EN 671: Solar Energy Conversion Technology

Performance Characteristics of solar PV Cells

Dr. Pankaj Kalita
Associate Professor
School of Energy Science and Engineering
Indian Institute of Technology, Guwahati

Performance characteristic of PV cells

- I-V Characteristics.
- Equivalent circuit diagram of a solar cell.
- Theoretical maximum power.
- Effect of insolation and temperature on I-V Characteristics.
- Solar cell efficiency and band gap.

Solar Cell Characteristics

- For an ordinary Si pn junction (Junction not illuminated, at room temperature)

$$\boxed{I = I_o\left[\exp\left(\frac{V}{V_T}\right) - 1\right]}$$

$I_o = \text{Revesrse saturation current}$

$V_T = \frac{kT}{e}$ Voltage equivalent temperature = 26 mV at 20°C

$k = 1.381\times10^{-23}\ \text{J/K}$ $\quad e = 1.602\times10^{-19}\ \text{J/V}$

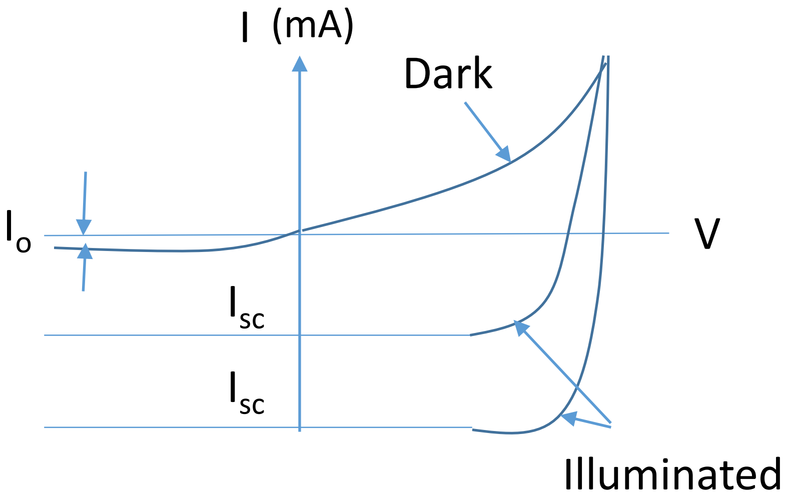
- When pn junction is illuminated:

$$\boxed{I = -I_{sc} + I_o\left[\exp\left(\frac{V}{V_T}\right) - 1\right]}$$

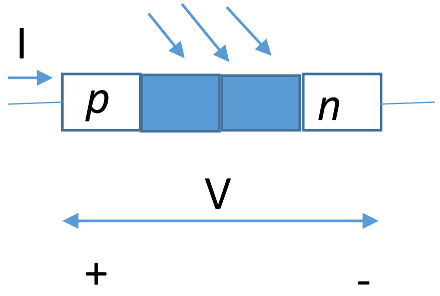
- When the junction is short-circuited at its terminal, V = 0 and a finite current $\boxed{I = -I_{sc}}$

V_{oc} at which current is zero is known as open circuit voltage

$$\boxed{V_{oc} = V_T \ln\left[\left(\frac{I_{sc}}{I_o}\right) + 1\right]}$$



I-V characteristics of dark and illuminated *pn* junction



Illuminated Junction

At room Temperature

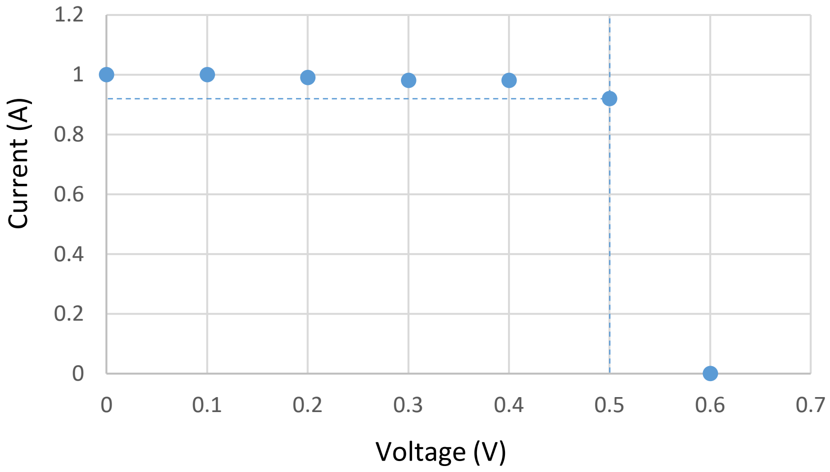
$$\boxed{I_{sc} = 2\ \text{A}, I_o = 1\,\text{nA}, \text{Hence}\ V_{oc}\ \text{is found to be} = 0.55\ \text{V}}$$

