Impact of Temperature on Solar Cell Performance

Motivation for the experiment

In the previous experiment, we found that a solar cell (p-n junction) under illumination generates a current. You have also measured the current- voltage characteristics and found that it is in the fourth quadrant. This shows that the solar cell can be used as a power source, when the current is fed into a load.

In real applications, sunlight is used as the source of illumination and energy is harvested from the sun by the solar cell (and hence the name) to generate power. In the field, the temperature of the solar cell itself will increase above the ambient temperature. The rise in temperature depends on many factors, such as heating of panels, wind flow and many other factors. As a rule of thumb, the typical increase in temperature of the solar cell above the ambient temperature is about 20-25^{0}C. For instance in Mumbai, the operating temperature of the cell can be as high as 50^{0}C and in Rajasthan as high as 75^{0}C. We need to understand how the cell behaves at high temperature to design a power plant based on solar cells.

In this experiment, we will study the influence of the temperature on the solar cell characteristics by heating a solar cell while it's in operation and study how the performance changes. The dark characteristics are also very important in the functioning of the solar cell. You will study how the temperature influences the dark characteristics, open circuit voltage, the short circuit current and the fill factor. This understanding is crucial to correctly design a solar cell system for power generation.

Dark characteristics

The solar cell is essentially a "special" semiconductor diode with large area. As you have seen in previous labs, the ideal semiconductor diode equation is given by:

$$I = I_0(e^{\frac{qV_D}{\eta kT}} - 1) \tag{1}$$

where I_0 is the saturation current, and η is the ideality factor. The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation. The reason the equation deviates from normal is because of recombination processes that occur inside the device, thereby reducing the current. Thus, a real diode always has ideality factor > 1.

However in this respect, the solar cell is different from a "regular" p-n diode, because its **ideality factor depends on the applied voltage, unlike the regular p-n diode**. The reason is that different recombination mechanisms dominate at different voltages. At high voltage, the recombination is dominated by surfaces and bulk regions, and ideality factor is close to 1. At low voltage, the recombinations in the junction dominate, and ideality factor is close to 2. Both these effects are captured by placing 2 diodes of ideality factors 1 and 2 respectively in parallel in the equivalent circuit (2 diode model) shown in Fig.1.

The current-voltage relationship of a solar cell (in dark) is given by Eq. 2:

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

Fig.1 shows a generalized equivalent circuit of the solar cell in the dark. It is important to remember that one has access only to terminals A and B of the solar cell. In the above expression V_D is the voltage across the equivalent diodes in the model, and V is the applied voltage across terminals A and B of the solar cell. **Note that V_D is not equal to V**. At large currents (or large values of R_s) V can be very different from V_D, the difference being the IR_s drop across the series resistor. R_s and R_{Sh} arise due to parasitic losses and manufacturing defects.

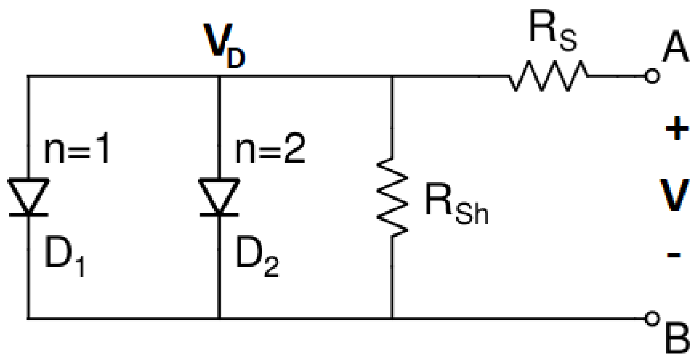

Figure 1: Equivalent circuit of solar cell under dark conditions.

Lighted Characteristics

Under illumination there is a constant generation of excess minority carriers that gives rise to a current I_L that flows opposite to diffusion current. The solar cell thus acts as a current generator. The model is modified by adding this current source to the diodes in parallel as shown in Fig.2.

