DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY
SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

18PY103J – Physics: Semiconductor Physics
Module-III, Lecture-14

Solar Cell

Solar Cell

A solar cell is a pn junction device with no voltage directly applied across the junction. The solar cell converts photon power into electrical power and delivers this power to a load.

The pn Junction Solar Cell

Consider the pn junction shown in Fig. 1, with a resistive load. Even with zero bias applied to the junction, an electric field exists in the space charge region as shown in the Fig. 1.

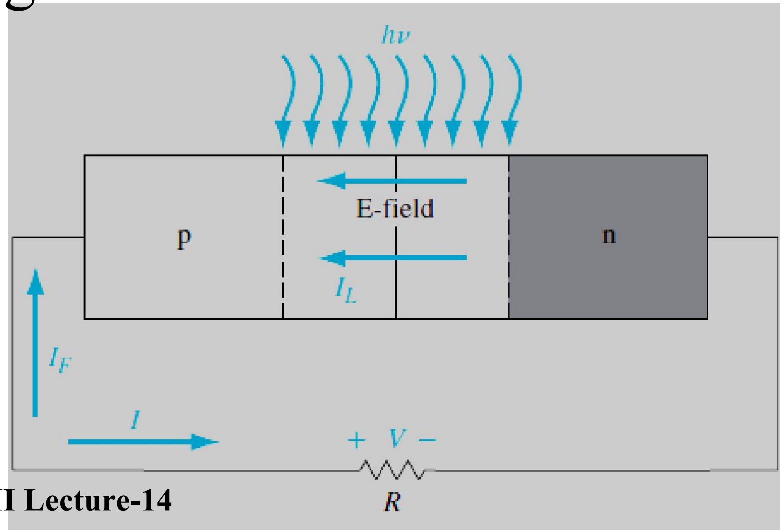

Figure 1 | A pn junction solar cell with resistive load.

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Incident photon illumination can create electron-hole pairs in the space charge region that will be swept out producing the photocurrent I_L in the reverse-biased direction as shown in Fig. 1.

The photocurrent I_L produces a voltage drop across the resistive load which forward biases the pn junction. The forward-bias voltage produces a forward-bias current I_F as indicated in the Fig. 1.

The net pn junction current, in the reverse-biased direction, is

$$I = I_L - I_F = I_L - I_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{1}$$

here the ideal diode equation has been used.

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As the diode becomes forward biased, the magnitude of the electric field in the space charge region decreases, but does not go to zero or change direction. The photocurrent is always in the reverse-biased direction and the net solar cell current is also always in the reverse-biased direction.

There are ***two limiting cases of interest***.

First limiting case is the ***short-circuit condition*** occurs when **R = 0** so that V = 0. The current in this case is referred to as the ***short-circuit current***,

Or

$$I = I_{sc} = I_L \qquad (2)$$

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The ***second limiting case*** is the ***open-circuit condition*** and occurs when $\boldsymbol{R} \rightarrow \infty$.

The net current is zero and the voltage produced is the *open-circuit voltage* V_{oc}. The photocurrent is just balanced by the forward-biased junction current, so we have

$$I = 0 = I_L - I_S\left[\exp\left(\frac{eV_{\infty}}{kT}\right) - 1\right] \qquad (3)$$

Then can find the open circuit voltage V_{oc} as

$$V_{OC} = V_t \ln\left(1 + \frac{I_L}{I_S}\right) \qquad (4)$$

where $V_t = nkT/q$

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A plot of the diode current I as a function of the diode voltage V from Eqn (4) is shown in Fig. 2. We may note the short-circuit current and open circuit voltage points on the figure.

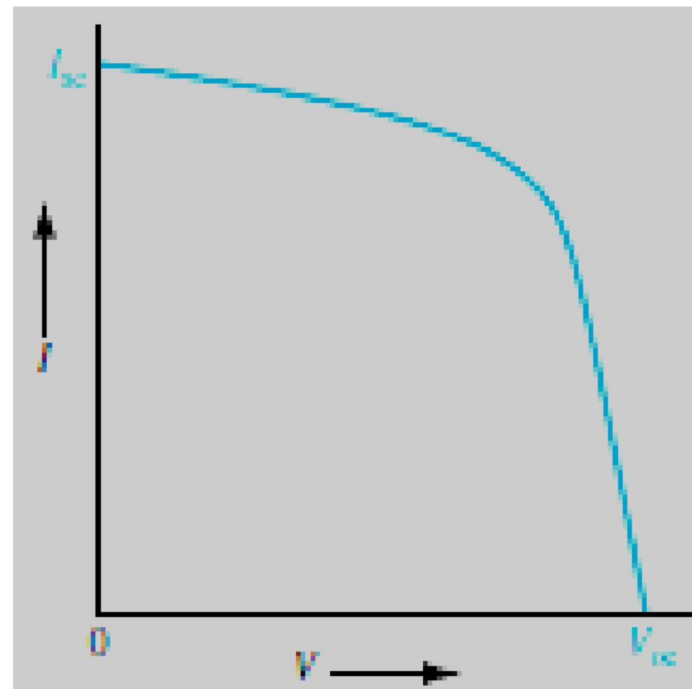

Figure 2 | ***I–V characteristics of a pn junction solar cell.***

The power delivered to the load is

$$P = V * I = I_L * V - I_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right] * V \qquad (5)$$