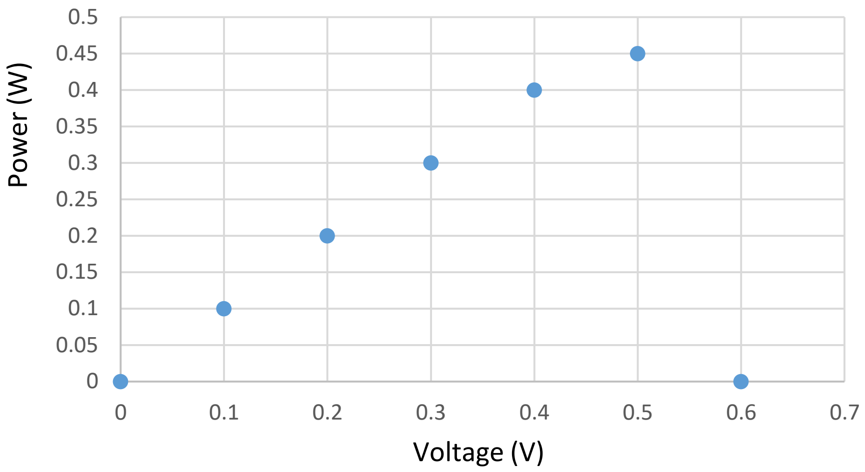
Illuminated *pn* junction can be considered as an energy source

I-V Characteristics

For energy source, by convention, the current coming out of the positive terminal is considered as positive. Mathematical, the characteristics of a solar cell may be written as,

$$\boxed{I = I_{sc} - I_o\left[\exp\left(\frac{V}{V_T}\right) - 1\right]}$$



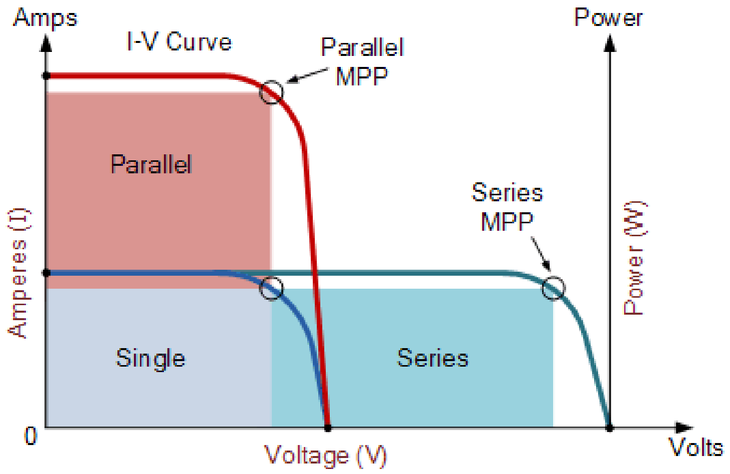


Fill factor of the cell,

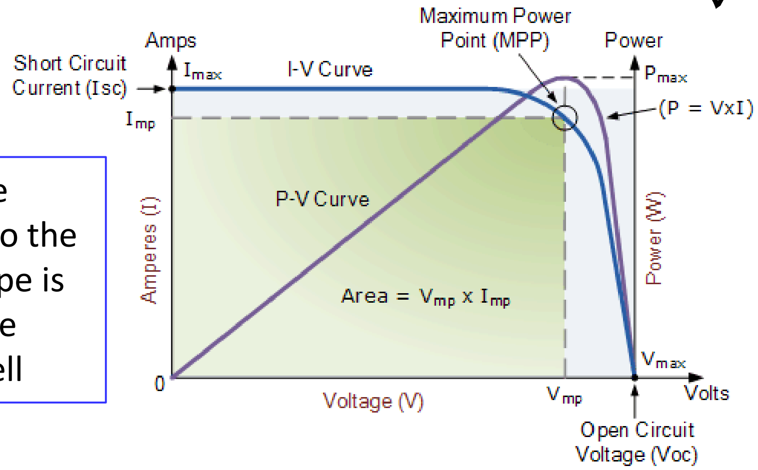
$$\boxed{\mathrm{FF} = V_m \times I_m / V_{oc} \times I_{sc}}$$

(Si – 0.5 to 0.83)

✓ An ideal cell would have a perfect rectangular characteristics.



Closeness of the characteristics to the rectangular shape is a measure of the quality of the cell



Instantaneous Efficiency,

$$\eta_i = \frac{V_m \times I_m}{\text{Solar Power}}$$

$$\Rightarrow \eta_i = \frac{FF \times V_{oc} \times I_{sc}}{I_T \times A_c}$$

Q.1: The fill factor for a solar cell of $V_{oc} = 0.2\ \mathrm{V}$ $\quad I_{sc} = -5.5\ \mathrm{mA}$

$V_{\max} = 0.125\ \mathrm{V}$ $\quad I_{\max} = -3\ \mathrm{mA}$

$$\boxed{\mathrm{FF} = V_m \times I_m / V_{oc} \times I_{sc} = 0.125 \times -3 / 0.2 \times -5.5 = 0.34}$$

