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Introduction to Solar Energy and Solar Photovoltaics

1.1 INTRODUCTION

The Sun has been worshipped through the ages as the provider of light and life. In ancient Egypt, the Sun was worshipped as Ra, in India as Surya and in Greek and Roman mythologies as Helios and Apollo, respectively. Eclipses of the Sun were considered as precursors of natural calamities and, as such, temples to the Sun God abounded in all cultures. The Copernican system placed the Sun at the centre of the solar system with the Earth as a planet at a distance of 149.6 km (93 million miles). The Sun can be considered as a black body with a surface temperature of 6000 K. The Earth intercepts 1,74,000 terawatts (TW) of incident solar radiation (insolation) in the upper atmosphere. Since about 30% is reflected back to space, while the rest is absorbed by clouds, oceans, and land masses, the total solar energy absorbed by the Earth's atmosphere, oceans, and land masses is approximately 38,50,000 exajoules (EJ) (1 exajoule = 10^{18} J) per year. It is commonly stated that the solar energy received on the Earth's surface in 1 hour is more than that used by the world in 1 year! The solar spectrum shown in Figure 1.1 [1] extends from the near ultraviolet (UV) (300 nm) to the infra-red (IR) (2.5 μm).

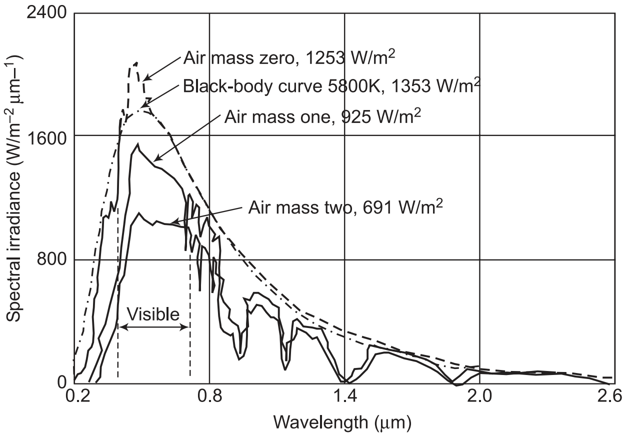

Figure 1.1 Solar spectrum at AM 0, AM 1 and AM 2.

With the looming problems of global warming (Figure 1.2) attributed to CO$_2$ emission due to the use of fossil fuels (Figure 1.3) into the Earth's atmosphere, development of renewable energy, solar energy [2, 3] in particular, has acquired great urgency. The Industrial Revolution was ushered in by the abundance of coal in Western Europe. This was followed by the discovery of oil and gas, the predominant sources of energy at present. However, all these sources are limited and are bound to be exhausted by 2100, if not earlier (Figure 1.4).

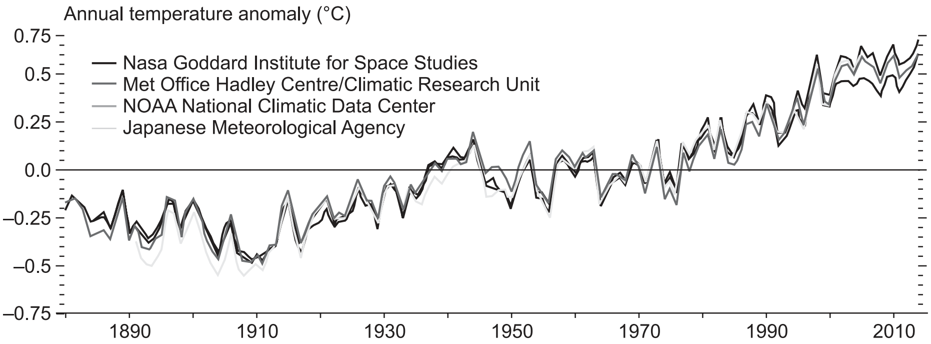

Figure 1.2 Global temperature rise, 1890–2010.

