Chapter 9
Solar Cells

In this chapter we study the basics of solar cells and their state of the art performance. It is important to realize that they are two distinctive applications for solar cells. Solar cells with high performance and high conversion efficiency characteristics are needed for space applications and satellites. These are typically single crystalline multi-junction devices that require high production costs. On the other hand, solar cells that can be mass produced in large areas and at extremely low cost are often characterized by low conversion efficiencies. These types of solar cells are implemented using thin film amorphous, poly-crystalline Si or even organic materials. Their production does not require high temperature processing, therefore, these devices can be built on flexible plastics. This enables large area and low cost production of thin film and organic solar cells.

Basic Principles

A solar cell is a PN junction that can be modeled according to Fig. 9.1. The model consists of a constant current source I_{ph}, the load current I and the reverse saturation current of the diode I_S. The current voltage characteristics of such a diode under illumination are also shown in Fig. 9.1. As can be seen, under illumination the device IV characteristics push to the fourth quarter, therefore the diode is capable of generating power with illumination. We shall look at the fourth quadrant more closely. Fig. 9.2. shows the I-V characteristics of an illuminated solar cell. The open circuit voltage V_{oc} is the

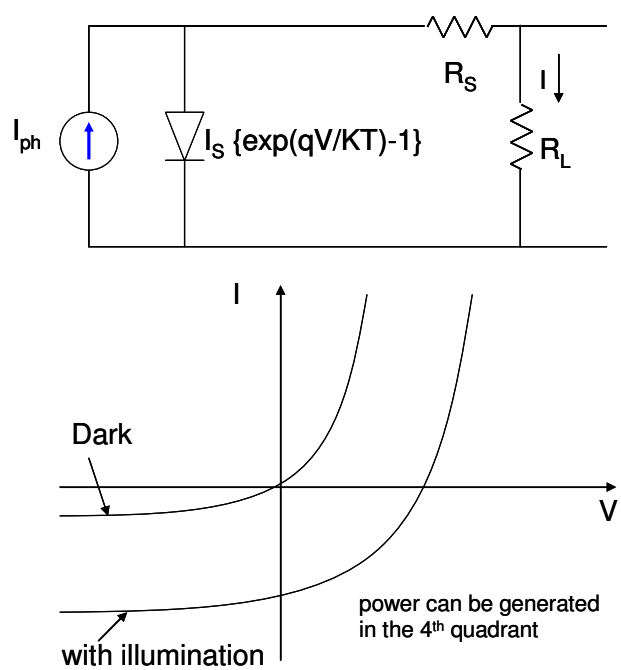

Fig. 9.1: (top) Equivalent model of a solar cell. (bottom) I-V characteristics of the diode in dark and with illumination.

maximum voltage at the load ($R_L = \infty$) and the short circuit current I_{SC} is the maximum current through the load under short circuit condition ($R_L = 0$). In order to achieve maximum output power from a solar cell, a load R_L is needed that would draw a current of I_m with a voltage of V_m where I_mV_m product (area of the gray rectangle in Fig. 9.2) is maximized.

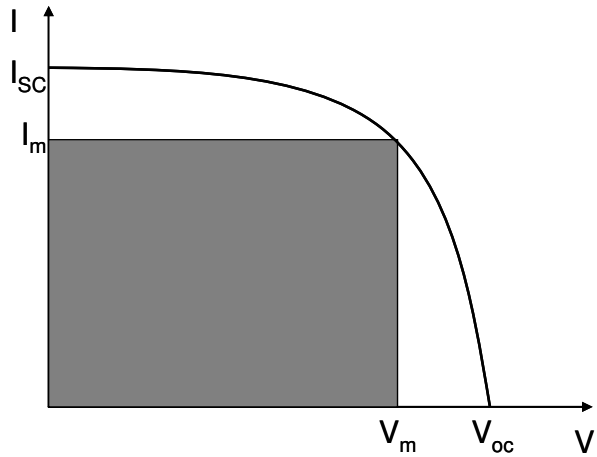

Fig. 9.2: I-V characteristics of an illuminated solar cell in the fourth quadrant.