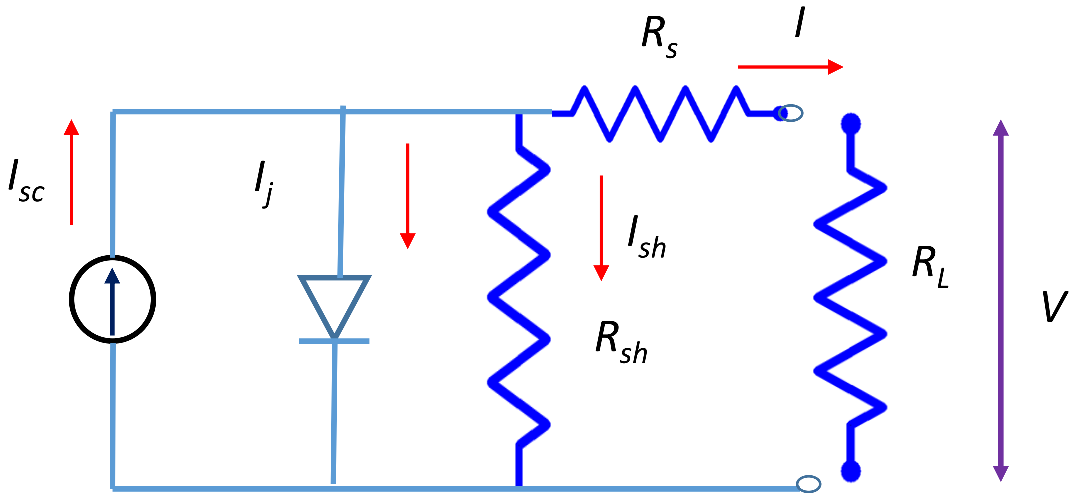
Q.2: Calculate the maximum power and electrical efficiency of a solar cell at an intensity of 200 W/m^2

$V_{oc} = 0.24\ \mathrm{V}$ $\quad I_{sc} = -9\ \mathrm{mA}$ $\quad V_{\max} = 0.14\ \mathrm{V}$ $\quad I_{\max} = -6\ \mathrm{mA}$ $\quad A_c = 4\ \mathrm{cm}^2$

$$\boxed{\mathrm{P}_{\max} = I_{\max} \times V_{\max} = -6 \times 0.14 = -0.84\ \mathrm{mW}}$$

$$\boxed{\begin{aligned} \eta_i &= \frac{V_m \times I_m}{\text{Solar Power}} \\ \Rightarrow \eta_i &= \frac{V_{oc} \times I_{sc}}{I_T \times A_c} = \frac{0.24 \times 9 \times 10^{-3}}{200 \times 4 \times 10^{-4}} = 2.7\% \end{aligned}}$$

Equivalent circuit diagram (Actual)



✓ Short circuit current is not equal to the light generated current but it is less by shunt current through R_{sh} and Internal voltage drop IR_s

For a practical cell, the characteristics is,

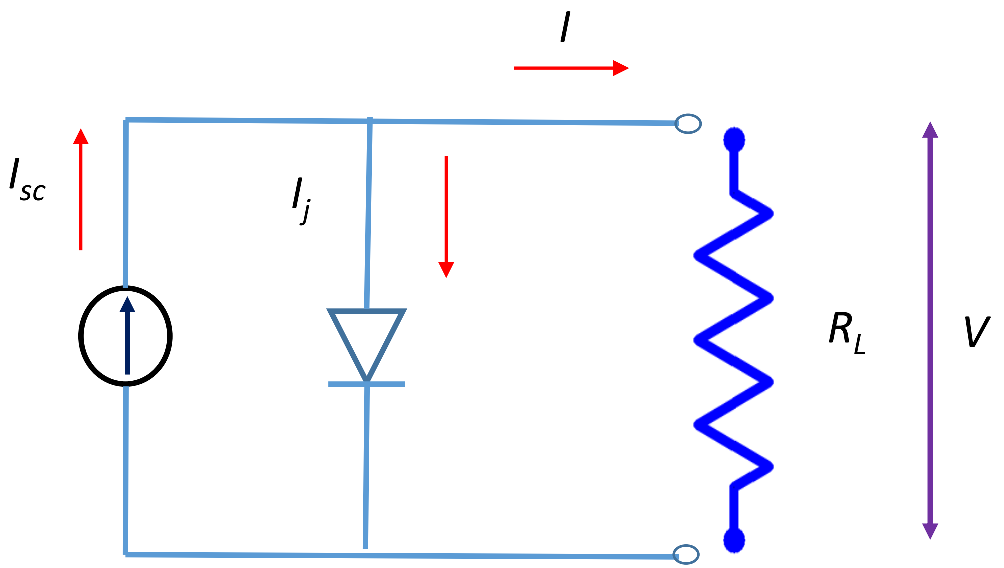
$$I = I_L - I_o\left[\exp\left\{\left(V + IR_s\right)/V_T\right\} - 1\right] - \left(V + IR_s\right)/R_{sh}$$

I_L Photo generated current

Series resistance and shunt resistance variation (high quality, one square inch silicon cell)

$$R_s = 0.05\Omega - 0.1\Omega$$
$$R_{sh} = 200\Omega - 300\Omega$$

Equivalent circuit diagram (Ideal)



Simplified equivalent circuit of a solar cell

- ✓ Shunt resistance is infinite
- ✓ series resistance is zero

The load current (I), at fixed values of the temperature and solar radiation, load current can be related with voltage as

$$\boxed{I = I_{sc} - I_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]} \qquad (1)$$

For an open circuit voltage, $\boxed{I = 0 \qquad V = V_{oc}}$

Substituting in Eqn (1) $\quad 0 = I_{sc} - I_0\left[\exp\left(\frac{eV_{oc}}{kT}\right) - 1\right]$

$$\Rightarrow \frac{I_{sc}}{I_o} = \exp\left(\frac{eV_{oc}}{kT}\right) - 1 \Rightarrow \exp\left(\frac{eV_{oc}}{kT}\right) = \frac{I_{sc}}{I_o} + 1$$

Taking ln, we have $\quad \boxed{V_{oc} = \frac{kT}{e} \times \ln\left(\frac{I_{sc}}{I_o} + 1\right)}$