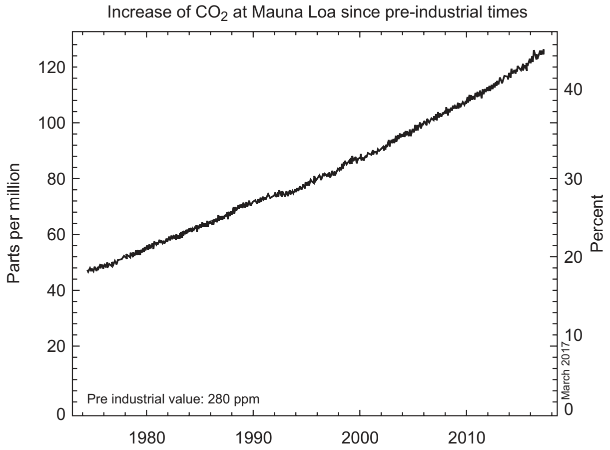

Figure 1.3 Global CO_2 rise at Mauna Loa, 1968–2008.

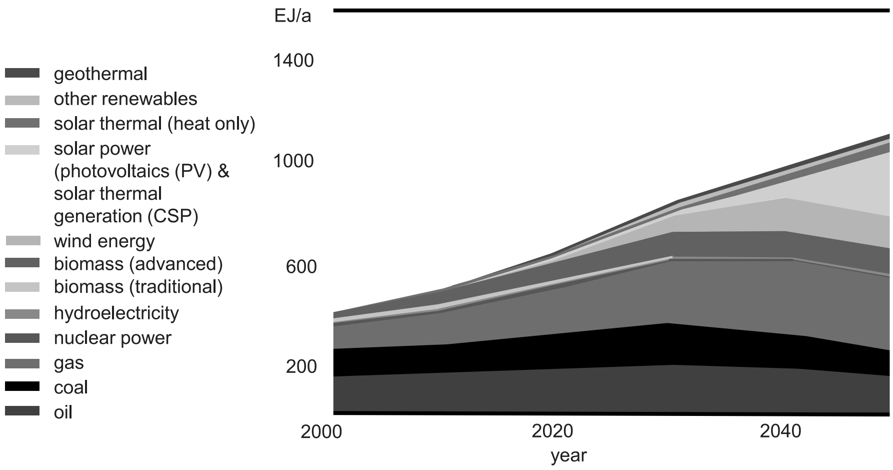

Figure 1.4 World energy supply, 2000–2050.

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Nuclear energy at one time promised energy ‘too cheap to meter’, but the fission process results in hazardous radioactive wastes whose disposal problems have not yet been solved. Supply of uranium as the primary fuel is not a problem at present, but nuclear reactors are also associated with the production of weapons of mass destruction. Although the amount of nuclear fuel required is orders of magnitude less than for a coal-fired plant, the conversion of heat into electricity requires huge amounts of cooling water (1 million gallon/day for a 1000 MW plant) which is a constraint on the location of such plants. The de-commissioning of such plants is also estimated to cost billions of dollars. Thus, 60 years since the first nuclear power reactor commenced operation, nuclear power supplies only 6.4% of the global power. The break-up of world’s energy supply among different sources is given in Figure 1.5, which shows the predominance of coal, natural gas and oil, with renewables (excluding biomass) supplying a mere 2.6%.

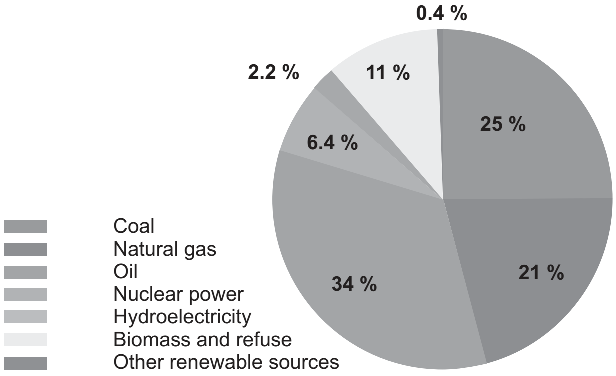

Figure 1.5 Break-up of world’s energy supply.

