2
Absorbing Solar Energy

2.1 Air Mass and the Solar Spectrum

Now that we have introduced the solar cell, it is time to introduce the source of the energy—the sun. The sun has many properties that could be discussed at length. For example, the color temperature of the light, the nuclear (fusion) processes that occur within the sun, or the geometry of Earth and the sun that establishes the size of the solar disk as viewed from Earth. However, for the purpose of solar cell studies, two parameters are most important: the irradiance—that is, the amount of power incident on a surface per unit area—and the spectral characteristics of the light. The irradiance value outside Earth's atmosphere is called the solar constant, and is 1365 W/m^2. After being filtered through Earth's atmosphere, several portions of the solar spectrum diminish, and peak solar irradiance is lowered to approximately 1000 W/m^2. This is the typical irradiance on a surface, or plane, perpendicular to the sun's rays on a sunny day. If one were to track the sun for eight hours, the average daily solar irradiance would be approximately 1000 (8/24) = 333 W/m^2. On a fixed (nontracking) surface, the typical values in sunny locations range between 180–270 W/m^2. Solar data used for the purposes of PV-system sizing and economics are often expressed in units of insolation. The relationship between the average irradiance and insolation is given by the equation

$$\text{insolation}\,\frac{\text{kWh}}{\text{day}\cdot\text{m}^2} = \text{irradiance}\cdot\frac{24\,\text{h}}{\text{day}}\cdot\frac{10^{-3}\ \text{kW}}{\text{W}}. \tag{2.1}$$

For an irradiance of 250 W/m^2 the insolation would be 6 kWh/day/m^2.

The solar spectrum and irradiance is established by the air mass. Air mass (AM) refers to the amount of air a beam of sunlight must go through before reaching the solar converter. It is determined by the angle, θ, that the sun makes with a vertical line perpendicular to the horizontal plane (see Appendix, Fig. A.1). It is given by

$$\text{AM (number)} = \frac{1}{\cos\theta}\ . \tag{2.2}$$

The solar spectrum outside the atmosphere, AM0, is close to a 5743 K (Planck) blackbody-radiation spectrum and has an irradiance of 1365 W/m^2. The shape of this blackbody spectrum is shown in Fig. 2.1. Air mass 1.0 refers to the thickness of the atmosphere sunlight passes through if the beam is directly overhead. An AM1 atmosphere reduces the direct flux by a factor 0.7. On a clear day, and when the sun is directly overhead, nearly 70% of the solar radiation incident to Earth's atmosphere reaches its surface undisturbed. About another 7% reaches the ground in an approximately isotropic manner after scattering from atmospheric molecules and particles. The rest is absorbed or scattered back into space. Both the direct and scattered fluxes vary with time and location because the amounts of dust and water vapor in the atmosphere are not constant even on clear days. For purposes of standard solar cell measurements, an average solar spectrum at AM1.5 is used (θ = 48.19 deg). It should be noted that the total irradiance used for AM1.5 was 844 W/m^2 in earlier work, but is often normalized to 1000 W/m^2 in more recent work (ASTM E 892, IEC 60904-3). It is therefore best to specify the AM and the irradiance when reporting measurement conditions. Figure 2.1 shows the spectral irradiance for the sun when viewed as a blackbody, but is scaled (diluted) such that the total power is approximately 1000 W/m^2.

An attempt to replicate the AM1.5 spectrum is made in standardized solar simulators. Figure 2.2(a) shows the solar spectrum at AM1.5 (see Appendix, Table A.1). The integral over the wavelength yields the total irradiance, 1000 W/m^2. The many notches in the spectrum are attributed to the absorption bands of various atmospheric gases such as H_2O, CO_2, O_3, and O_2. Absorption by ozone is essentially complete below a wavelength of 0.3 μm. The relatively large attenuation below 0.8 μm is due to scattering of molecules and particulates. These scattering processes become weaker at longer wavelengths, as has been shown by both theory and observation. This also explains the spectrum of the diffuse radiation, which is richer than the direct radiation in the blue portion of the spectrum. When analyzing the performance of solar cell systems, the cell output is usually assumed to be proportional to the solar radiation intensity with little regard to the variations in the spectral distributions. This practice is satisfactory for engineering and design purposes, but may be problematic for reporting accurate solar conversion efficiencies. The amount of cloud cover is a dominant factor in determining the transmission and scattering of solar radiation in practical PV applications.