The power ‘P’ from PV cell is given by $\quad \mathrm{P} = I \times V \qquad (2)$

Using eqn.(1) $\quad \mathrm{P} = \left[I_{sc} - I_0\left\{\exp\left(\frac{eV}{kT}\right) - 1\right\}\right] \times V \qquad (3)$

For max power, $\boxed{\frac{\mathrm{dP}}{\mathrm{dV}} = 0}$

$$0 = \frac{\mathrm{d}}{\mathrm{d}V}\left[I_{sc} \times V - I_0 \left\{ \exp\left(\frac{eV}{kT}\right) - 1 \right\} \times V \right]$$

$$0 = I_{sc} - I_o \left[V \times \frac{e}{kT} \exp\left(\frac{eV}{kT}\right) + \exp\left(\frac{eV}{kT}\right) - 1 \right]$$

$$\Rightarrow \frac{I_{sc}}{I_o} + 1 = \exp\left(\frac{eV}{kT}\right)\left[\frac{eV}{kT} + 1\right] \qquad (4)$$

In the Eqn. (4), V can be replaced by 'V_m'(max)

Now Eqn. (4) can be written as $\boxed{\frac{I_{sc}}{I_o} + 1 = \exp\left(\frac{eV_m}{kT}\right)\left[\frac{eV_m}{kT} + 1\right]}$ (5)

The load current I_m corresponding to max power can be determined by substituting Eqn. (1) in Eqn. (5)

Eqn .(1)

$$\frac{I_m}{I_o} = \left(\frac{I_{sc}}{I_o} + 1\right) - \exp\left(\frac{eV}{kT}\right)$$

$$\frac{I_m}{I_o} = \exp\left(\frac{eV_m}{kT}\right)\left[\frac{eV_m}{kT} + 1\right] - \exp\left(\frac{eV}{kT}\right)$$

$$\Rightarrow \frac{I_m}{I_o} = \frac{eV_m}{kT} \exp\left(\frac{eV_m}{kT}\right) \qquad (6)$$

Using eqn.(4)

$$\frac{I_m}{I_o} = \frac{\frac{eV_m}{kT}}{\left[\frac{eV}{kT}+1\right]} \times \left(\frac{I_{sc}}{I_o}+1\right) = \frac{\frac{eV_m}{kT}}{\left[\frac{eV}{kT}+1\right]} \times \left(\frac{I_{sc}+I_o}{I_o}\right) \qquad (7)$$

Multiplying both sides of the above equation with I_o

Maximum Current

$$I_m = \frac{\frac{eV_m}{kT}}{1+\frac{eV_m}{kT}}\left(I_o + I_{sc}\right) \qquad (8)$$

Maximum power

$$P_m = I_m \times V_m = \frac{\frac{eV_m^2}{kT}}{1+\frac{eV_m}{kT}}\left(I_o + I_{sc}\right) \qquad (9)$$

- **open-circuit voltage (V_{OC}):** This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition). This value is much higher than Vm which relates to the operation of the PV array which is fixed by the load.

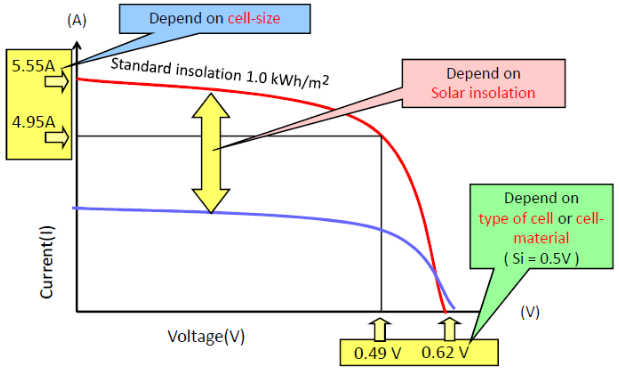
- **short-circuit current** (I_{SC}): The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition). This value is much higher than Imp which relates to the normal operating circuit current.

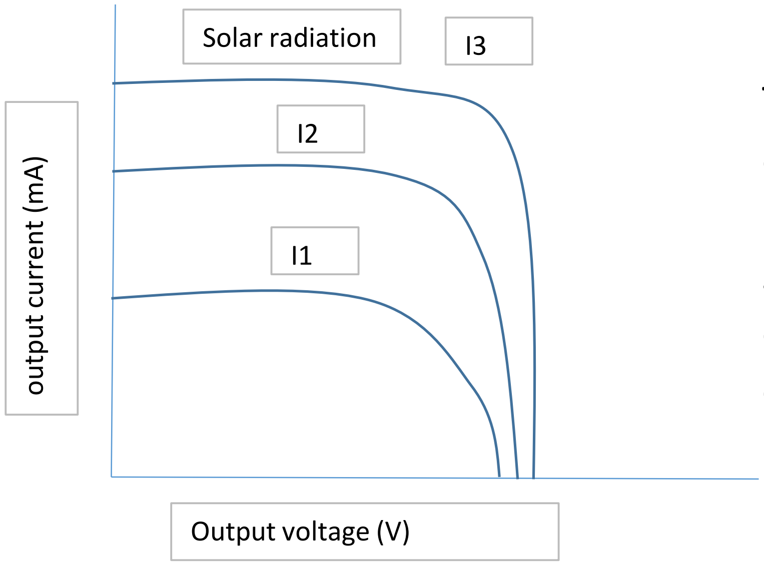
- **Maximum power point** (**MPP):** This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = Im x Vm. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).

