Introduction to Renewable Energy Technologies

Lecture-17

Solar PV Cells and Modules

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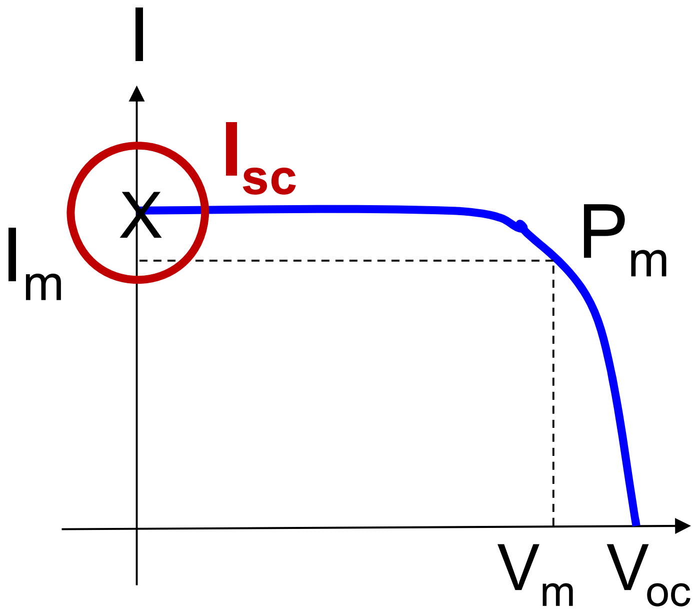
Recap of last lecture

- Solar cell structure and terminology
- Choice of anti - reflection coating
- Absorption probability
- I-V model of solar cell
- IQE: demonstration recombination

In this lecture

- Discuss about Short circuit potential and Open circuit voltage
- Explain the maximum power and efficiency of the solar cell
- Identifying the design and structure of Solar PV module
- I-V relationship of solar module
- Fabrication of solar module

Short-Circuit Current, I_{sc}

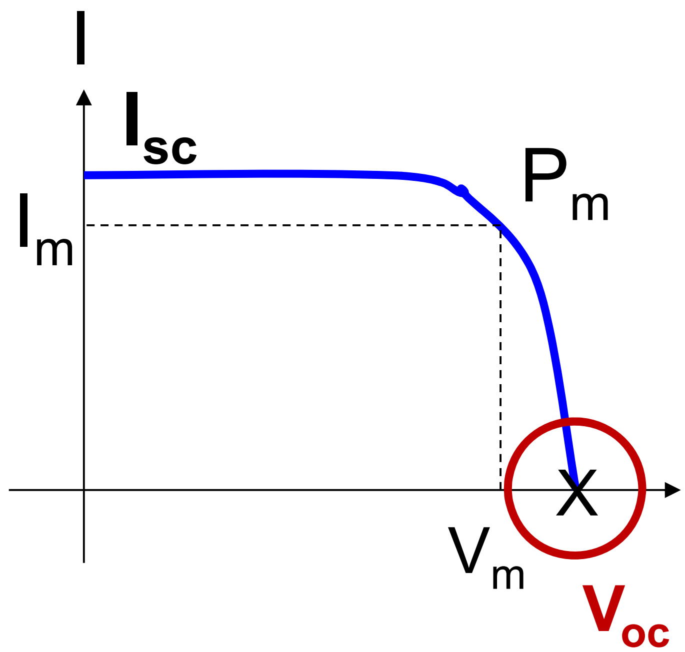


At V=0 → $I_{total} = -I_L = I_{sc}$

$$\boxed{I_{sc} = q\,A\,(W + L_p + L_n)}$$

- 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).
- The short-circuit current is due to the generation and collection of light-generated charge carriers.
- Short-circuit current is the largest current which may be drawn from the solar cell.

Open Circuit Voltage: V_{oc}

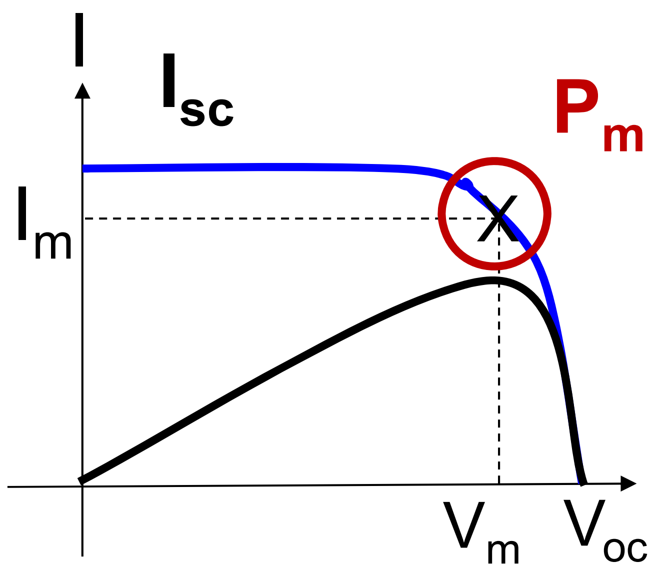


- The open-circuit voltage, V_{oc}, is the maximum voltage available from a solar cell, and this occurs at zero current.
- The open-circuit voltage corresponds to the amount of forward bias on the solar cell junction due to illumination.

