o **Photovoltaic principles**

The photovoltaic effect can be observed in nature in variety of materials, but the materials that have shown the best performance in sunlight are the semi-conductors. When photons from the sun are absorbed in a semi-conductor, they create free electrons with higher energies. These are then flow out of the semi-conductor by an electric field to do useful work. The electric field in most solar cells is provided by a junction of materials which have different electrical properties. To obtain a useful power output from photon, three processes are required:

1 The photon has to be absorbed in the active part of the material and resultin electrons being excited to a higher energy potential.

2 The electron-hole charge carriers created by the absorption must be physically separated and moved to the edge of the cell.

3 The charge carriers must be removed from the cell and delivered to a useful load before they lose their extra potential.

For completing the above processes, a solar cell consists of:

a) Semi-conductor in which electron hole pairs are created by absorption of incident solar radiation,
b) Region containing a drift field for charge separation, and
c) Charge collection front and back electrodes.

The photo-voltaic system can be described easily for p-n junction in a semiconductor is shown in Figure below.

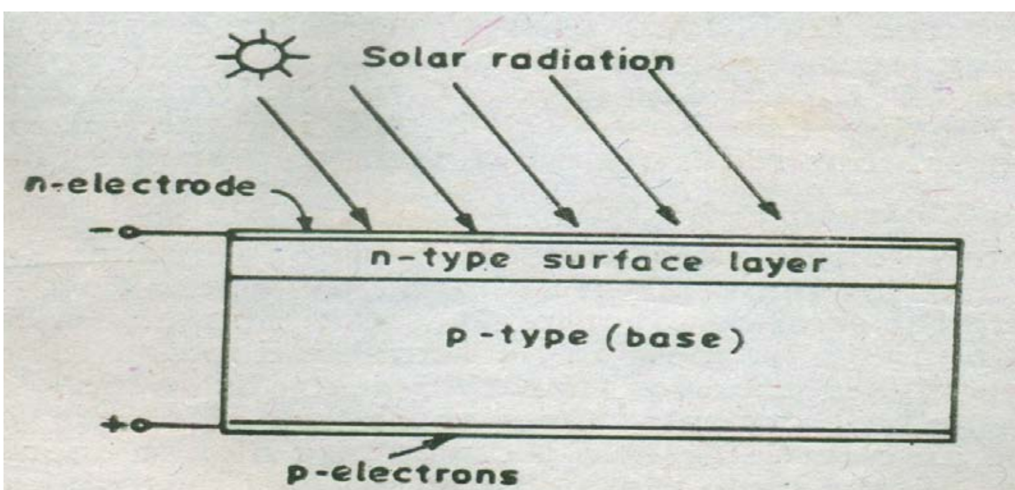


Fig. 15 3·1. A typical *n*- on *p*-photovoltaic.

Simple Construction of a solar cell

A solar cell is a p-n junction with a very narrow and more heavily doped n-region. The illumination is through the thin n-side. The depletion region (W) or the space charge layer (SCL) extends primarily into the p-side. There is a built-in field E_o in this depletion layer. The electrodes attached to the n-side must allow illumination to enter the device and at the same time result in a small series resistance. They are deposited on the n-side to form an array of **finger electrodes**on the surface as shown in Figure below. A thin **antireflection coating**on the surface (not shown in the figure) reduces reflections and allows more light to enter the device. The back of the p side is completely covered with a metallic layer to make electrical contact through which charges are removed. An approximate thickness of n layer and p layer is shown in the figure.