- Fill factor (**FF):** The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions. The fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide.

- **Efficiency**: The efficiency of a photovoltaic array is the ratio between the maximum electrical power that the array can produce compared to the amount of solar irradiance received.

Performance characteristics





Effect of illumination level

- Voltage on normal operation point
  0.5V (in case of Silicon PV)
- Current depend on
  - Intensity of insolation
  - Size of cell

Solar cell output power output increases with the solar radiation.

The changes in the short-circuit current are essentially proportional to the changes in solar radiation. However, the changes in voltage are comparatively less

Maximum conversion efficiency of a solar cell is given by the ratio of the maximum useful power to the incident solar radiation. Thus

$$\eta_{\max} = \frac{I_m V_m}{I_T A_c} = \frac{(FF) \times I_{sc} V_{oc}}{I_T A_c}$$

I_T = Incident solar flux

A_c = Area of the cell

For an efficient cell, it is desirable to have high values of fill factor, short circuit current and open circuit voltage. High value of short circuit current are obtainable with low band gap materials, while high values of open circuit voltage and FF are possible with high band gap material

Q.3: The dark current density for a silicon solar cell at 38°C is 4.3 x 10^{-8} A/m^2 and the short circuit current density is 235 A/m^2. (a) Calculate the voltage and current density that maximized the power of the cell. (b) What would be the corresponding maximum power output per unit cell area and the corresponding conversion efficiency if the global solar radiation incident on the cell is 865 W/m^2. (c) Calculate the cell area required for an output of 45 W.

Given Data, $\frac{I_0}{A_c} = 4.3\times10^{-8}\,\text{A/m}^2$ $\quad \frac{I_{sc}}{A_c} = 235\text{A/m}^2$ $\quad T = 38+273 = 311\text{ K}$

we have,

$$\frac{I_{sc}}{I_0} = \exp\left(\frac{eV_{oc}}{kT}\right) - 1$$

$$\Rightarrow \frac{235}{4.3\times10^{-8}} = \exp\left(\frac{1.602\times10^{-19}\times V_{oc}}{1.381\times10^{-23}\times311}\right) - 1$$

Taking "ln" on both the sides,

$$\Rightarrow 22.42 = 37.29\times V_{oc}$$

$$\Rightarrow V_{oc} = 0.601\text{ V}$$

Also we have,

$$\frac{I_{sc}}{I_o} + 1 = \left[\frac{eV_m}{kT} + 1\right]\times\exp\left(\frac{eV_m}{kT}\right)$$

$$\Rightarrow \frac{235}{4.3\times10^{-8}} + 1 = \left[\frac{1.602\times10^{-19}\times V_m}{1.381\times10^{-23}\times311} + 1\right]\times\exp\left(\frac{1.602\times10^{-19}\times V_m}{1.381\times10^{-23}\times311}\right)$$

$$\Rightarrow 5465116280 = (37.29\times V_m + 1)\times\exp(37.29\times V_m)$$

now, we need to solve it by trial and error,

$$V_m = 0.521\text{ V}$$

Maximum Power Density:

$$\frac{I_m}{A_c} = \frac{\frac{eV_m}{kT}}{1+\frac{eV_m}{kT}}\left(\frac{I_o}{A_c}+\frac{I_{sc}}{A_c}\right)$$

$$\Rightarrow \frac{I_m}{A_c} = \frac{19.428}{20.428}\times 235 = 223.496\ \mathrm{A/m^2}$$

Maximum power per unit cell area:

$$\mathrm{P}_{\max} = I_{\max}\times V_{\max}$$

$$\Rightarrow \mathrm{P}_{\max} = 223.496\times 0.521 = 116.441\ \mathrm{W/m^2}$$

Maximum Conversion efficiency:

$$\eta_{\max} = \frac{\mathrm{P}_{\max}}{I} = \frac{116.441}{865} = 0.1346 \text{ or } 13.46\%$$

Let A_c be the area of the cell

$$\eta_{\max} = \frac{\mathrm{P}}{I\times A_c} = \frac{45}{865\times A_c} = 0.1346$$

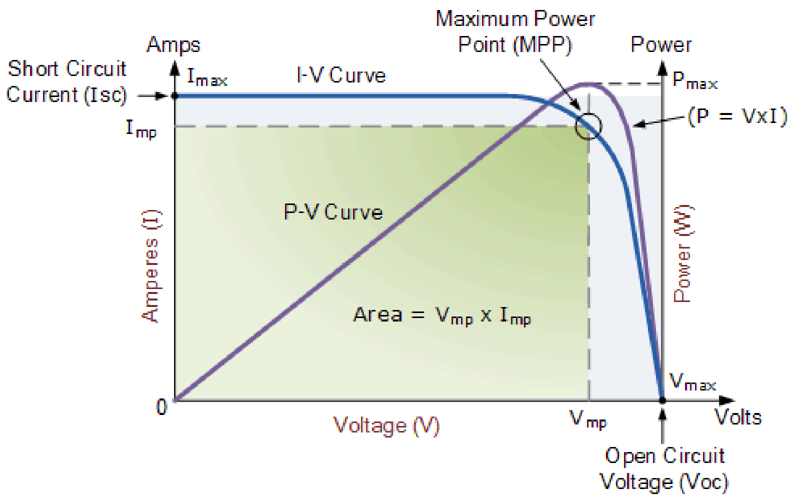
$$\Rightarrow A_c = 0.3865\ \mathrm{m^2}$$