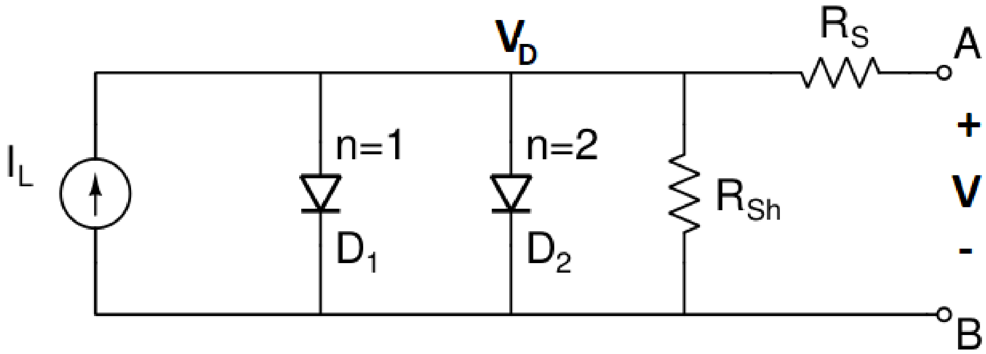

Figure 2: Equivalent circuit of a solar cell under illumination.

Under illumination, the diode equation becomes

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

When the illumination is increased, more photons are absorbed and the magnitude of I_L increases. Due to the difference in sign, this manifests as a down-shift in the I-V curve i.e. the shape of the lighted I-V curve is essentially the same as the dark I-V displaced by I_L. The fill factor, which is the "squareness" of the lighted I-V characteristic depends on the shape of the dark I-V curve. The short circuit current (I_{SC}) is the current in the circuit by shorting leads A and B. The open circuit voltage V_{OC}) is the voltage between A and B at zero current.

Temperature Dependence

It turns out that both I_{01} and I_{02} are temperature dependent and their temperature dependence comes through n_i (see optional reading material at the end of this document), which varies exponentially with temperature. This causes both the dark as well as lighted characteristics to depend on temperature.

In this experiment, we will measure dark and lighted characteristics and investigate how the parameters I$_{SC}$, V$_{OC}$, fill factor and cut-in voltage vary with temperature. Fig.3 shows I-V characteristics of a solar cell at different temperatures under dark conditions. It is very clear from the characteristics that the cut-in voltage decreases as temperature increases.

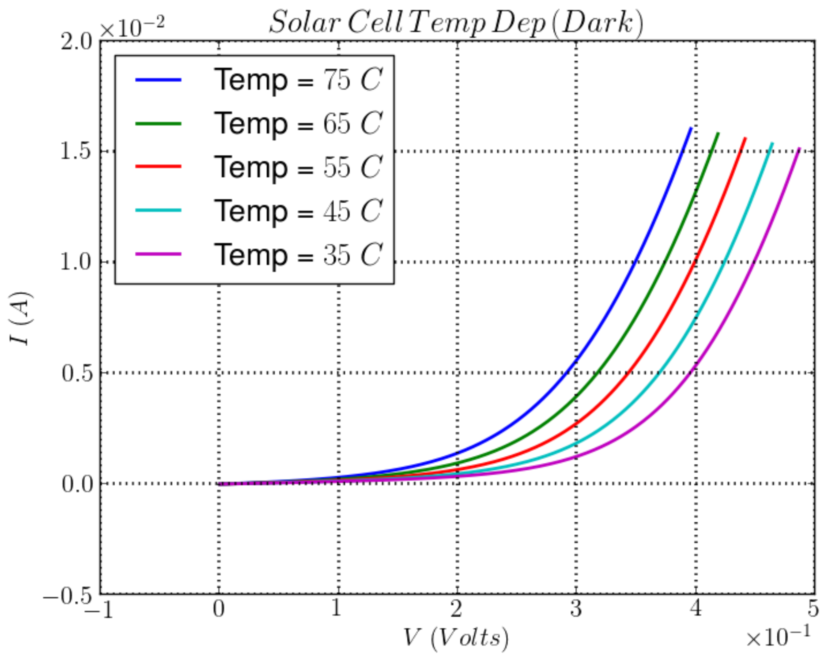

Figure 3: Temperature dependent I-V characteristics under dark conditions. (1st quadrant of I-V curve)

Fig.4 shows I-V characteristics of solar cell at different temperatures under illumination of constant intensity. The data shown is for 4^{th} quadrant in the I-V curve, and only the magnitude of I is used in this figure.