When the junction is illuminated with photons with $h\nu > E_g$, electron hole pairs are generated with a generation rate of G (cm^{-3}/Sec). The number of minority holes generated within the diffusion length (L_h) on the n-side is AL_hG. Similarly, the number of minority electrons generated within the diffusion length (L_e) on the p-side is AL_eG. The total photo-generated current across the junction is

$$I_{ph} = qAG(L_h + L_e) \tag{9.1}$$

The photo-current is directed from n-side to the p-side and is opposed to the main diode current. Therefore, for the illuminated diode, the total current is

$$I = qA\left(\frac{L_h p_{n0}}{\tau_h} + \frac{L_e n_{p0}}{\tau_e}\right)\left(e^{\frac{qV}{kT}} - 1\right) - qAG(L_h + L_e) \tag{9.2}$$

Now we can find the short circuit current by setting V=0

$$I_{SC} = -I_{ph} = -qAG(L_h + L_e) \tag{9.3}$$

The open circuit voltage can be calculated by setting the total diode current I=0

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{L_h + L_e}{\frac{L_h p_{n0}}{\tau_h} + \frac{L_e n_{p0}}{\tau_e}}G + 1\right) = \frac{kT}{q}\ln\left(\frac{I_{ph}}{I_S} + 1\right) \simeq \frac{kT}{q}\ln\left(\frac{I_{ph}}{I_S}\right) \tag{9.4}$$

Hence, for a fixed I_{ph}, V_{oc} increases logarithmically with decreasing saturation current I_S. Under illumination the solar cell diode acts as a power source with

$$P = IV = I_S V\left(e^{\frac{qV}{kT}} - 1\right) - I_{ph}V \tag{9.5}$$

By taking derivative of power with respect to voltage, we can find optimum current I_m and optimum voltage V_m to obtain maximum power. The differentiation yields

$$V_m = V_{oc} - \frac{kT}{q}\ln\left(1 + \frac{qV_m}{kT}\right) \tag{9.6}$$

This equation needs to be solved iteratively to find V_m. For I_m we can write

$$I_m = I_S \frac{qV_m}{kT} e^{\frac{qV_m}{kT}} \simeq I_{ph}\left(1 - \frac{kT}{qV_m}\right) \tag{9.7}$$

The fill factor is an important figure of merit in solar cells and is defined as

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} = \frac{I_{ph}\left(V_{oc} - \frac{kT}{q}\ln\left(1 + \frac{qV_m}{kT}\right) - \frac{kT}{q}\right)}{I_{ph}V_{oc}} = 1 - \frac{kT/q}{V_{oc}}\left[1 + \ln\left(1 + \frac{qV_m}{kT}\right)\right] \tag{9.8}$$

High fill factor is an indication of ideal performance i.e. small series resistance of the cell. The conversion efficiency η_C of a solar cell is another figure of merit that needs to be considered and is defined as

$$\eta_C = \frac{V_m I_m}{P_{inc}} = \frac{V_m^2 I_S \frac{q}{kT} e^{\frac{qV_m}{kT}}}{P_{inc}} \tag{9.9}$$

While I_{SC} increases linearly with P_{inc}, the increase of V_{oc} with respect to P_{inc} is rather logarithmic as shown in Fig. 9.3. We can write the conversion efficiency η_C as a function the fill factor FF through the following equation.

$$\eta_C = \frac{V_m I_m}{P_{inc}} = \frac{FF \cdot I_{SC} V_{oc}}{P_{inc}} \tag{9.10}$$

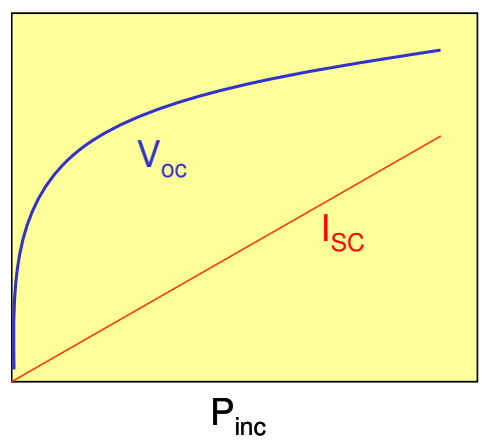

Fig. 9.3: Variation of short circuit current and open circuit voltage of a solar cell with incident photon power.