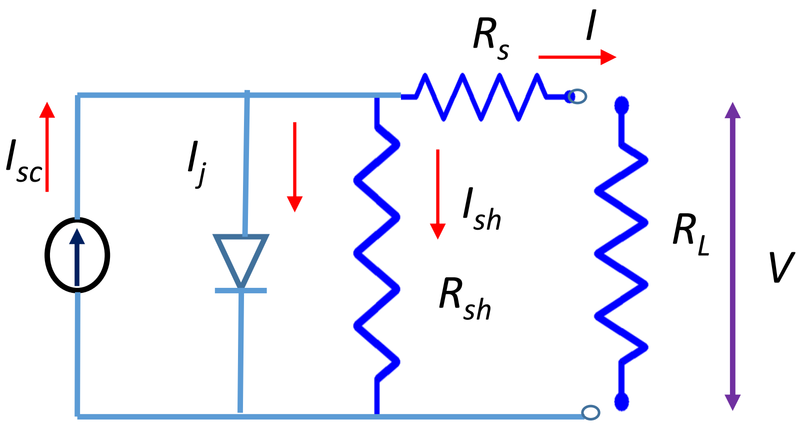
✓Characteristics of solar PV cell

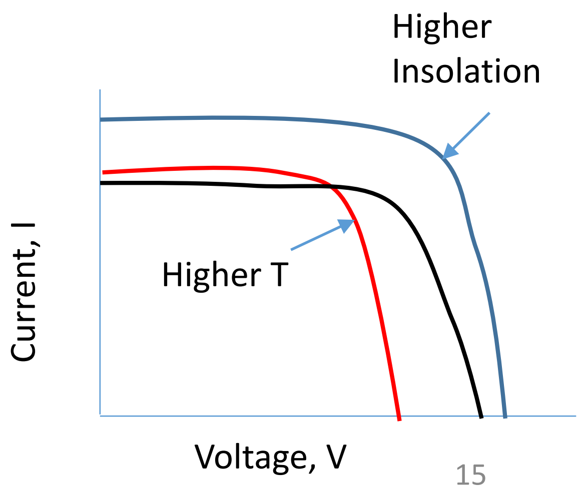
✓FF, I_{sc}, V_{oc}, I_m, V_m, Maximum efficiency

✓Derived the estimation of maximum power of a solar cell

$$\boxed{P_m = I_m \times V_m = \frac{\frac{eV_m^2}{kT}}{1+\frac{eV_m}{kT}}\left(I_o + I_{sc}\right)}$$







Effect of solar cell temperature on solar cell efficiency

- A fraction of the total solar radiation incident on a solar cell produces electricity and remaining radiation is converted into thermal energy
- A part of the produced thermal energy raises the temperature of solar cell and the rest is dissipated from the top & bottom of the cell.
- The temperature of the cell determines the electrical performance of the cell . For unit area , the energy balance can be written as

$$\boxed{\alpha\tau I(t) = \eta_c I(t) + U_L (T_c - T_a)}$$

τ Transmissivity of the cover of the solar cell

α Absorptivity of the solar cell

η_c Electrical efficiency

U_L Overall loss coefficient (top loss + bottom loss)

- NOCT: The nominal operating cell temperature is the temperature of the solar cell corresponding to 20 °C, 800 W/m^2 solar irradiance, 1 m/s wind speed and no load condition.
- For no load condition, $\eta_c = 0$

$$\boxed{\frac{\alpha\tau}{U_L} = \frac{T_{C,\mathrm{NOCT}} - T_a}{I(t)_{\mathrm{NOCT}}}}$$

- The Cell temperature can be found as,

$$\boxed{T_c = T_a + \frac{\alpha\tau}{U_L}\left(1 - \frac{\eta_c}{\alpha\tau}\right) I(t)}$$