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We may find the current and voltage which will deliver the maximum power to the load by setting the derivative equal to zero, or dP/dV = 0.

Using Eqn. (5), we find

$$\frac{dP}{dV} = 0 = \mathrm{I_L} - \mathrm{I_S}\left[\exp\left(\frac{\mathrm{e}V_m}{\mathrm{kT}}\right) - 1\right] - \mathrm{I_s V_m}\left(\frac{\mathrm{e}V}{\mathrm{kT}}\right)\exp\left(\frac{\mathrm{e}V_m}{\mathrm{kT}}\right) \quad (6)$$

where V_m is the voltage that produces the maximum power.

We may rewrite Eqn. (6) in the form

$$\left(1 + \frac{V_m}{V_t}\right)\exp\left(\frac{\mathrm{e}V_m}{\mathrm{kT}}\right) = 1 + \frac{I_L}{I_S} \quad (7)$$

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The value of V_m may be determined by trial and error. Figure 3 shows the maximum power rectangle where I_m is the current when $V = V_m$.

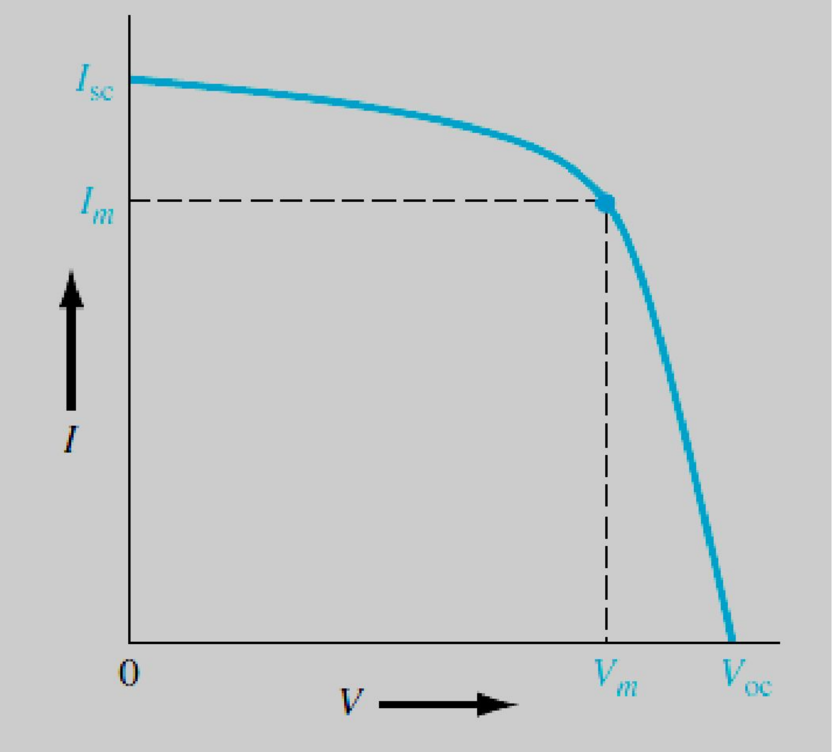

Figure 3 | Maximum power rectangle of the solar cell *I–V* characteristics.

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Efficiency of a Solar Cell:

To determine the efficiency of the solar cell following parameters are to be described

- **Short-Circuit Current I_{sc}**

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).

$$I_{sc} = -I_L \tag{8}$$

Here Short-Circuit Current is nothing but light generated current.

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Open-Circuit Voltage V_{OC}

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

$$V_{OC} = \frac{nkT}{q} \ln\left(1 + \frac{I_L}{I_S}\right) \qquad (9)$$

Fill Factor FF

Fill Factor FF, is a measure of the realizable power from a solar cell. Typically, the fill factor is between 0.7 and 0.8. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc} so that

$$FF = \frac{P_m}{I_{sc}V_{oc}} = \frac{I_m V_m}{I_{sc}V_{oc}} \qquad (10)$$

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Conversion Efficiency η

The *conversion efficiency* η of a solar cell is defined as the ratio of output electrical power to incident optical power. For the maximum power output, we can write

$$\eta = \frac{P_m}{P_{in}} \text{ x } 100\% = \frac{I_m V_m}{P_{in}} \text{ x } 100\% = \frac{I_{sc} V_{oc} FF}{P_{in}} \text{ x } 100\% \qquad (11)$$

The maximum possible current density and the maximum possible voltage in the solar cell are I_{sc} and V_{oc}, respectively.

