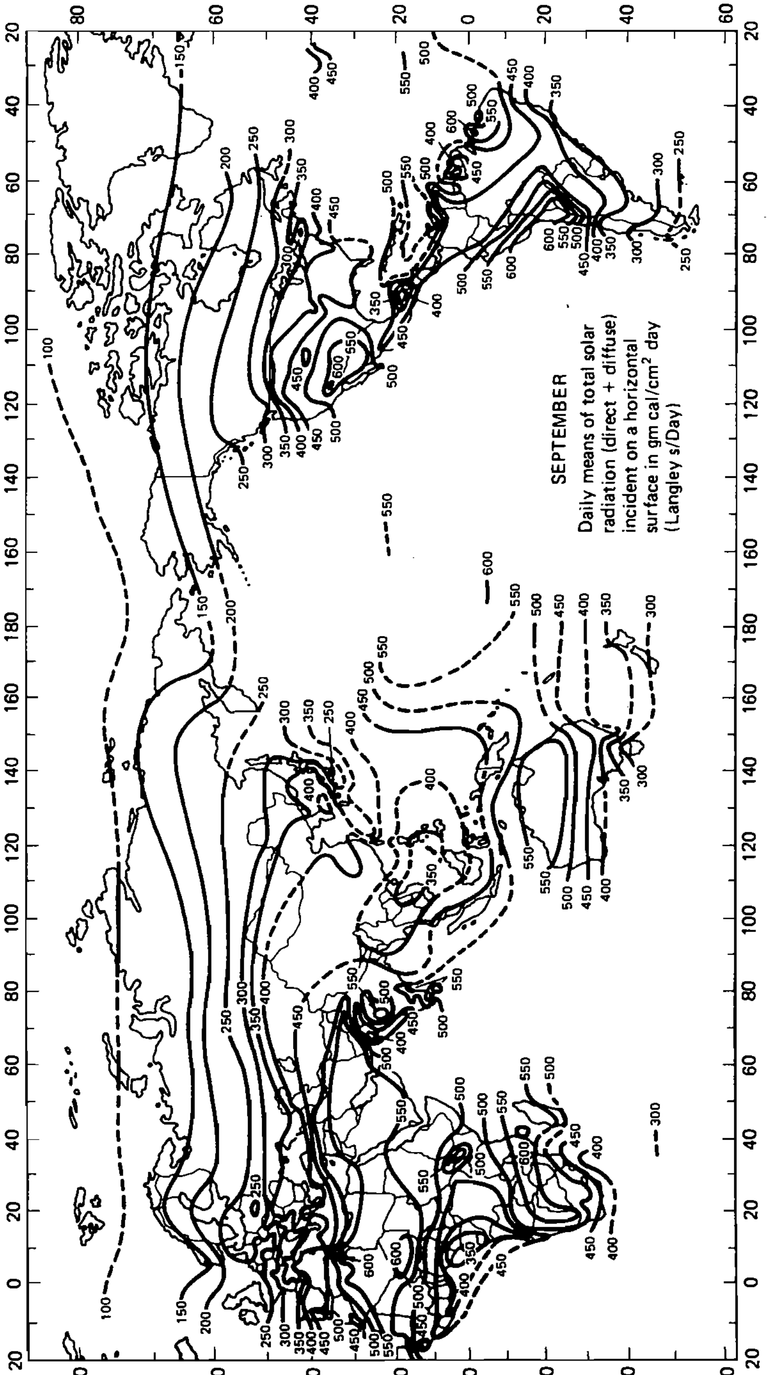


Figure 1.5. Worldwide distribution of solar energy during the month of September. The contours are daily means of global solar radiation incident on a horizontal surface expressed in *langleys*. A langley equals 1 cal/cm². To convert to MJ/m², multiply by 0.0418. To convert to kWh/m², multiply by 0.0116. The distribution of solar energy during September is roughly indicative of annual average daily radiation for a given site. Similar curves for other months of the year appear in Ref. 1.7. (After Ref. 1.7.)

for such data is Ref. 1.7. This lists, for each month of the year, average daily global radiation on a horizontal surface for hundreds of insolation monitoring stations around the world. It also lists this information estimated from sunshine-hour records, taking into account climatic and vegetation data for several hundred other locations. This information has been incorporated into a sequence of world maps showing contours of constant insolation for each month of the year. Such contours are illustrated in Fig. 1.5 for a month of equinox, September. This month corresponds approximately to average insolation levels throughout the year for most locations.