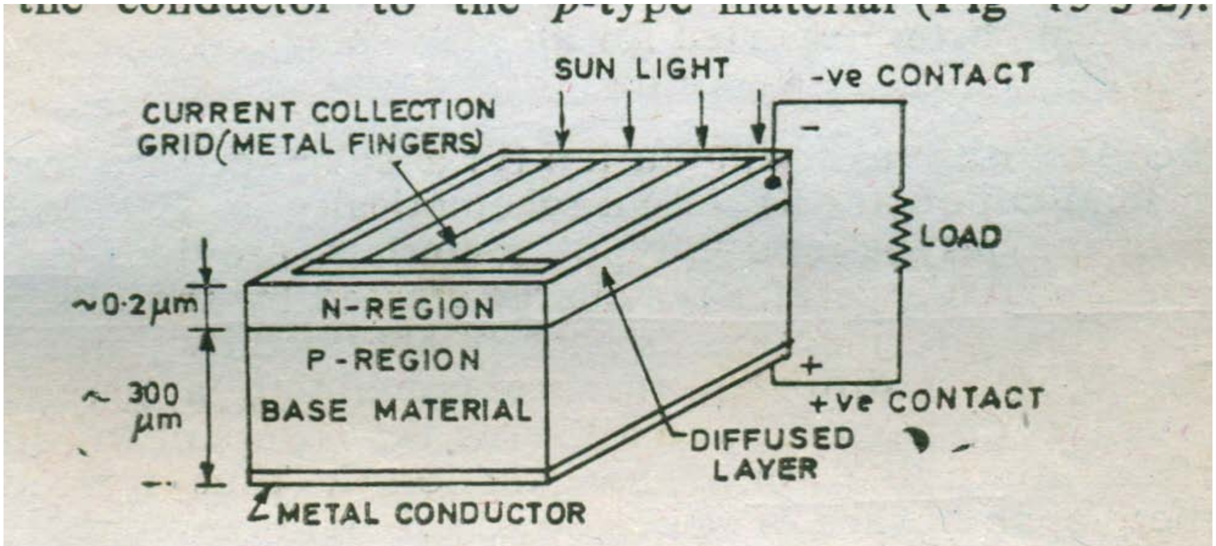


Fig. 15·3·2. Schematic of completely coving back a typical solar cell showing the physical arrangement of the major components.

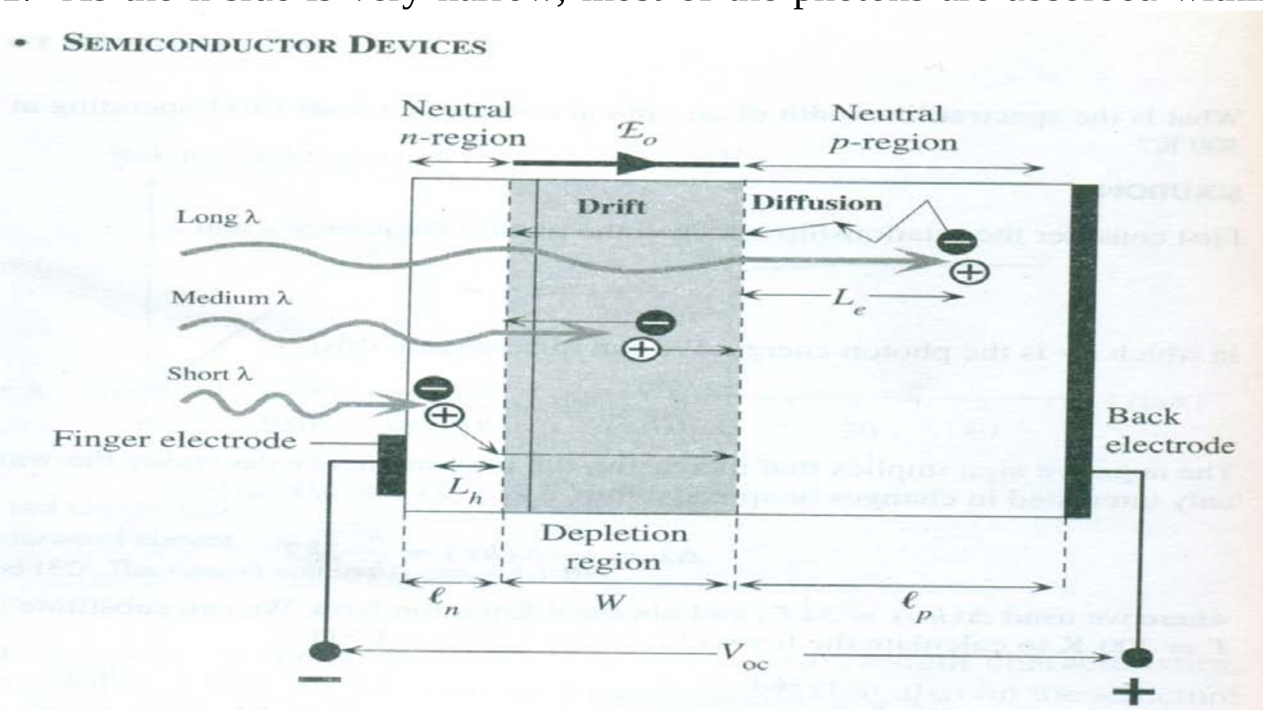
Electrical contacts are made with n side and p side materials and contact are connected through an external electrical conductor. Thus free electrons will flow from the n-type material through the conductor to the p-type material.
Here the free electrons from n side enter p side and recombine with holes and become bound electrons; thus both free electrons and holes will be removed. The flow of electrons through the external conductor constitutes an electric current which will continue as long as more free electrons and holes are being

