# 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 photo voltaic energy conversion, but in practice nearly all photo voltaic energy conversions use semiconductor materials in the form of a p-n junction as shown in Fig. 1.

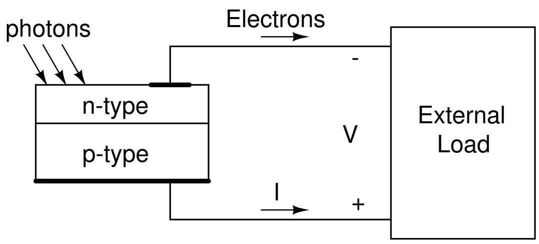


Figure 1: Solar Cell

A basic cell generates typically a DC photo-voltage of 0.5 - 0.6 V and, under short circuit, a photo current of some tens of mA/cm$^2$. Depending on the application, the cells can be connected in series or parallel to get the desired voltage or current.

The generation of current in a solar cell involves two key processes:

1. The absorption of incident photons to create electron-hole pairs.

2. The second process relates to carrier collection.

Electron-hole pairs are generated in the solar cell provided that the incident photon has energy greater than that of the band gap. However, excess electrons (in the p-type material), and excess 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. The carriers that recombine in the semiconductor do not contribute to current in the external circuit.

The photocurrent can be written as the sum of two components-

1. Carriers generated by light in the depletion region of the pn junction are separated by the built-in field to the respective electrodes and give rise to a photocurrent in the external circuit.

2. Excess carriers generated by light in the diffusion length from the edge of the depletion layer also contribute to the photocurrent.

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.

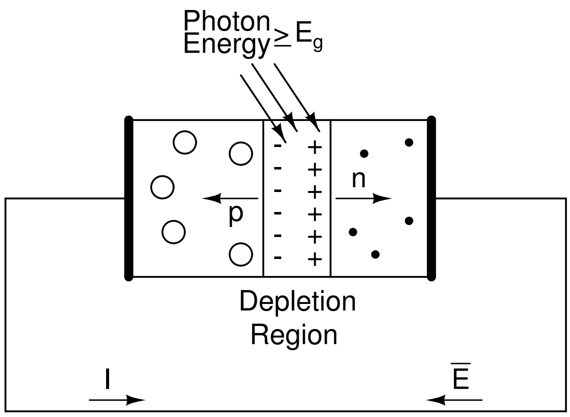


Figure 2: Principle of Working of Solar Cell

In this experiment, we will study the solar cell characteristics in two separate parts: I-V Characteristics, 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 area 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:

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

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

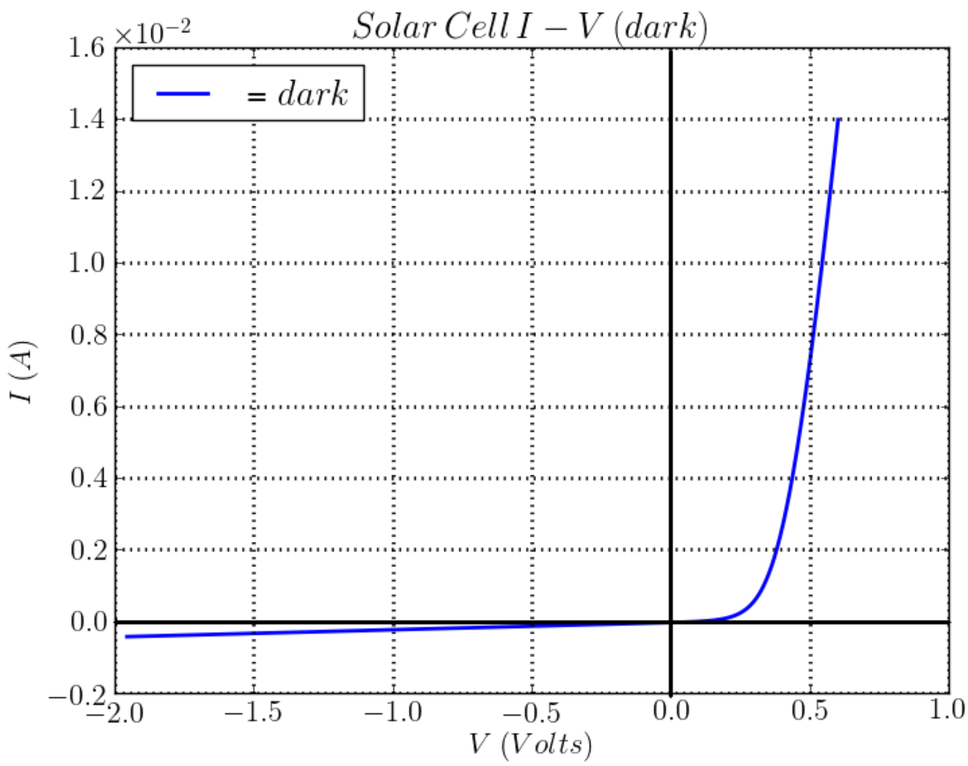


Figure 3: Solar I-V under no illumination

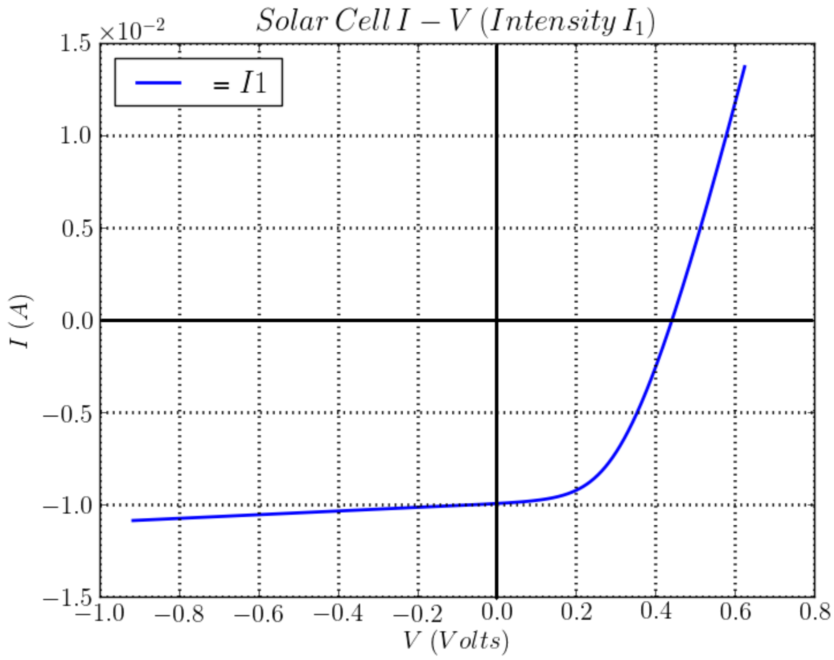


Figure 4: Solar I-V under illumination

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.