Silicon Solar Cells

Silicon is an ideal material for use in solar cells. It is non-toxic and has a well-established technological base. In a standard Si solar cell for use in space top contact fingers

composed of Ti/Pd/Ag is deposited on a thin n-type region. The n-type region is formed by shallow diffusion (~0.25µm junction depth) of Phosphorus into a p-type wafer. The back side of the wafer has P+ contact region with rear metal contact composed of Ti/Pd/Ag. To reduce the reflection from the top surface of the cell a single layer of antireflection (SLAR) coating of TiO_2 or Ta_2O_5 is evaporated. For improved performance a double layer (DLAR) coating of TiO_2 followed by Al_2O_3 is used. A conversion efficiency of ~20% is achieved under zero Air Mass (AM0) which is the condition in space.

Instead of crystalline Si, thin film a-Si which is often hydrogenated for improved lifetime is used to reduce the price for large area solar cells used on earth surface. The conversion efficiency is much lower (~5%) but the low deposition temperature of a-Si (~200°C) allows the use of low-cost plastic materials. A-Si solar cells are formed from PIN diode structure and are sometimes implemented in a tandem (two stacked PIN structure) to increase the conversion efficiency to ~8%.

GaAs Solar Cells

GaAs has better characteristics than Si to form solar cells. Because of the larger bandgap, it has smaller reverse saturation current, which results in an increase of V_{oc} under constant photon current. Moreover, according to Fig. 9.4, the absorption coefficient of GaAs in the visible spectra is sharper and higher as it is a direct bandgap material, resulting in higher conversion efficiency. Additionally, the bandgap of GaAs is more suited to solar radiation spectrum than that of Si. To reduce the cost, GaAs space cells can be grown on top of inactive Ge substrates. Single junction GaAs solar cells have approached efficiencies close to 30%.

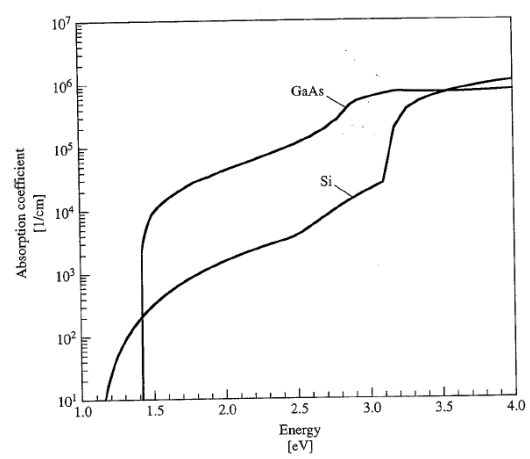

Fig. 9.4: Absorption coefficient of Si and GaAs.

To further increase the efficiency, multiple junction solar cells and textured cells with pyramid surface are pursued with maximum efficiency of ~40% reported in the literature. Fig. 9.5 shows the evolution of solar cells and their efficiency over the years. Note that increased global funding due to recent high cost of energy will soon push the efficiencies of both crystalline and thin film solar cells to the point that this technology becomes economically viable.