by setting $I_{total} = 0$

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

Maximum power: P_m

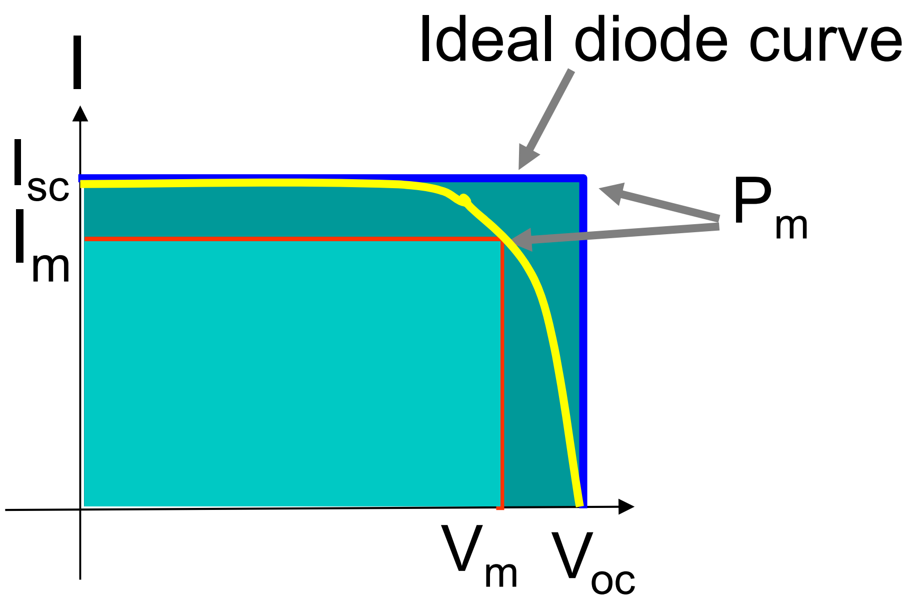


- Power out of a solar cell increases with voltage, reaches a maximum (P_m) and then decreases again.

$$\boxed{P_m = I_m \times V_m}$$

Remember we get DC power from a solar cell

Fill Factor: FF

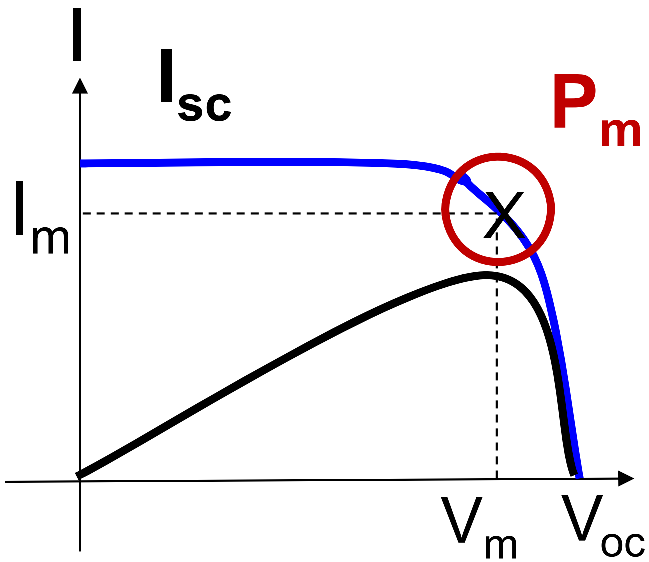


- The FF is defined as the ratio of the maximum power from the actual solar cell to the maximum power from a ideal solar cell

Graphically, the FF is a measure of the "squareness" of the solar cell

$$FF = \frac{Max\ \ power\ \ from\ real\ cell}{Max\ \ power\ \ from\ ideal\ cell} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

Efficiency: η



- Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

$$\eta = \frac{Max.\,Cell\ Power}{Incident\ light\ Intensity} = \frac{V_m I_m}{P_{in}}$$

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

- The efficiency is the most commonly used parameter to compare the performance of one solar cell to another.
- Efficiency of a cell also depends on the solar spectrum, intensity of sunlight and the temperature of the solar cell.

Typical industrial Si cell parameters

V_{oc} – 0.55 to 0.62V

I_{sc} – 33 to 37 mA/cm²

V_m = 0.8 to 0.9 of V_{oc}

I_m = 09 to 0.95 of I_{sc}

FF = 70 to 78%

Efficiency ??