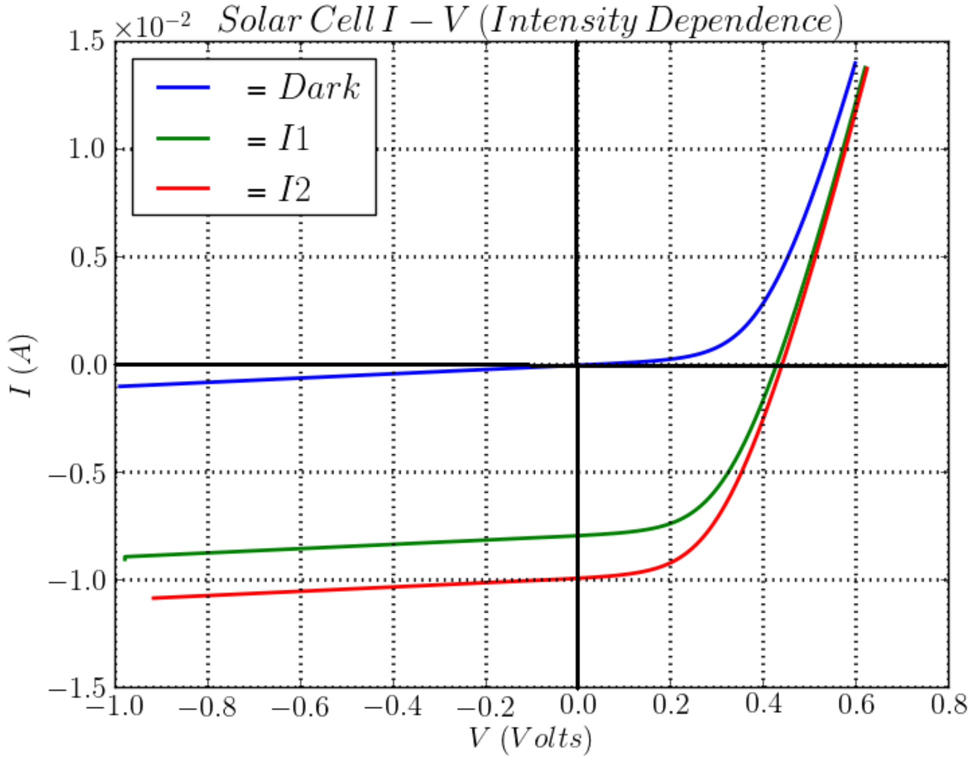


Figure 5: Solar I-V under different illumination levels($I_2 \ > I_1$)

## 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, the short-circuit current and the light-generated current are identical.

## 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 2.

$$V_{OC} = \frac{\eta kT}{q} ln\left(\frac{I_L}{I_0} + 1\right) \tag{2}$$

# 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 voltages 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.

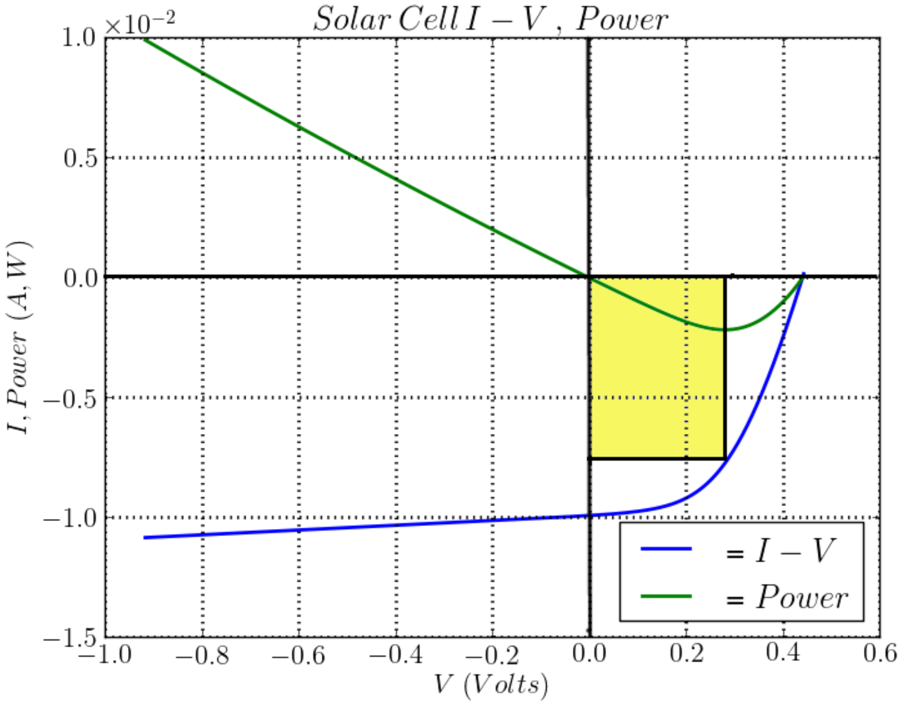


Figure 6: I-V and power characteristic of the solar cell

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, $\eta$ 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.

$$I = I_{01}[e^{\frac{qV}{kT}} - 1] + I_{02}[e^{\frac{qV}{2kT}} - 1] - \frac{V + IR_s}{R_{Sh}} - I_L \tag{3}$$

$I_{01}$ 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.