- Electrical efficiency is a function of temperature,

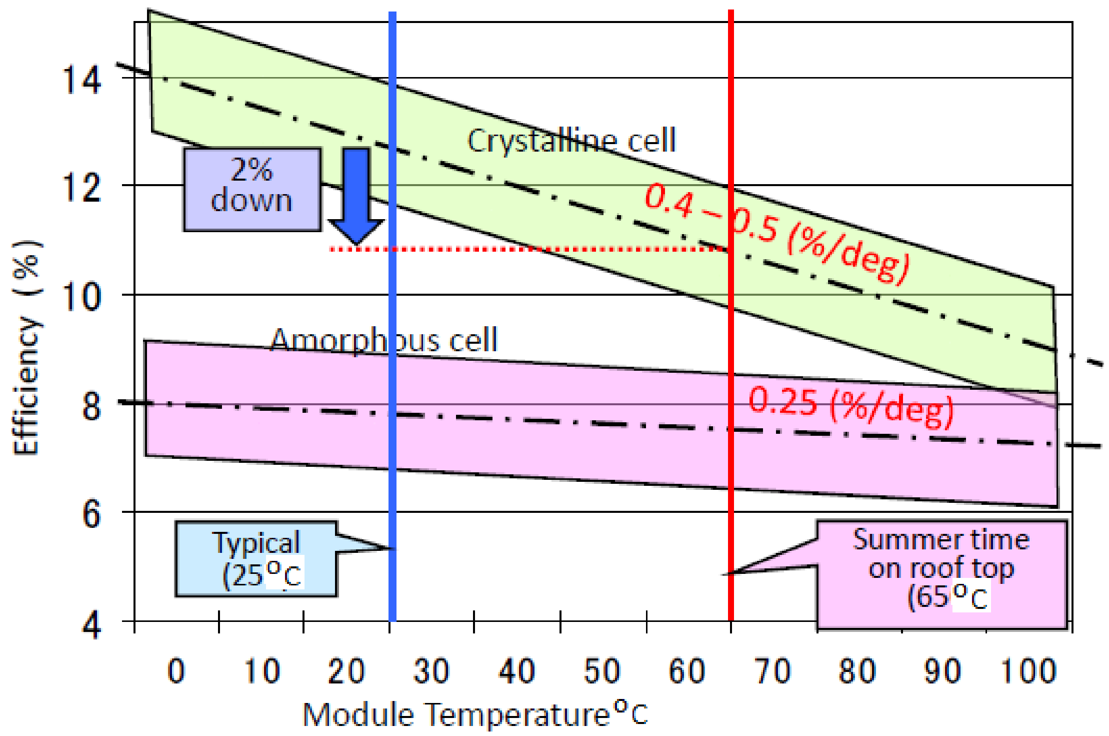
$$\boxed{\eta_{ee} = \eta_o\left[1 - \beta_o\left(T_c - 298\right)\right]}$$

η_o Electrical efficiency of solar cell under standard test conditions

β_o Si efficiency temperature coefficient (0.0045 K^{-1})

T_c Solar cell temperature

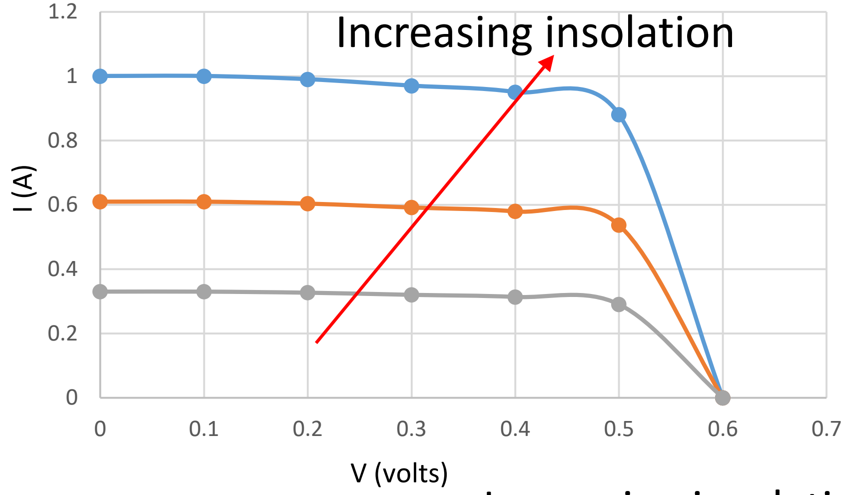
Conversion efficiencies of solar cells with temperature

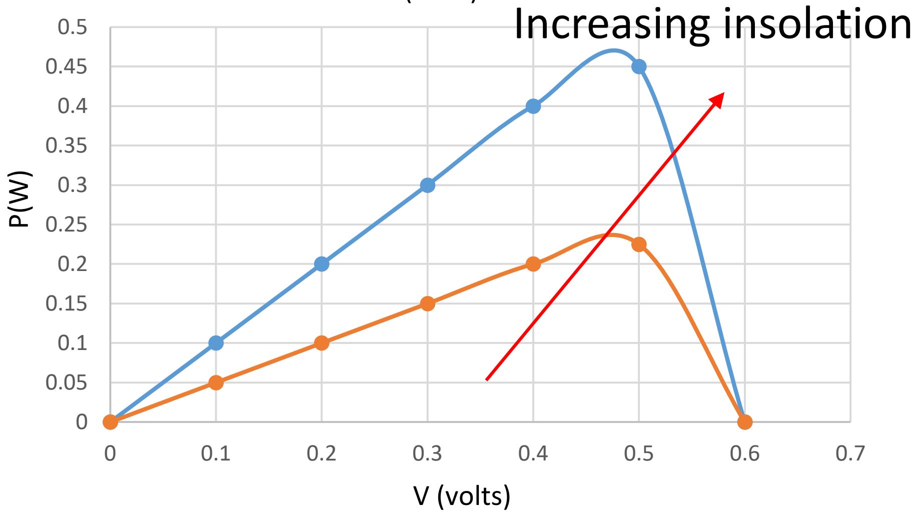


- **When module temperature rises up, efficiency decreases.**
- **The module must be cooled.**

