Solar Cell I-V Characteristics

Theory

A solar cell is an electronic device which directly converts light energy to electrical energy. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversions use semiconductor materials in the form of a p-n junction as shown in Fig. 1.

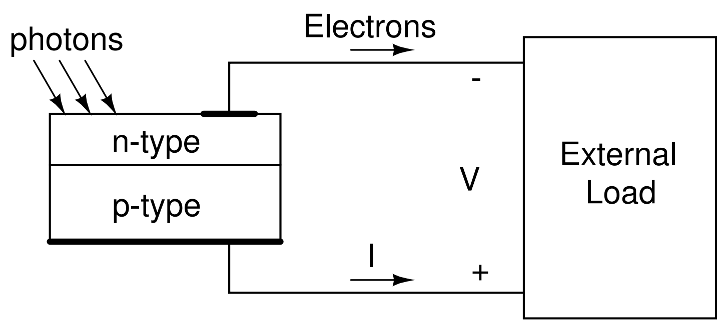

Figure 1: Solar Cell

A basic cell generates typically a DC photo-voltage of 0.5 V to 1.0 V and, under short circuit, a photo current of some tens of mA/cm^2. Since the voltage is too small for most applications, to produce a useful voltage, the cells are connected in series into modules.

The generation of current in a solar cell involves two key processes. The first process is the absorption of incident photons to create electron-hole pairs. Electron-hole pairs will be generated in the solar cell provided that the incident photon has energy greater than that of the band gap. However, electrons (in the p-type material), and holes (in the n-type material) are meta-stable and will only exist, on average, for a length of time equal to the minority carrier lifetime before they recombine. If the carriers recombine, then the light-generated electron-hole pair is lost and no current or power can be generated.

The second process is the collection of these carriers by the p-n junction. Thus preventing this recombination by using a p-n junction to spatially separate the electron and the hole. The carriers are separated by the action of the electric field existing at the p-n junction. If the light-generated minority carrier reaches the p-n junction, it is swept across the junction by the electric field at the junction, where it is now a majority carrier. If the p-side is connected to the n-side externally (i.e., if the solar cell is short-circuited), the light-generated carriers flow through the external circuit as shown in Fig. 2.

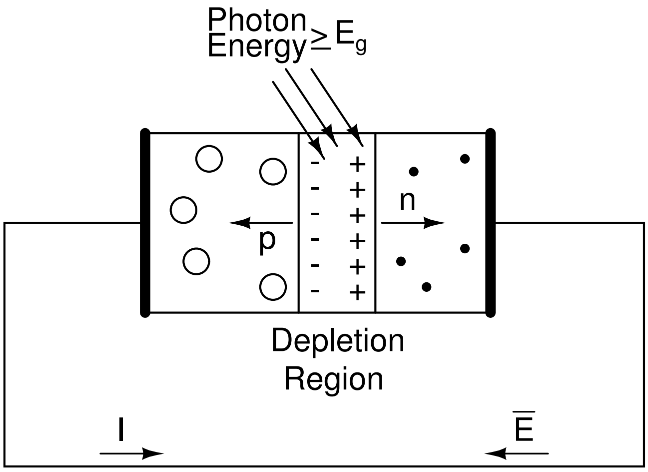

Figure 2: Principle of Working of Solar Cell

The solar cell characteristics is studied under 3 separate parts: I-V Characteristics, Temperature Dependence of Solar Cell and Effect of R_s and R_{sh} as given below.

1 I-V Characteristics

When a solar cell is subjected to no illumination, it behaves like a large p-n junction diode; thus the I-V characteristics under dark conditions is similar to that of a diode. This is called as the dark I-V charcteristics of a solar cell. The same is shown in Fig. 3. When illuminated, the light has the effect of shifting the I-V curve down into the fourth quadrant as shown in Fig. 4. The light generated current adds to the normal “dark” currents in the diode so that the diode law becomes:

$$I = I_0[e^{\frac{qV}{\eta kT}} - 1] - I_L \quad (1)$$

Where,
η = Ideality factor,
I_0 = Saturation current,
I = Total Diode Current, and
I_L = Light Generated Current.