formed by the solar radiation. This is the basis of photovoltaic conversion that is the conversion of solar energy into electrical energy

WORKING OF A SOLAR CELLS DEVICE

Figure below shows the working principle of a solar cell device.

1. As the n-side is very narrow, most of the photons are absorbed within the



e

depletion region (W) and within the neutral p-side (L_p) and photo generate electron hole pairs (**EHPs**) in these regions. **EHPs**photo generated in the depletion region are immediately separated by the built-in field E_o which drifts them apart. The electron drifted towards the neutral n+ side whereupon it makes this region negative by an amount of charge -e. Similarly, the holes are drifted to the neutral p-side and thereby make this side positive. Consequently an **open circuit voltage**develops between p-side with respect to the n-side. When an external load is connected, then the excess electrons in the n-side travel around the external circuit, do the work, reach the p-side and recombine with the excess hole there.

2. The **EHPs**photo generated by long-wavelength photons that are absorbed in the neutral p-side diffuse around in this region as there is no electric field. If the recombination lifetime of the electron is τ_e, it diffuses a mean distance L_e=

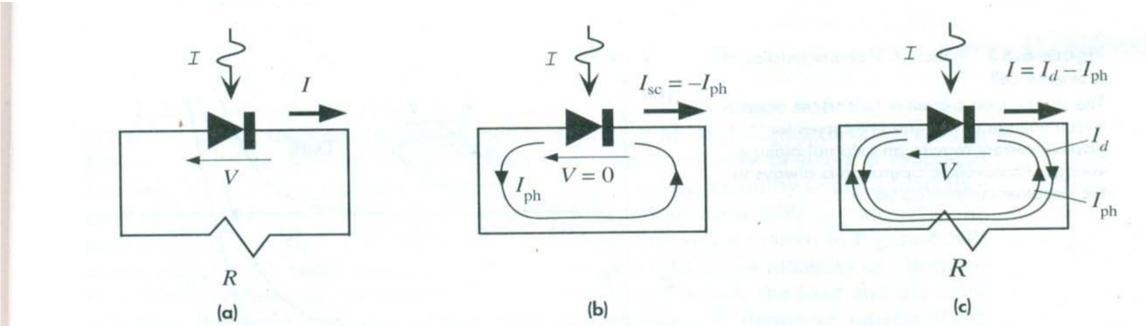
$\sqrt{(2D_e\tau_e)}$ where D_e is its diffusion coefficient in the p-side. Those electrons within a distance L_e to the depletion region readily diffuse and reach this region whereupon they become drifted by E_o to the n-side as shown in Figure
Consequently only those **EHPs**photo generated within the minority carrier diffusion length L_e to the depletion layer can contribute to the photovoltaic effect. Once an electron diffuses to the depletion region, it is swept over to the n-side by E_o to give an additional negative charge to this region. Those photo generated **EHPs** further away from the depletion region than L_e are lost by recombination. It is therefore important to have the minority carrier diffusion length L_e be as long as possible. This is the reason for choosing this side of a Si p-n junction to be p-type which makes electrons the minority carriers; the electron diffusion length in Si is longer than the holediffusion length.