The solar spectrum discussed above can be used to determine the number of photons that can produce electrons in the solar cell. The wavelength scale on the solar spectrum can be converted to photon energy, e, from the relationship

$$\text{Photon Energy} \equiv e = \frac{hc}{\lambda} \cong \frac{1.239}{\lambda(\mu m)} \text{ [in eV]}. \tag{2.3}$$

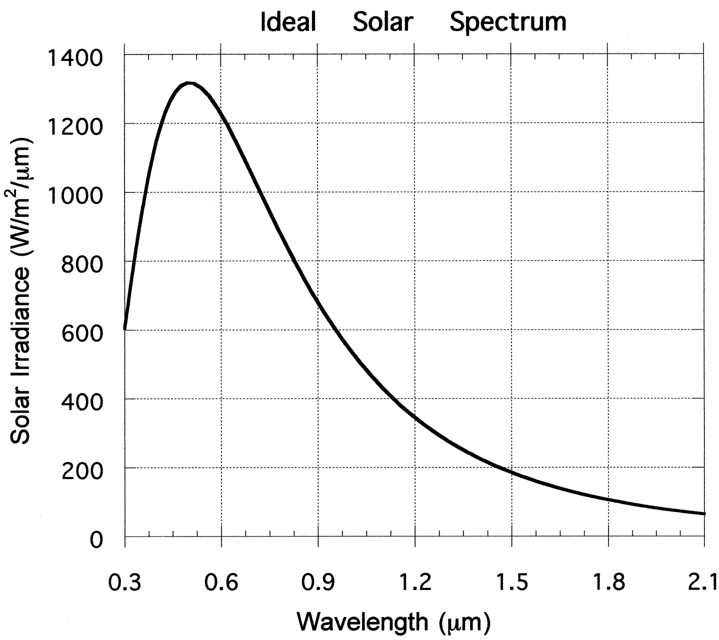


Fig. 2.1 Solar spectrum obtained from the Planck blackbody equation and T_s= 6000 K. The plot is normalized so that the total power (area under the curve) is 1000 W/m^2.

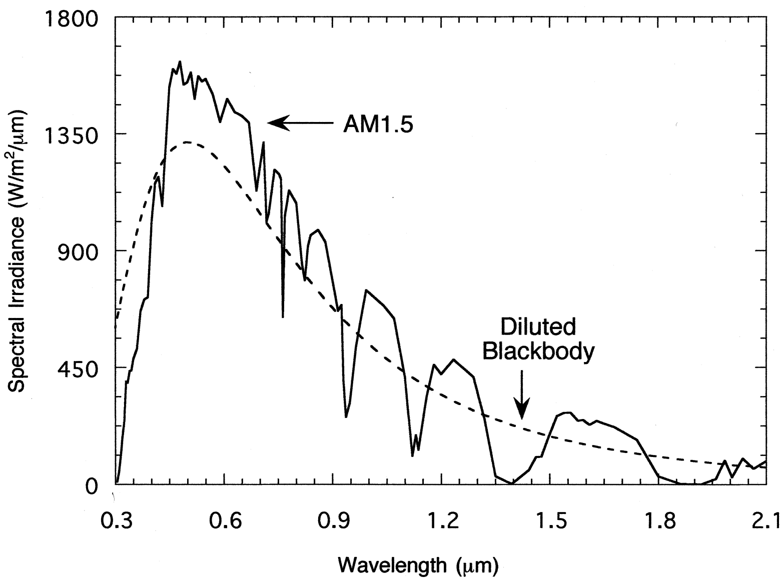
Thus, a photon at a wavelength of 550 nm has an energy of approximately 2.2 eV. Knowing the energy per photon at each wavelength, the *y* axis in the solar spectrum shown in Fig. 2.2(a) can be converted to a number of photons per second per unit area and photon energy. Such a plot, corresponding to Fig. 2.2(a), is shown in Fig. 2.2(b). To convert the solar irradiance, P, one uses the relationship

$$\frac{d\Gamma}{de} \equiv \Gamma_e = \frac{d\Gamma}{d\lambda} \cdot \frac{d\lambda}{de} = \Gamma_\lambda \frac{\lambda}{e} = \frac{P_\lambda}{e} \cdot \frac{\lambda}{e}, \tag{2.4}$$

where e is the photon energy and Γ is the photon flux density. A plot of photon-flux density such as the one shown in Fig. 2.2(b) is useful in establishing the limits on the photocurrent from a solar cell. The expected maximum current can be calculated if the number of absorbed photons per unit area is multiplied by the charge per electron, q. For example, if a solar cell could absorb all photons with an energy of 1.6 eV and higher, and each photon created an electron collected by the external contacts, then a current of approximately 20 mA/cm^2 would result in the external circuit.