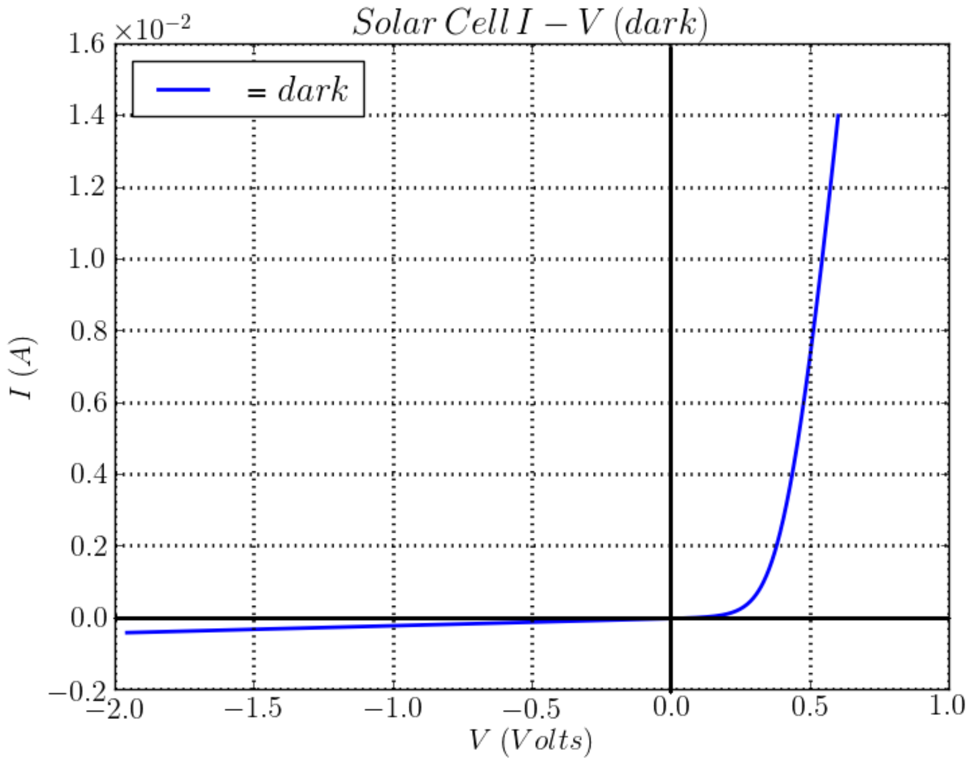

Figure 3: Solar I-V under no illumination

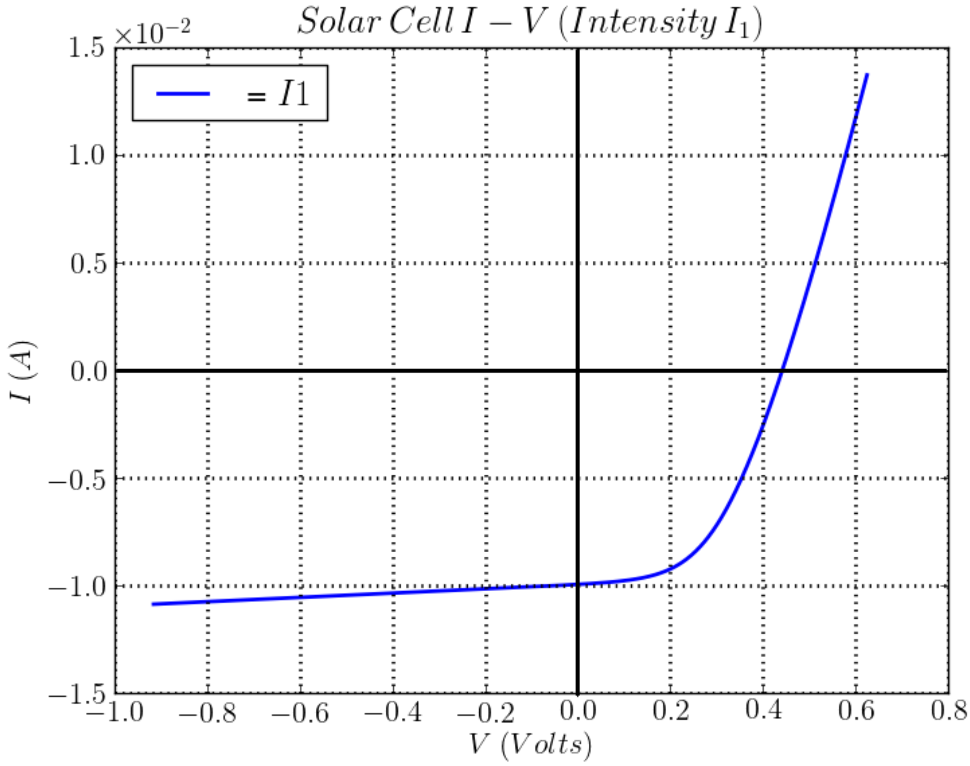

Figure 4: Solar I-V under illumination

When light is incident on the solar cell as shown in the Fig.4, the photo generated current shifts the I-V curve downwards depending on the intensity of the photo-generated current (I_L) as I_L depends on the intensity of the incident light. Greater the intensity, greater will be the amount of shift.