3. The short-wavelength photons are absorbed in the neutral n region and generate **EHPs**. Holes within the diffusion length L_h reach the depletion layer and become swept across to the p-side.
EHPs photo generated by energetic photons absorbed in the n-side near the surface region of outside the diffusion length L_h to the depletion layer are lost by recombination as the lifetime in the n-side is generally very short (due to heavy doping). The n-side is therefore made very thin, typically less than 0.2 μm.. The **EHPs** photo generated very near the surface of the n-side, however, disappear by recombination due to various surface defects acting as recombination centers.

4. The photo generation of **EHPs**that contributes to the photovoltaic effect therefore occurs in a volume covering L_h+ W+ L_e. If the terminals of the device are shorted as in Figure.3, then the excess electron in the n-side can flow through the external circuit to neutralize the excess hole in the p-side. This current due to the flow of the photo generated carriers is called the **Photocurrent.**

Current through a solar cell

Consider an ideal p-n junction photovoltaic device connected to a resistive load R as shown in Figure (a) :



Note that I and V in the figure define the convention for the direction of positive current and positive voltage. If the load is short circuited, then the only current in the circuit is that generated by the incident light. This is the photocurrent I_{ph} shown in Figure (b) which depends on the number of **EHPs**photo generated within the volume enclosing the depletion region and the diffusion lengths to the depletion region. The greater is the light intensity, the higher is the photo generation rate and the larger is I_{ph}. If I is the light intensity, the **short circuit current**is

$$I_{sc} = - I_{ph} = - KI$$

where K is a constant that depends on the particular device.

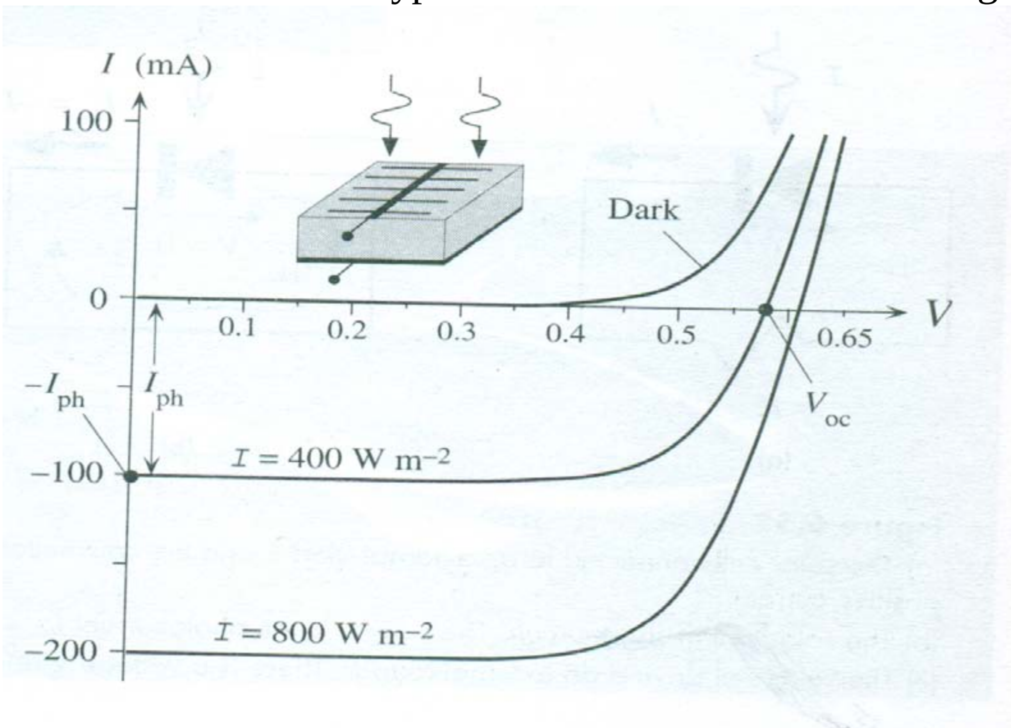
If R is not a short circuit, then a positive voltage V appears across the p-n junction a result of the current passing through it as shown in Figure 4c. In addition to I_{ph} there is also a forward diode current I_d in the circuit as shown in Figure ©, which arises from the voltage developed across R. Since I_d is due to the normal p-n junction behavior, it is given by the diode characteristics,