As another example, consider a Si wafer of a 200-μm thickness and a 1-cm^2 area illuminated by AM1.5 sunlight. As a first approximation, we can consider all the charge carriers to be uniformly distributed within the volume of the solar

(a)



(b)

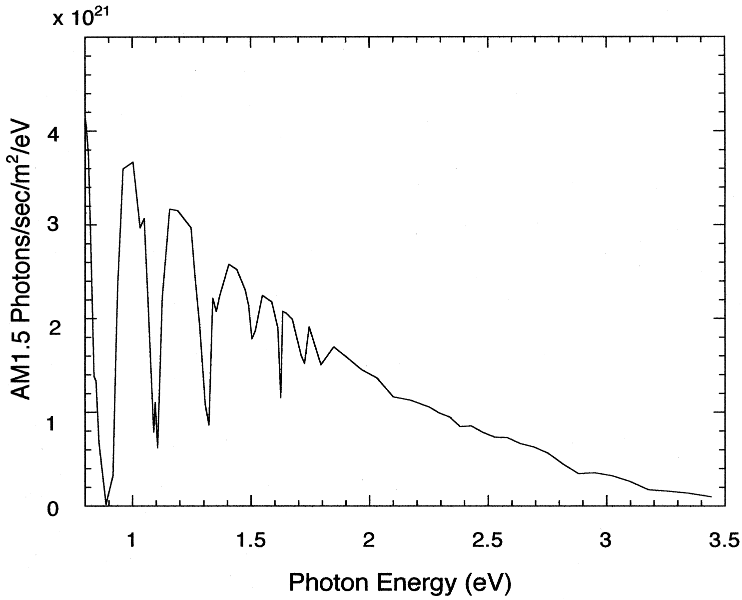


Fig. 2.2 The solar spectrum at AM1.5, 1000 W/m^2 conditions for (a) Irradiance normal to the beam, and (b) corresponding photon flux (number of photons). For the AM1.5 data, see the Appendix, Table A.1.

cell. If the J_{SC} value for a solar cell made with Si is approximately 30 mA/cm^2, the total incident photon flux density [integral of Fig. 2.1(b)] is greater than $J_{SC}/q = 1.9 \times 10^{17}$ photons/sec/cm^2, and the excited electron concentration is $J_{SC}/(q \times 200 \times 10^{-4}$ cm$) = 9 \times 10^{18}$ electrons/sec/cm^3. Of course, the steady-state electron concentration (in electrons/cm^3) present in the solar cell at AM1.5 would be much lower than this value. This is because the charge carriers are swept out of the device so that they can be collected by the contacts to flow through the load. An analogy would be to ask how many cars are present on a busy section of road at a given moment versus how many cars have passed a point on the road per hour. In Chapter 3, we will see that the electron concentration in a solar cell is obtained from a balance between the number of charge carriers produced by photon absorption, and the subsequent charge-carrier recombination and diffusion in the light-absorbing material.

2.2 Optical Properties of Solar Cell Materials

2.2.1 Absorptivity

Just how many photons can be absorbed by a solar cell is determined by the optical properties of the device, which in turn, is a property of the material used to absorb the light and the geometry in which it is used. One of the most fundamental questions in solar cell design and analysis is whether much of the solar spectrum can be absorbed. There are several useful optical parameters to be considered when characterizing a solar cell or solar cell material. Some are fundamental constants of the material, others are "lumped" parameters that only characterize the particular device or solar geometry in question. Listed in the order of most to least fundamental (basic), the constants are the complex index of refraction, the extinction coefficient, the absorption coefficient, and the absorptivity. In this section, we shall examine each of these to demonstrate their interrelationship and connection to solar cell design.

When determining a solar cell's light absorption, it is the optical parameter called the absorptivity that is most useful when assessing potential absorber materials for solar cells, or when optimizing a given absorber material for a solar cell. The quantum absorptivity is the fraction of the incoming light at a given photon energy, e, that is absorbed by the material to produce an excited state such as an electron-hole pair. It is measured, and calculated, as a function of the photon energy, yielding a(e), or, alternatively, it can be expressed as a function of the photon wavelength, yielding a(λ). The absorptivity can be multiplied by the incoming photon flux to determine how many electron-hole pairs can be produced. Multiplying this result by the elemental charge, q, and integrating over the solar spectrum then yields the upper limit for how much current can be extracted from a device made with the solar-absorber material. The absorptivity can be measured directly, or it can be calculated using the basic optical properties that are constant for a material. Not all absorption in a solar cell material creates