It is found that ideally I_{SC} increases marginally with increase of temperature (not very obvious from this figure). The expected fractional increase in I_{SC} with temperature [1] is given as:

$$\left[\frac{1}{I_{SC}}\right]\left[\frac{\Delta I_{SC}}{\Delta T}\right] \sim 0.0003/K \tag{4}$$

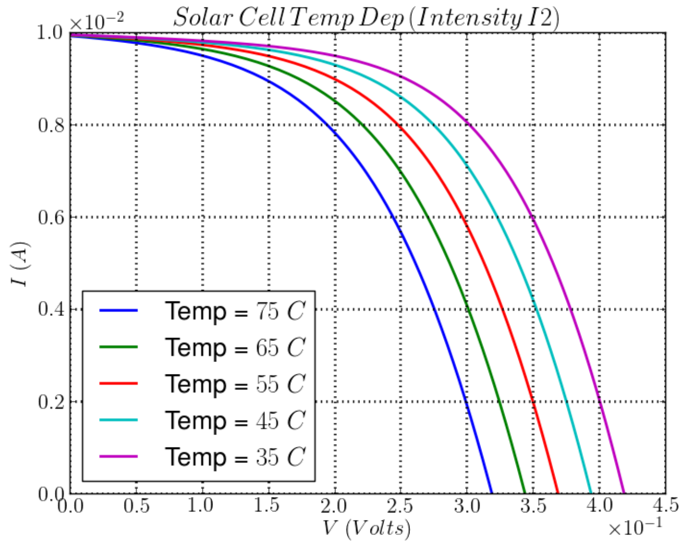

Figure 4: Temperature dependent I-V characteristics under illumination. (4^{th} quadrant of I-V curve, showing only magnitude of current and not its sign)

The increase is related to small reduction in the semiconductor band gap with increase of temperature, that results in the semiconductor absorbing more photons from the incident sun light. In contrast with I_{SC}, the cut-in voltage and V_{OC} show very substantial decrease with increase in temperature. The expected fractional decrease of V_{OC}[1] is given as:

$$\left[\frac{1}{V_{OC}}\right]\left[\frac{\Delta V_{OC}}{\Delta T}\right] \sim -0.003/K \tag{5}$$

which works out to be decrease of roughly $2mV$ per degree.

References

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

Optional reading: Parameters governing saturation current

It is suggested that you read this section after you have studied diode physics in EE207.

For a one sided junction,

$$I_{01} = q\left(\frac{D_p}{\tau_p}\right)^{\frac{1}{2}}\left(\frac{n_i^2}{N_D}\right) \tag{6}$$

$$I_{02} = \left(\frac{qW\sigma v_{th}N_T n_i}{2}\right) \tag{7}$$

where,

$$n_i^2 = N_C N_V e^{\frac{-E_g}{kT}} \tag{8}$$

D and τ are the diffusion constant and lifetime respectively, n_i the intrinsic carrier concentration, N_D the donor doping density, W the depletion width, N_C and N_V are the effective densities of states for conduction band and valence band respectively, σ as capture cross-section and v_{th} the thermal velocity.

The term involving I_{02} is caused by the presence of defects with energy near the midgap. This can be seen in Eq. 7 where I_{02} is proportional to the defect density N_T. Usually I_{02} is much larger than I_{01}. Hence, at low voltages, the term I_{02} in Eq. 2 dominates the I-V characteristic. The inverse of the slope of the curve of $ln\ I$ v/s V_D is given by η kT/q. where η the ideality factor equal to 2. The magnitude of I_{02} and the range of voltage where η =2 is a measure of defect density in the material.

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As the applied voltage V increases, the term I_{01} dominates the I-V characteristic as the I_{01} term increases more steeply with voltage (ideality factor η =1). The magnitudes of I_{01} and I_{02} is a measure of the “goodness” of the diode. The smaller the values, the better the technology and will make a better solar cell.