$$I_d = I_0 [\exp(eV / nkT) - 1] \quad (1)$$

Where I_o is the "reverse saturation current" and n is the ideality factor (n =1 - 2). In open circuit, the net current is zero. This means that the photocurrent I_{ph} develops just enough photovoltaic voltage V_{oc} to generate a diode current $I_d = I_{ph}$. The total current through the solar cell is given by

$$I = - I_{ph} + I_0 [\exp(eV / nkT) - 1] \quad (2)$$

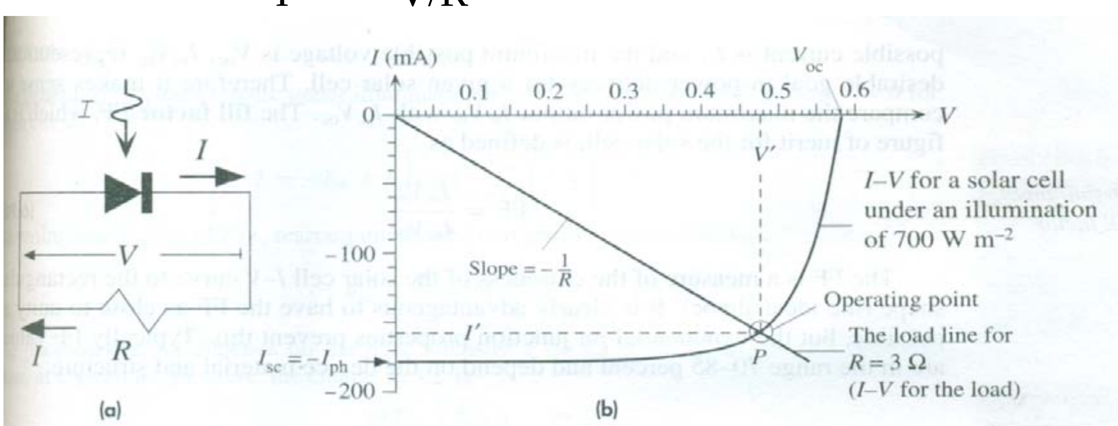
The overall I-V characteristics of a typical Si solar cell are shown in Figure.



It can be seen that it corresponds to the normal dark characteristics being shifted down by the photocurrent I_{ph} which depends on the light intensity I. The open circuit out-put voltage V_{oc}, of the solar cell is given by the point where the I-V curve cuts the V axis (I = 0).

Equation (2) gives the I-V characteristics of the solar cell. When the solar cell is connected to a load as in Figure (a) below I through R is now in opposite direction to the conventional current flow from high to low potential. Thus

$$I = -V/R$$



The actual current $I^{/}$ and voltage $V^{/}$ in the circuit must satisfy both the I– V characteristics of the solar cell equation (2) and (3) and that of the load. $I^{/}$ and $V^{/}$ in the solar cell circuit are most easily found by using a **load line construction**.