In principle, renewable energy in the form of hydroelectric, solar wind, biomass, ocean, tidal and geothermal energy provides attractive and viable alternatives. However, these sources are not distributed uniformly, are variable in nature, and, especially in the case of solar, not available round-the-clock when the need is the highest. Other disadvantages are their diffused nature and much lower energy density than available, say in a gallon of petrol. Since the output of these energy sources is variable in time, energy storage is desirable that adds to the system cost. Further, energy storage technologies are still in a state of transition as discussed in Chapter 10.

1.1.1 Definitions

According to Sze [4],

Solar Constant: Solar intensity outside atmosphere: 1,367 W/m^2 = AM 0 (1.1)

Atmospheric Mass (AM): AM 0 = solar intensity at the top of the atmosphere

For AM 0: Photon flux = 5.8×10^{17}/cm^2 sec (1.2a)

Average photon energy = 1.48 eV (1.2b)

AM 1 = Solar intensity on earth’s surface with sun vertically overhead = 925 W/cm^2

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For AM 1: Photon flux = 5.0×10^{17}/cm^2/sec (1.3a)

Average photon energy = 1.32 eV (1.3b)

As shown in Figure 1.6. AM X is defined by X = sec θ

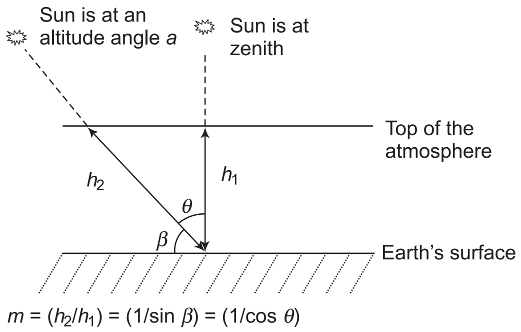

Figure 1.6 Inclination of solar radiation defines AM X.

where θ = angle between the Sun and the zenith.

For example, for AM 2, $\theta = 60°$,

solar intensity = 691 W/m^2 (1.4)

Wavelength for maximum intensity of solar spectrum = 550 nm (1.5)

Above the atmosphere, the spectrum extends from the near-ultraviolet into the near-infrared (300–2500 nm) region (Figure 1.1). The spectral maximum lies in the green at 550 nm to coincide with the colour of plant life. Due to atmospheric absorption, the insolation on Earth's surface with the Sun at its zenith is 925 W/m^2 (AM 1). For calculation of average insolation during the day, the value of AM 2 used with $\theta = 60°$ is 691 W/m^2. The photons fluxes are 5.8×10^{17}/cm^2/sec at AM 0 and 5.0×10^{17}/cm^2/sec at AM 1 as given above. These figures are important in determining the maximum photocurrent that can be obtained.

India lies in the tropical belt between latitudes of 8°4′ and 37°6′ with an average of 300 sunny days per year and hence is favourably located with respect to solar insolation. Rajasthan and Gujarat have the highest insolation of 6 kWh/m^2 in summer, with annual output greater than 2150 kWh/m^2. The North Eastern states with prolonged monsoon months have lower values of annual output that are <1500 kWh/m^2. Interestingly, Ladakh, at an altitude of 4000 m, has very clear skies most of the year and has high insolation that is ideal for Solar Photovoltaics (SPV). Since temperature is an important factor, it must be recognized that the ambient temperature in Rajasthan and Gujarat climbs to 45°C in summer, which lowers the SPV output as discussed in Section 2.7. In Ladakh, the winter temperature can plunge to –30°C. Heavy rain and high humidity have also to be taken into account while designing solar panels.

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For maximum solar insolation throughout the year in the northern hemisphere, fixed solar panels are mounted facing the geographical south and tilted at an angle equal to the latitude of the location. The tilting provides additional practical benefits in draining off incident rain water and reducing the collection of dust. Single or double-axis tracking of the Sun increases the energy output and is discussed in detail in Chapters 4 and 9.

Solar energy is diffuse when compared with other forms and the energy available with an intensity of 1 kW/m^2 is only 150 W/m^2 if the conversion efficiency is 15%. For comparison, the amount of electrical energy consumed worldwide in 2002 was 49.3 quads (1 quad = 10^{12} BTU = 2.9×10^{11} kWh). This energy could be generated by a PV system working at 15% efficiency with an aerial coverage of 193 km × 193 km in an area of high solar insolation.