1.9 SUMMARY

Although sunlight outside the earth's atmosphere is relatively constant, the situation at the earth's surface is more complex. Terrestrial sunlight varies dramatically and unpredictably in availability, intensity, and spectral composition. On clear days, the length of the sunlight's path through the atmosphere or the optical air mass is an important parameter. The indirect or diffuse component of sunlight can be particularly important for less ideal conditions. Reasonable estimates of global radiation (direct plus diffuse) received annually on horizontal surfaces are available for most regions of the world. However, there are uncertainties involved in using this for a specific site because of the large deviations that can be caused by local geographical conditions and approximations involved in conversion to radiation on inclined surfaces.

EXERCISES

1.1. Estimate the solar constant for Mercury and Mars given that the mean distances from the sun to Earth, Mercury, and Mars are 150, 58, and 228 million kilometers, respectively.

1.2. The sun is at an altitude of 30° to the horizontal. What is the corresponding air mass?

1.3. Calculate the sun's altitude at solar noon on June 21 at Sydney (latitude 34°S), San Francisco (latitude 38°N), and New Delhi (latitude 29°N).

1.4. The global radiation at solar noon on a summer solstice in Albuquerque, New Mexico (latitude 35°N), is 60 mW/cm². Assume that 30% of this is diffuse radiation and make the approximations that the ground surrounding the module is nonreflecting and the diffuse radiation is uniformly distributed across the sky. Estimate the radiation intensity on a flat surface facing south at an angle of 45° to the horizontal.

REFERENCES

[1.1] M. Wolf, "Historical Development of Solar Cells," in *Solar Cells*, ed. C. E. Backus (New York: IEEE Press, 1976).

[1.2] R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer* (New York: McGraw-Hill, 1972).

[1.3] M. P. Thekackara, *The Solar Constant and the Solar Spectrum Measured from a Research Aircraft*, NASA Technical Report No. R-351, 1970.

[1.4] P. R. Gast, "Solar Radiation," in *Handbook of Geophysics*, ed. C. F. Campen et al. (New York: Macmillan, 1960), pp. 14-16 to 16-30.

[1.5] *Terrestrial Photovoltaic Measurement Procedures*, Report ERDA/NASA/1022-77/16, June 1977.

[1.6] B. Y. Liu and R. C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation," *Solar Energy 4* (July 1960), 1-19.

[1.7] G. O. G. Löf, J. A. Duffie, and C. O. Smith, *World Distribution of Solar Energy*, Report No. 21, Solar Energy Laboratory, University of Wisconsin, July 1966.

Chapter 2

REVIEW OF SEMICONDUCTOR PROPERTIES

2.1 INTRODUCTION

In Chapter 1, the properties of sunlight were reviewed. It is now appropriate to look at the properties of the other important component in photovoltaic solar energy conversion, semiconducting material.

The aim of this chapter is *not* to treat the properties of semiconductors rigorously from fundamentals. Rather, it is to highlight those properties of semiconductors that are important in the design and operation of solar cells. As such, the chapter may suffice for quick revision for readers already acquainted with these properties while containing adequate information to allow those not as well acquainted to establish a framework on which subsequent material can be supported. To strengthen this framework, readers in the latter category are referred to one of the many textbooks specifically directed at treating semiconductor properties more fundamentally (Refs. 2.1 to 2.4).