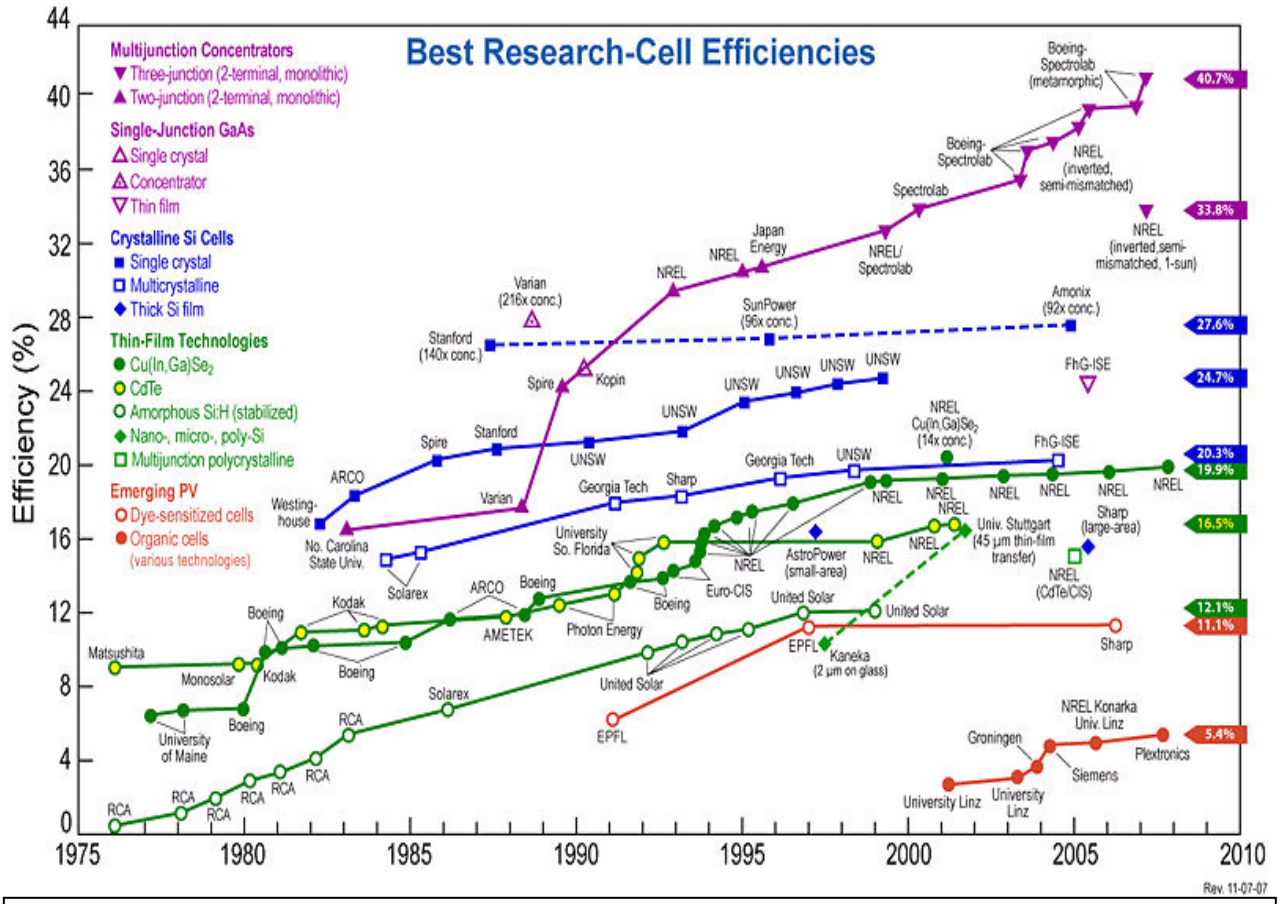

Fig. 9.5: Evolution of various type of Solar cells

The final note in this chapter is on the solar spectral irradiance. Typical spectral irradiance is shown in Fig. 9.6. The radiation at the top of the atmosphere (shown in yellow) is denoted as air mass zero (AM0) and is used for the calculation of conversion efficiencies of space solar cells. At the sea level and under direct vertical solar irradiation an irradiation of air mass 1 (AM1) is achieved as shown by the red curve. For a typical solar cells higher losses of solar energy compared to AM1 are expected as the sun ray enters the atmosphere at certain angle and

therefore travels more distance in the atmosphere. A path of 1.5 times of direct irradiation to the sea level (AM1.5) is often used to measure the conversion efficiency of typical ground-base solar cells. Note that how ozone (O3) reduces harmful radiation of ultra violet spectrum at low spectral wavelength (higher energy).