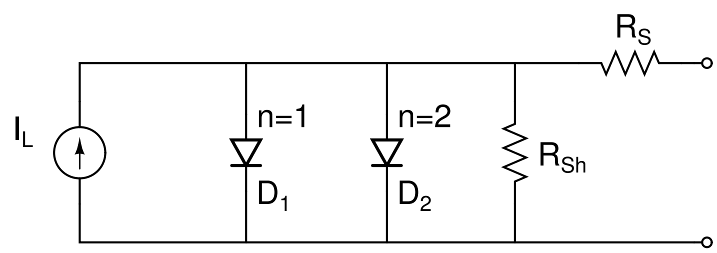


Figure 7: Two Diode Equivalent model of a Solar Cell

## 2 Effect of R$_s$ and R$_{sh}$

**Series Resistance:** Series resistance in a solar cell has two causes: 1) the contact resistance between the metal contact and the silicon; and 2) the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current. Series resistance does not affect the solar cell at open-circuit voltage since the overall current flow through the solar cell, and therefore through the series resistance is zero. However, near the open-circuit voltage, the IV curve is strongly effected by the series resistance and is shown in the figure below.

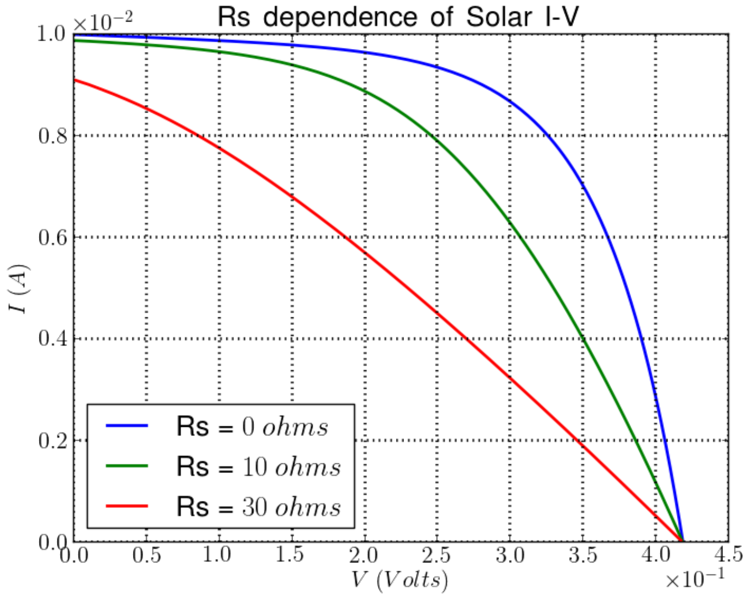


Figure 8: Effect of series resistance on solar I-V characteristics under Illumination

**Shunt Resistance:** Typically due to manufacturing defects. Low shunt resistance results in a parallel path for the light generated current and reduces the voltage across the cell. The effect of shunt resistance is particularly severe at low light levels and lower voltages.

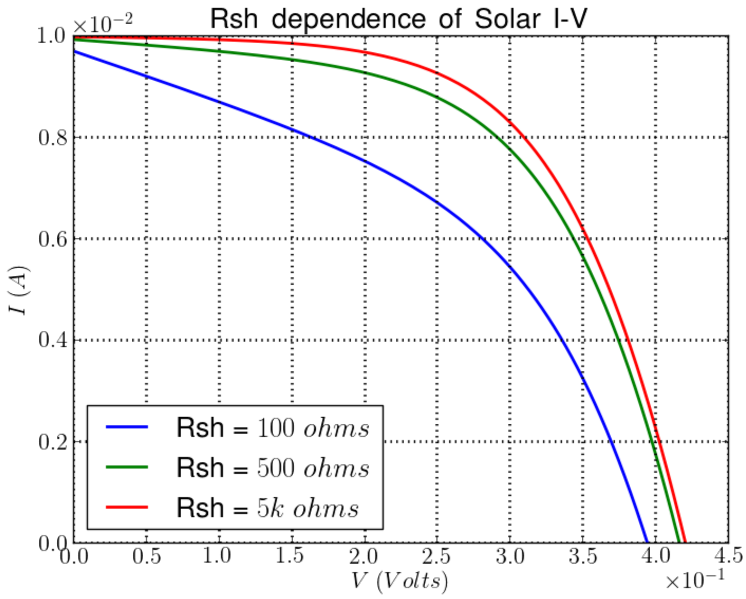


Figure 9: Effect of shunt resistance on solar I-V characteristics under Illumination

# References


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