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The conventional pn junction solar cell has a single semiconductor bandgap energy. When the cell is exposed to the solar spectrum, a photon with energy less than E_g will have no effect on the electrical output power of the solar cell.

A photon with energy greater than E_g will contribute to the solar cell output power, but the fraction of photon energy that is greater than E_g will eventually only be dissipated as heat.

The maximum efficiency of a silicon pn junction solar cell is approximately 28 percent. Non ideal factors, such as series resistance and reflection from the semiconductor surface, will lower the conversion efficiency typically to the range of 10 to 15 percent.

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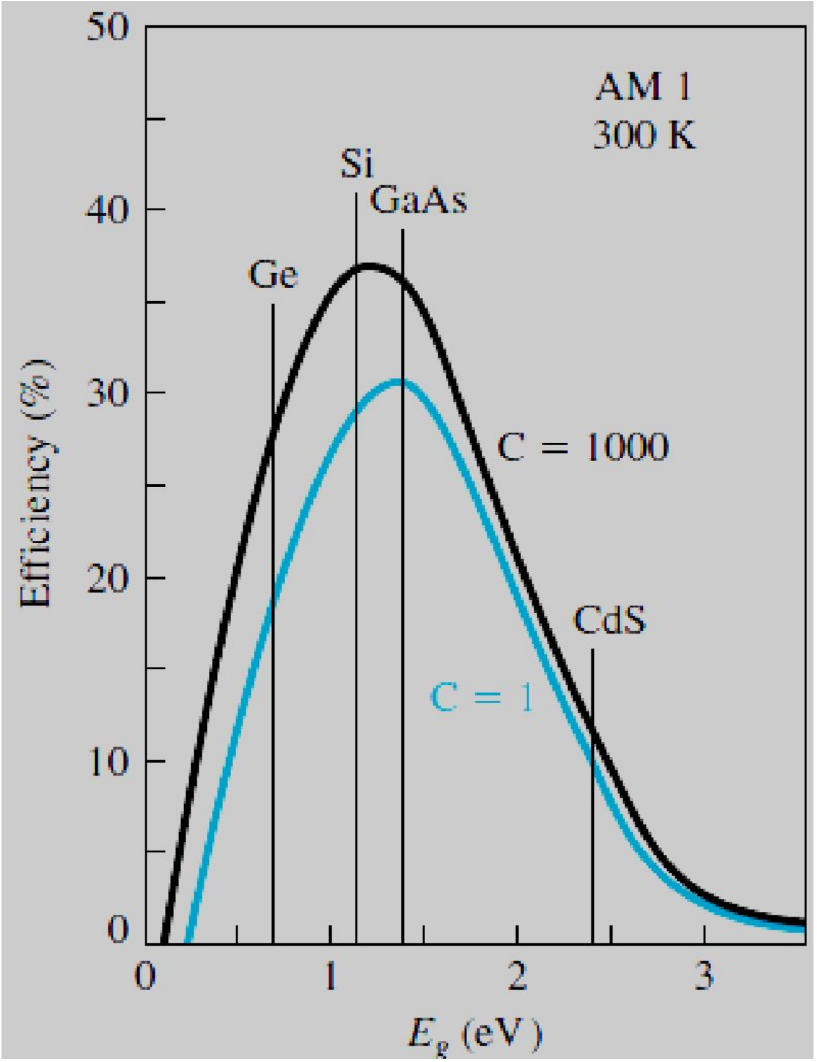

Figure 4 | Ideal solar cell efficiency at *T* = 300 K for C = 1 sun and for a C =1000 sun concentrations as a function of bandgap energy.

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A large optical lens can be used to concentrate sunlight onto a solar cell so that the light intensity can be increased up to several hundred times. The short-circuit current increases linearly with light concentration while the open-circuit voltage increases only slightly with concentration.

We can see that the conversion efficiency increases only slightly with optical concentration through Fig. 4. The primary advantage of using concentration techniques is to reduce the overall system cost since an optical lens is less expensive than an equivalent area of solar cells.

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Loss in Solar Cell : Factors which affect Efficiency of the Solar Cell

1. Loss due to Low Energy Photons ($h\nu < E_g$)
2. Loss due to High Energy Photons ($h\nu > E_g$)
3. Voltage Loss
4. Fill Factor Loss
5. Loss due to Reflection
6. Loss due to less Absorption
7. Loss due to covering of Metal Contact
8. Recombination Loss