The I-V characteristics corresponding to dark and two different light intensities are shown in the Fig. 5.

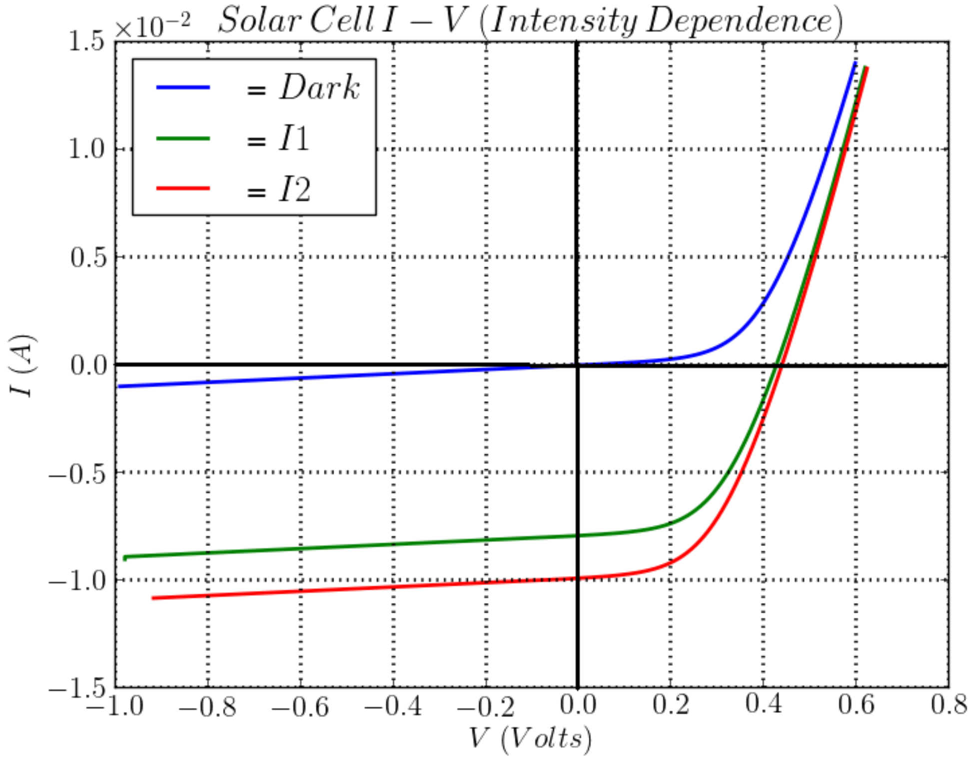

Figure 5: Solar I-V under different illumination levels($I_2 > I_1$)

Short-Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually it is written as I_{SC}. The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell, at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell. It is given by the equation 2.

$$I_{SC} = I_0[e^{\frac{qV}{\eta kT}} - 1] - I_L \tag{2}$$

Open Circuit Voltage

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. An equation for V_{OC} is found by setting the net current equal to zero in the solar cell given by equation 3.

$$V_{OC} = \frac{\eta k T}{q} ln\left(\frac{I_L}{I_0} + 1\right) \tag{3}$$

Fill Factor

The Fig. 6 shows the I-V and P-V characteristics of a solar cell under illuminated condition (the fourth quadrant characteristic part). The I-V curve falls in the fourth quadrant and therefore the power is negative and therefore power is supplied to the load. For higher volatges the I-V curve enters into the first quadrant and therefore the power is positive and therefore power is dissipated. Solar cell will act as as power source in the fourth quadrant.