The total solar energy incident on a surface has three components: (a) direct radiation; (b) diffuse radiation; and (c) reflected radiation. Meteorological handbooks provide data on direct and diffuse components of solar radiation on a flat surface kept horizontal to the Earth's surface at different locations on the Earth. The installation of viable solar PV systems, as must be emphasized, is extremely site-specific and must take into account many factors such as the diurnal and annual variation of solar insolation from meteorological data, the number of sunless days, the temperature variation throughout the year, wind speed, etc. The system requirements then have to be considered—whether the system is to stand-alone, requires energy storage or is to be grid-connected. These factors are dealt with in detail in Chapters 9 and 10.

Plant life on Earth is dependent on photosynthesis that captures approximately 3000 EJ per year in biomass. Indeed, this was what led Professor Jagdish Chandra Bose [5] to write in his diary on 5 March 1885:

I have been long thinking whether the vast Solar Energy that is wasted in the tropical regions can in any way be utilized. Of course trees consume solar energy. But is there no direct way of utilizing the radiant energy of the Sun?

It is not very well-known that during his researches on radio waves, he also developed a solar cell called 'Tejometer', based on PbS.

1.2 SOLAR ENERGY CONVERSION

1.2.1 Solar Thermal (STH)

Absorption of solar energy incident on the Earth's surface causes heating, thus leading to the first method of its utilization. This is termed as the Solar Thermal process, or technology, as discussed by Tiwari [6]. In simple terms, a large flat plate collector, called solar absorber, placed perpendicular to the incident radiation can be heated up to transfer the heat to a circulating fluid. This acts as a heat transfer medium, transferring the energy to a boiler for steam generation. The steam is then used to drive a turbine to generate electricity by conventional means. The amount of energy collected obviously depends on the area of the collector and its absorption coefficient. Parabolic collectors are used to focus the Sun's rays to generate high temperatures for higher efficiencies in the Carnot cycle.

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Arrays of focusing collectors, programmed to track the path of the Sun called a heliostat, can be used to focus radiation on a solar tower to provide concentration of 3000 or higher. Such a system was first set up in Spain and later in California to generate > 100 MW of electricity. Its advantages are the centralized generation of large amounts of electricity for distribution and the use of conventional turbine technology. Use of a fluid with high thermal capacity instead of water permits the overnight storage of energy. The disadvantages include the requirement of large areas for mounting the reflectors in a region with high solar insolation. These systems are not suitable for rooftop installation, and efficiencies are limited by the Carnot cycle.

There are many designs available, with or without concentration. These systems have wide applications in solar crop drying, solar distillation, solar cooking and in the dairy industry. Another method utilizes the collectors for solar water or air heaters without conversion into electricity. Small rooftop collectors can be used directly to provide hot water and/or room heating.

1.2.2 Solar Photovoltaics (SPV)

Solar photovoltaic devices, called solar cells, convert solar radiation directly into electricity using the properties of semiconductors [7, 8]. These involve no moving parts and can be connected in series and parallel to construct modules that can provide power from a few watts to megawatts depending on the module area and efficiencies.

Solar cells have a working life greater than 25 years with no fuel being required. The relatively weak intensity of 1 kW/m^2 at zenith, its variation during the day, and its absence at night are the main limitations. The capital cost of installation, though decreasing rapidly to below US$1/watt, is also relatively high and has been a deterrent requiring subsidies in different countries. Being a product of the rapidly evolving electronics industry, solar cells have made remarkable progress in reaching higher efficiencies with lower cost/watt in the last two decades. This will be one of the main subjects of this book.

There are attempts to combine solar thermal with solar PV systems since PV can convert only ~20% of the incident energy into electricity, the rest being lost as heat. These are called hybrid PV–thermal systems and may be of two types. In one system, the heat is transferred to water tubes below the PV system to provide room heating. Another system places a thermoelectric material to utilize the temperature gradient between the base of the PV panel and its support to generate additional electricity in what is termed as the Thermophotovoltaic system. Both these systems dispose off some of the excess heat and thus cool the PV system, marginally enhancing its efficiency. However, since the efficiency of thermoelectrics is still rather low (< 5%), added system complexity has not made this an attractive proposition so far.