The I-V characteristic of the load line is a straight line with a negative slope –I/R. This is called the load line is shown in figure (b) along with the I-V characteristics of solar cell under a given intensity of illumination. The load line cuts the solar cell characteristic at the P where the load and the solar cell have the same current and voltage $I^/$ and $V^/$. Point P on the I– V characteristics represents the **operating point of the circuit.**

The power delivered to the load is $P_{out} = I^/ V^/$, which is the area of the rectangle bound by the I and V axes and the dashed lines shown in figure 6.b. Maximum power is delivered to the load when this rectangular area is maximized (by changing R or the intensity of illumination), when $I^/ = I_m$ and $V^/ = V_m$

<u>Parameters used to characterize the outputof solar Cell.</u>

The two limiting parameters are used to characterize the output of solar cells for given irradiance, operating temperature and area are:

1) **Short circuit current, (**I_{sc}), the maximum current, at zero voltage. Ideally,
   if, V = 0, then $I_{sc} = I_{ph}$. Note that I_{sc} is directly proportional to the available sunlight.
2) **Open circuit voltage (V_{oc}) -** the maximum voltage, at zero current. The value of V_{OC}. increases logarithmically with increased sunlight.
   Note that at I = 0

$$V_{oc} = nkT/e\, [\ln(I_{ph} / I_{sc}+1)] \quad \dots\dots\dots\dots\dots\dots \quad (3)$$

For each point on the I-V curve, the product of the current and voltage represents the power output for that operating condition. A solar cell can also be characterized by its maximum power paint, when the product $I^/_{mp}$ *x* $V^/_{mp}$, is at its maximum value. The maximum power output of a cell is graphically given by the largest rectangle that can be fitted under the 1-V curve. That is.

$$d(IV) / dV = 0, \quad \text{giving}$$

$$V_{mp} = V_{oc} - nkT / q \,\ln (V_{mp} / (nkT/q) + 1) \quad \dots\dots\dots \quad (4)$$

For example, if n= 1.3 and V_{oc}= 600 mV, as for a typical silicon cell, V_{mp} is about 93 mV smaller than $V_{oc.}$

The power output at the maximum power point under strong sunlight (1 kW/m^2) is known as the 'peak power' of the cell. Hence photovoltaic panels are usually rated in terms of their 'peak' watts (W_p).

The fill factor (FF)

The fill factoris a measure of the junction quality and series resistance of a cell. It is defined as

$$FF = V_{mp} I_{mp} / V_{oc} I_{sc} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