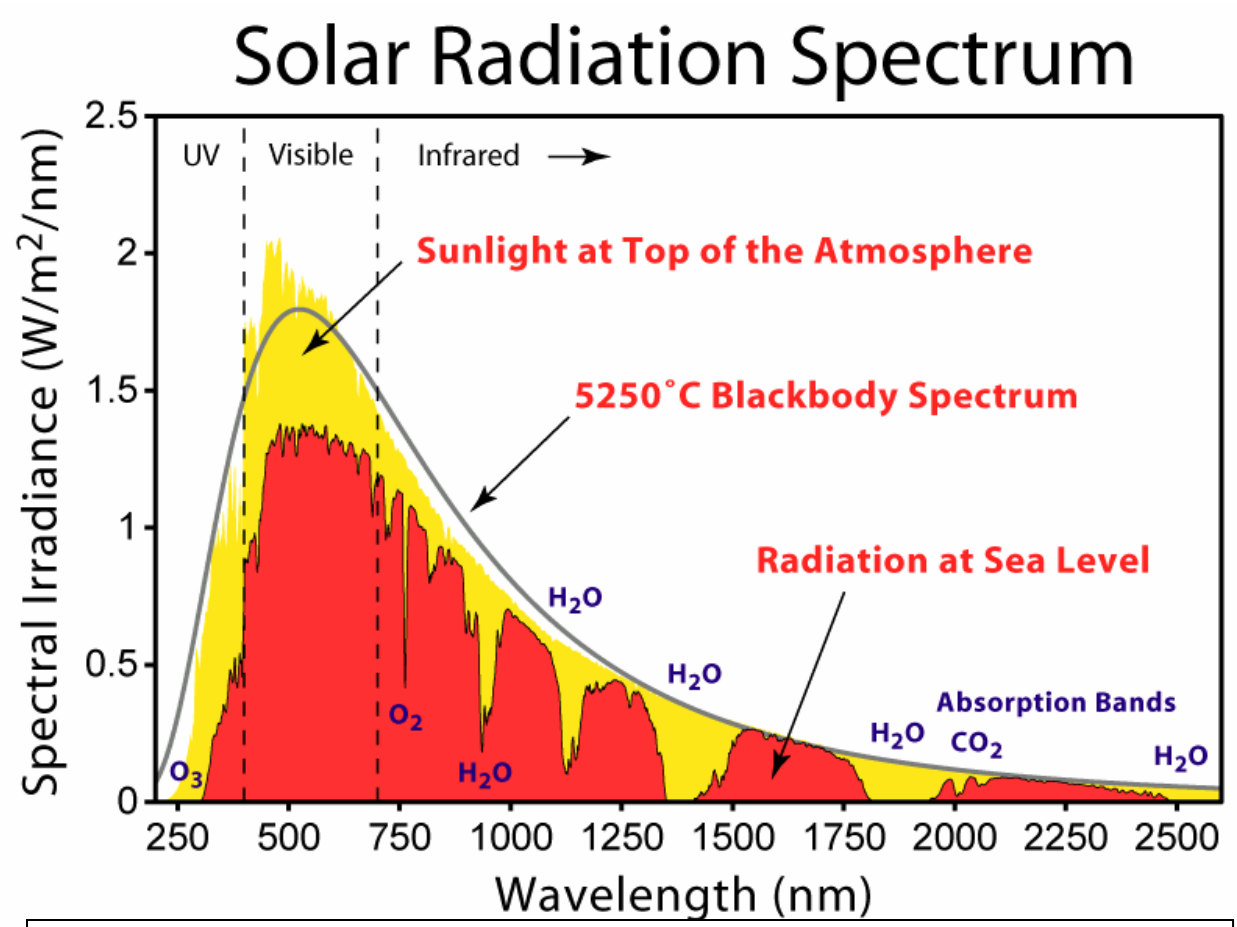

Fig. 9.6: Solar spectral irradiation