Early Research

Historically the first solar cell was constructed by Charles Fritts in the 1880s. In 1931 a German engineer, Dr Bruno Lange developed a photo cell using silver selenide (Ag_2Se) in place of copper oxide. The prototype selenium cells converted less than 1% of incident light into electricity. Following the work of Russell Ohl in the 1940s, Chapin, Fuller and Pearson [9] created the first crystalline silicon solar cell at Bell Telephone Laboratories, which was reported in a very brief paper in 1954. A thin layer of *p*-Si (0.0001 inch = 2.5 μm) was formed over a *n*-type base. The spectral response extended from 0.5 to 1.1 μm and peaked at $\lambda = 0.7$ μm. The output voltage was 0.5 V. An efficiency of 6% was estimated from the cell delivering an equivalent power of 60 W/m^2. The paper suggested a limiting efficiency of 22% for a Si *p-n* junction cell with negligible losses. A theoretical analysis of the cell, termed the Bell Solar battery, was given shortly after by Prince [10] using the *I-V* relation:

$$I = I_s\,[\exp\,(\mathrm{qV/kT}) - 1] - I_L \tag{1.6}$$

where I_s = saturation reverse bias current and I_L = light-generated current. It was shown that the series resistance, R_s, was a major factor in reducing the efficiency.

In the same year, Reynolds et al. invented a solar cell based on a CdS/Cu$_2$S heterojunction at the Wright Patterson Air Force Base [11]. Their first experiments were conducted on 3 mm thick CdS single crystals grown by the vapour transport technique and not on thin films, as often mentioned. In was used as the base electrode, and metals such as Ag, Cu, Au and Pt as the counter electrode. Pronounced rectification was first observed. In direct sunlight an open-circuit voltage of 0.4 V and short-circuit current of 15 mA/ cm^2 were observed, the currents increasing to 300 mA/cm^2 in focused sunlight. Assuming fill factor (FF) = 0.75 and 100 mW/cm^2 illumination, the efficiency can be estimated to be 4%. Response of a smaller magnitude was also observed using pressed pellets of CdS. The spectral response showed a large peak at 500 nm and a broader peak near 680 nm. The first peak corresponds to the band gap of CdS, while the second peak remained unexplained at that time. In the case of Cu diffusing into CdS and forming a heterojunction, the 680 peak can be attributed to the band gap of Cu$_2$S.

These early solar cells cost US$ 286/W$_\mathrm{P}$ and reached efficiencies of 4.5–6%. The 'Vanguard' satellite launched in 1958 provided the first application of these cells to supplement and recharge batteries Telstar and other communication satellites followed. Applications in Space Technology have remained prime drivers for high-efficiency solar cells, where low weight and area are major considerations and cost is not a factor. By 2015, through intensive worldwide research, the module efficiencies exceeded 20% and the maximum efficiency of laboratory devices was 43% [12].

1.3 PRINCIPLE

According to Einstein's revolutionary concept of the photon, which explained the Photoelectric Effect and for which he was awarded the Nobel Prize in 1919, light can be considered to consist of photons, the energy being given by

$$E = h\nu = hc/\lambda \tag{1.7}$$

Since the velocity of light $c = \nu.\lambda$ (1.8)

where ν = frequency, λ = wavelength, and h = Planck's constant = 6.64×10^{-34} J.

Inserting values of the constants c and h, this equation becomes

$$E\ (\mathrm{eV}) = 1.24/\lambda\ (\mu\mathrm{m}) \tag{1.9}$$

As the wavelength of solar radiation varies from 0.3 to 3 µm, the corresponding photon energies are 4.1–0.41 eV, respectively.

Semiconductors such as silicon and germanium have energy band gaps, E_g of 1.14 eV and 0.67 eV, respectively, at 300K between the valence and conduction bands. This is in contrast with metals that have overlapping bands with no band gap and insulators for which the band gap is very high (> 5 eV). Thus, when radiation with energy equal to or higher than the band gap energies is incident on such semiconductors, electrons in the valence band are excited into the conduction band. The electrons act as free carriers in the conduction band, while the vacancy left behind in the valence band 'holes' acts as charge carriers with positive charge. Therefore, the absorbed photon creates an electron–hole pair, and each is free to move in opposite directions in the presence of an electric field.