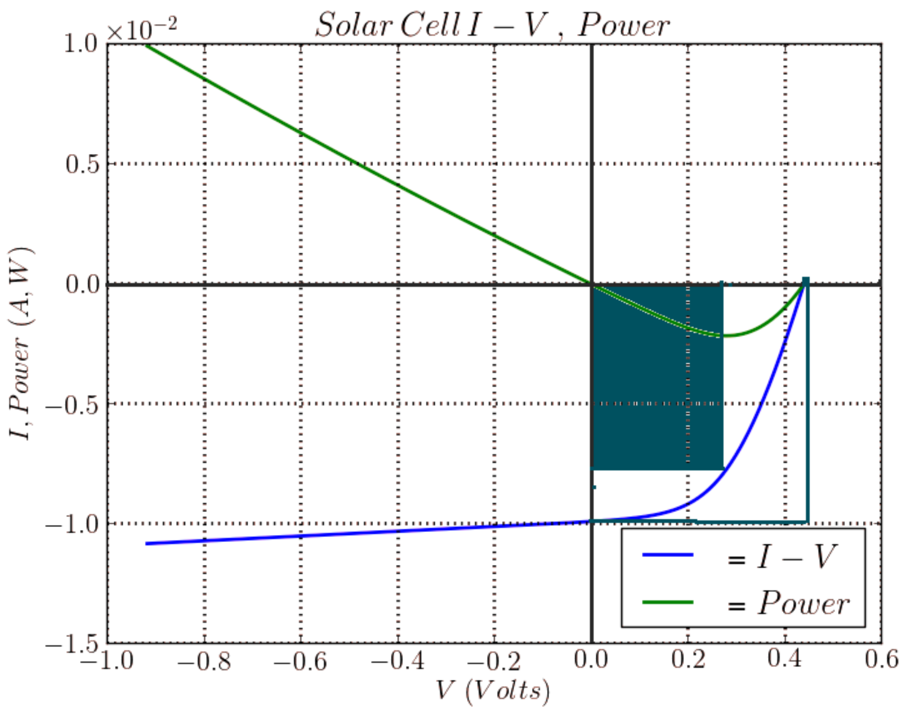

Figure 6: I-V and power characteristic of the solar cell

The shaded area in the Fig. 6 gives the squareness of the solar cell and is also the largest rectangle that will fit in the I-V curve. Fill factor indicates how the I-V curve “fills” the rectangle formed by V_{OC} and I_{SC}, and is the ratio of two areas defined by the I-V curve.The fill factor (FF) of a solar cell is an important performance indicator. The short-circuit current and the open-circuit voltage is the maximum current and voltage respectively from a solar cell. The product of V_{MP} and I_{MP} is the maximum obtainable power from a given cell.

Equivalent Circuit-Two Diode Model of Solar Cell

The ideality factor, η of the solar cell is dependent on the voltage across the diode. For lower voltages, recombination at the junction dominates and the ideality factor will be close to 2. For higher voltages, ideality factor will be around 1 due to bulk recombination. Therefore a two diode model can be used to define a solar cell as shown in Fig. 7. The diode equation will be modified as given below.

$$I = I_{01}[e^{\frac{qV}{kT}} - 1] + I_{02}[e^{\frac{qV}{2kT}} - 1] - \frac{V + IR_s}{R_{Sh}} - I_L \tag{4}$$

I_{01} and I_{02} are the reverse saturation currents of the diodes D_1 and D_2. Notice that the current generated by the photons in the incident light I_L is represented by a current source. The two resistors R_S and R_{Sh} account for the losses in a solar cell. R_S is a series resistance primarily due to the ohmic loss in the surface of the solar cell. The shunt resistance, R_{Sh}, is mainly due to manufacturing defects. In reality, R_{Sh} is much larger than a few hundred ohms and can in most cases be neglected. The series resistance, however, can drastically reduce output power.

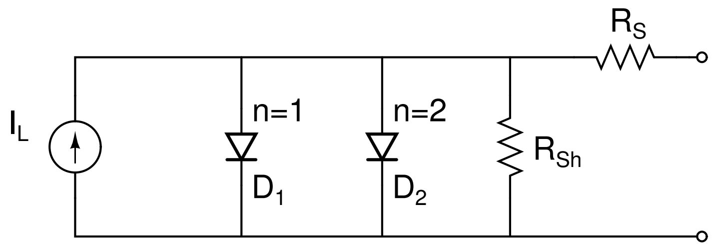

Figure 7: Two Diode Equivalent model of a Solar Cell

References

1. J C C Fan, “Theoretical Temp Dependence of Solar Cells”, Solar Cells 17, 309(1986).