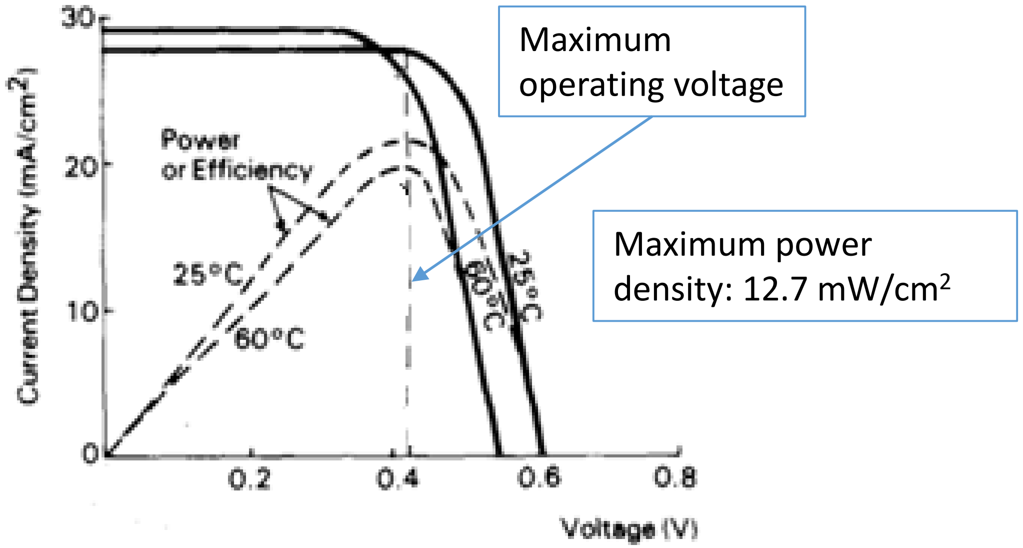
- ✓ At fixed insolation, if temperature is increased, there is a marginal increase in the cell current but a significant reduction in the cell voltage.
- ✓ An increase in temperature causes reduction in the band gap-causes some increase in photo generation rate and thus a marginal increase in current.
- ✓ The reverse saturation current increases rapidly with temperature (cell voltage decreases by 2.2 mV per °C), (lighter the silicon resistivity more marked is the temperature effect).
- ✓ Fill factor decreases with temperature.

Effect of variation of insolation and temperature





Effect of variation of insolation on the characteristic of solar cell



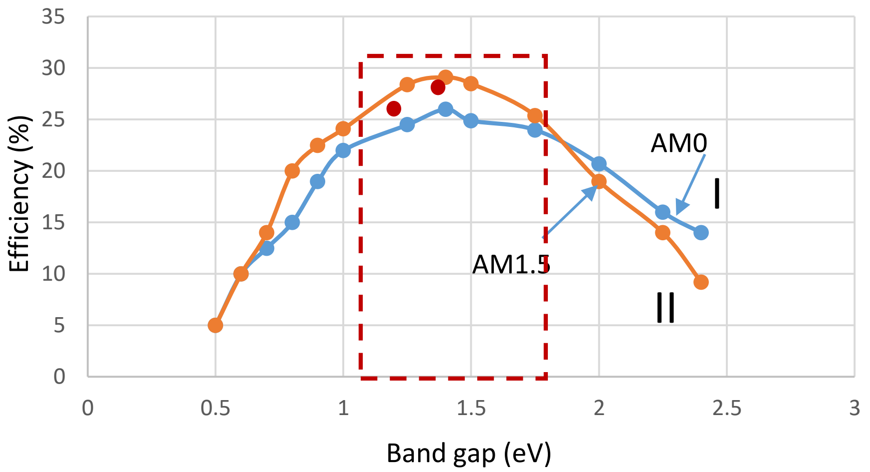
Effect of variation of temperature on the characteristic of solar cell

$$\boxed{I'_{sc} = \frac{I_T}{I_{T,o}} \times I_{sc}}$$

Solar cell efficiency and band gap

- Curve-I: extraterrestrial radiation (AM0) is incident on the fuel cell
- Curve-II: Incident global radiation to be AM1.5 under a clear sky (1000 W/m^2)

Ideal solar cell materials should have band gaps in the range of 1.1 to 1.7 eV



Efficiency values of some solar cells

Type	Area (cm^2)	Open circuit Voltage (V)	Short Circuit mA/cm^3	Fill Factor (%)	Efficiency (%)
Silicon Single crystal	40	0.706	42.2	82.8	24.7
Silicon Multi crystalline	1.0	0.661	32.3	80.9	20.3
GaAs Single Crystal	39	1.0	28.2	83.1	25.1
GaAs Multi Crystalline	40	0.994	23.0	78.7	18.2
Thin film					
CIGs	0.41	0.698	35.1	79.5	19.5
CdTe	1.0	0.845	25.9	75.5	16.5

Efficiency values of some PV modules

Type	Area (cm^2)	Open circuit Voltage (V)	Short Circuit mA/cm^3	Fill Factor (%)	Efficiency (%)
Silicon Single crystal	778	5.6	3.93	80.3	22.7
Silicon Multi crystalline	1017	14.6	1.36	78.6	15.3
Thin film					
CIGs	3459	312	2.16	68.9	13.4
CdTe	4874	2621	3205	62.3	10.7

Data taken from book “solar energy principles of thermal collection and storage” by Sukhatme and Nayak, Tata McGrow Hill Education Private Limited, 2010

Summary

- ✓ Characteristics of solar PV cell.
- ✓ FF, I_{sc}, V_{oc}, I_m, V_m, Maximum efficiency.
- ✓ Derived the estimation of maximum power of a solar cell.
- ✓ Effect of variation of solar insolation and temperature on the characteristics of solar cell.
- ✓ Solar cell efficiency and band gap.

Thank you