The conductivity σ of a semiconductor is determined by the free carrier concentration and their mobility given by Equation (1.10):

$$\sigma = ne\mu_n + pe\mu_p \tag{1.10}$$

where n and p are the concentrations of electrons and holes, respectively, in cm^3, and μ_n and μ_p are the electron and hole mobility in cm^2/V.sec.

Mobility μ is defined as the carrier velocity/electric field:

$$\mu = \text{velocity/electric field} = \mathrm{v}/E = (\text{cm/sec/volt/cm}) = \mathrm{cm}^2/\text{V.sec.} \tag{1.11}$$

Carrier motion due to an electric field is called drift and is determined by carrier mobilities μ_n and μ_p for electrons and holes, respectively.

Carriers can also move due to diffusion in a concentration gradient, determined by the diffusion coefficients D_n and D_p. These are directly proportional to the carrier mobilities μ_p and μ_n through the Einstein relations:

$$D_n = (kT/q)\,\mu_n \text{ and } D_p = (kT/q)\mu_p \tag{1.12}$$

Diffusion current densities for electrons and holes in one dimension are given by:

$$J_n = +\,qD_n\,(dn/dx) \tag{1.13a}$$

$$J_p = -\,qD_\mathrm{p}\,(dp/dx) \tag{1.13b}$$

In the absence of radiation n and p are relatively small, determined by the band gap and impurity doping levels, and hence the dark conductivity σ_D is low. When light is incident on the semiconductor, excess carriers, Δn and Δp are created and hence the conductivity increases to:

$$\sigma_L = (n + \Delta n\ )\,e\mu_n + (p + \Delta p)\,e\mu_p \tag{1.14}$$

This is the principle of photoconductivity for which it is desirable that $\Delta n >> n$ and $\Delta p >> p$, such that $\sigma_L >> \sigma_D$.

The concentration of excess carriers is obviously determined by the photon intensity and also the lifetime of the excess carriers in their respective bands. Thus,

$$\Delta n = f.\ \tau_n \text{ and } \Delta p = f.\ \tau_p \tag{1.15}$$

where f = number of photons absorbed/cm^2.sec, and τ_n and τ_p are the respective electron and hole life times. This brings out the importance of having large electron and hole life times for good photoconductivity and also for the PV effect as shown below. A semiconductor photoconductor relies on an applied electric field to separate the excess charge carriers to detect incoming radiation.

A solar cell, on the other hand, must convert solar radiation into electric power without an applied electric field. It, therefore, consists of a semiconductor *p-n* junction with band gap E_g to provide a built-in electric field that separates the charge carriers. When solar radiation is incident, radiation with $h\nu$ greater than E_g is absorbed, giving rise to electron–hole pairs, while the semiconductor is transparent to radiation with energy $h\nu < E_g$. Hence, some of the photon flux is absorbed and the cell current is determined by the band gap E_g. A voltage difference arises between *p* and *n* layers which is termed the PV effect. The steps involved in electric power generation by a solar cell are:

(a) Absorption of solar radiation with creation of electron–hole pairs
(b) Separation of the pairs due to built-in electric field
(c) Collection of carriers by respective electrodes and
(d) Passage of current through an external load.

It is to be emphasized that the carrier transport is through the motion of the minority carriers through the *p-n* junction (Figure 1.7), that is, holes for the *n* region and electrons from the *p* region. Carriers generated at the junction are subject to the built-in electric field and their motion is by drift. However, a large fraction of the carriers are created away from the junction and diffuse through the junction. This is determined by the diffusion length L_n and L_p of electrons and holes, respectively, which are given by:

$$L_n = (D_n \tau_n)^{1/2} \text{ and } L_p = (D_p \tau_p)^{1/2} \tag{1.16}$$

For large diffusion lengths, which are necessary for large photocurrents in the cells, the minority carrier lifetimes τ_n and τ_p should be large. This requires high-quality defect-free materials as discussed in Section 2.8. Figure 1.7(a) shows the band diagram of a *p-n* junction in the dark, while Figure 1.7(b) shows the effect of illumination that results in forward biasing the diode. Thus, the highest open-circuit voltage V_{OC} that can be obtained in principle is the barrier height of the *p-n* junction, though in practice it is much less due to reasons discussed below.