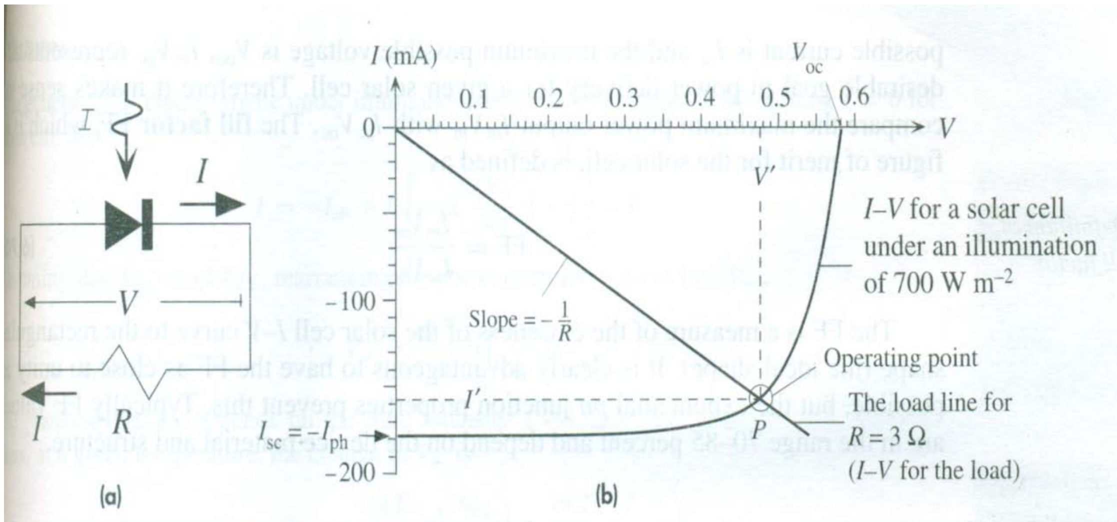
Hence the power at maximum power point

$$P_{mp} = V_{oc} I_{sc} FF \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Obviously, the nearer the fill factor is to unity, the higher the quality of the cell.

Example 1

Consider a solar cell as shown in the figure is driving a load of 3 Ω. The cell has an area of 3cm x 3cm andis illuminated with light of 700Wm^{-2}. Find the current and voltage in the circuit. Find the power delivered tothe load, the efficiency of the circuit in the circuit, and fill factor of the solar cell.



Solution.

From the I- V curve, I = -V (3Ω), the load line is drawn with a slope1/3Ω. It cuts the I-V characteristics of the cell at $I^/$ = 157mA and $V^/$ = 0.475 which are current and voltage respectively. The power delivered to the load is

$$P_{out} = I^/V^/ = (157 \times 10^{-3})(0.475) = 0.0746 \text{ W or } 74.6\text{mW}$$

The input of sunlight power is

$$P_{in} = \text{(light intensity)(Surface area)} = (700\text{Wm}^{-2})(0.03\text{m})^2$$
$$= 0.63 \text{ W}$$

The efficiency $\eta = (100\%)\frac{P_{out}}{P_{in}} = (100\%)\frac{0.0746\,W}{0.63\,W}$

$$= 11.8\ \%$$

The fill factor can be calculated with reference P of the figure and the intercept of the curve with V and I axis as

$$FF = \frac{Im\,Vm}{Isc\,Voc} \approx \frac{I^/\ V^/}{I_{sc}\,V_{oc}} = \frac{(157mA)\,(0.475V)}{(178mA)\,(0.58)}$$
$$= 0.722 \quad \text{or} \quad 72\%$$

Example2.

A solar cell under illumination of 500 Wm^{-2} has a short circuit current I_{sc} of 150mA and open circuit voltage V_{oc} of 0.53 V. What are the I_{sc} and V_{oc} when the light intensity is doubled ? Assume n =1.5

Solution:
Equation for current through a solar cell

$$I = - I_{ph} = I_0 [\exp(eV / nkT) - 1]$$

For open circuit voltage I =0 , so

$$0 = -I_{ph} = I_0 [\exp(eV_{oc} / nkT) - 1]$$

Assuming Voc>> nkT/e, re arranging (neglecting 1)

$$Voc = \frac{nkT}{e} \ln(\frac{I_{ph}}{I_0})$$

The photocurrent depends on light intensity, I_{ph} = KI, where K is a constant. Thus at a given temperature , the change in Voc is

$$V_{oc2} - V_{oc1} = \frac{nKT}{e} \ln(\frac{I_{ph2}}{I_{ph1}}) = \frac{nKT}{e} \ln(\frac{I_2}{I_1})$$

The short circuit is the photocurrent, so at double the intensity this is

$$Is_{c2} = Is_{c1} (\frac{I_2}{I_1}) = (150 \text{ mA}) \times (2)\ 300\text{mA}$$

Assuming n =1.5, the new open circuit voltage is

$$V_{oc2} = V_{oc1} + \frac{nKT}{e} \ln(\frac{I_2}{I_1}) = 0.530 \text{ V} + (1.5)(0.026)\ln(2)$$
$$= 0.557 \text{ V}$$

This is a 5% increase compared with the 100% increase in illumination and the short circuit current.