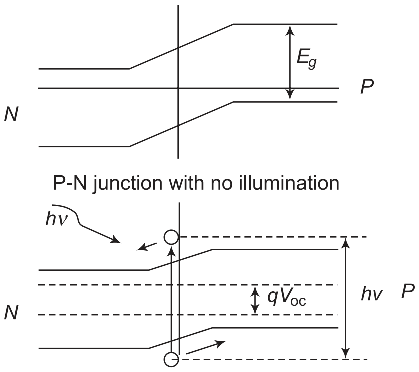

Figure 1.7 Schematic of a p-n junction.

The usual configuration of a PV cell consists of a *p*-type substrate into which *n*-type impurities are diffused to form a *n-p* junction. This needs some explanation. The front layer is intentionally kept shallow, such that the junction is near the surface where the solar intensity is high. Thus, as discussed in Chapter 2, when dealing with the spectral response the major part of the light-induced current is generated in the *p*-type layer at the back. The diffusion length of electrons being larger (40 cm^2/sec) than that of holes (10 cm^2/sec), it is advantageous to have a *p*-type layer at the back where electrons are the minority carriers. In the case of space-quality solar cells, it is found that thin cells suffer less radiation damage. Therefore, Li-diffused Si *n*/*p* cells were developed in the 1960s that showed superior resistance to damage. This is discussed in Section 4.8.2.

It can be seen intuitively that the highest voltage output is dependent on the band gap E_g of the semiconductor. This criterion prefers a high band gap material. On the other hand, such a high band gap reduces the number of photons absorbed and hence decreases the output current. Since output power = output voltage × current, there is an optimum band gap for maximum solar energy conversion. This is shown in Figure 1.8. The actual power output depends on the properties of the semiconductor and cell structure as discussed in Section 1.6. However, the diagram shows a broad road map indicating that maximum efficiencies may be obtained with band gaps E_g ranging from 1.3–1.6 eV. The lower curve is for AM 1 condition with no concentration of solar radiation $C = 1$, while the upper curve is for concentrator cells with $C = 1000$. It is observed that the maximum efficiencies increase from $\eta = 28\%$ to $\eta = 36\%$ with concentration. Further, the maximum efficiencies shift slightly to the lower band gaps. The assumptions under which these deductions are made are discussed quantitatively in Section 4.5.5. Concentrator cells are discussed in Chapter 5.

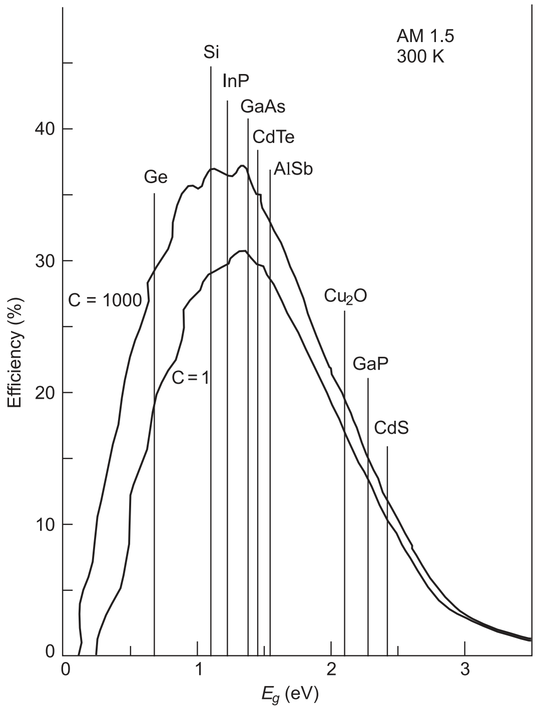

Figure 1.8 Maximum theoretical efficiency vs E_g band gap of semiconductor for concentration $C = 1$ and $C = 1000$.