Calculate the efficiency of a typical solar cell with the these parameters

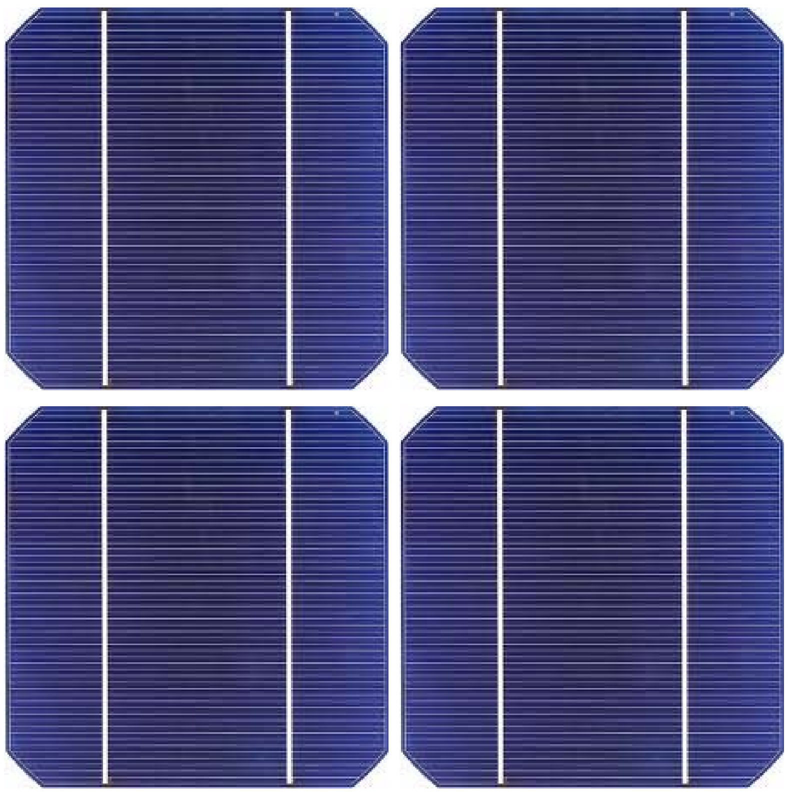
Solar PV Module

Solar PV module

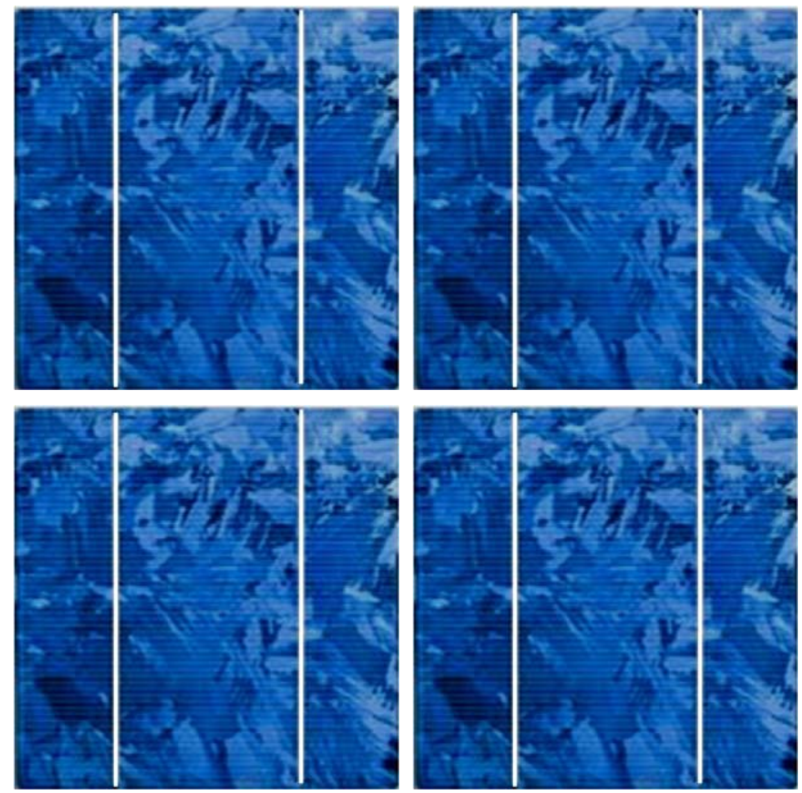
Different type of PV module

Identifying Solar PV Module

Closer look of arrangement of cells in PV modules



Monocrystalline PV module



Polycrystalline PV module

PV module

An array of several solar cells connected in series and parallel for getting larger power output

Inter connection of solar cells:

- **Thin film technology**: While process of manufacturing of solar cell
- **Wafer based technology**: Solar cells are manufactured first and then interconnected

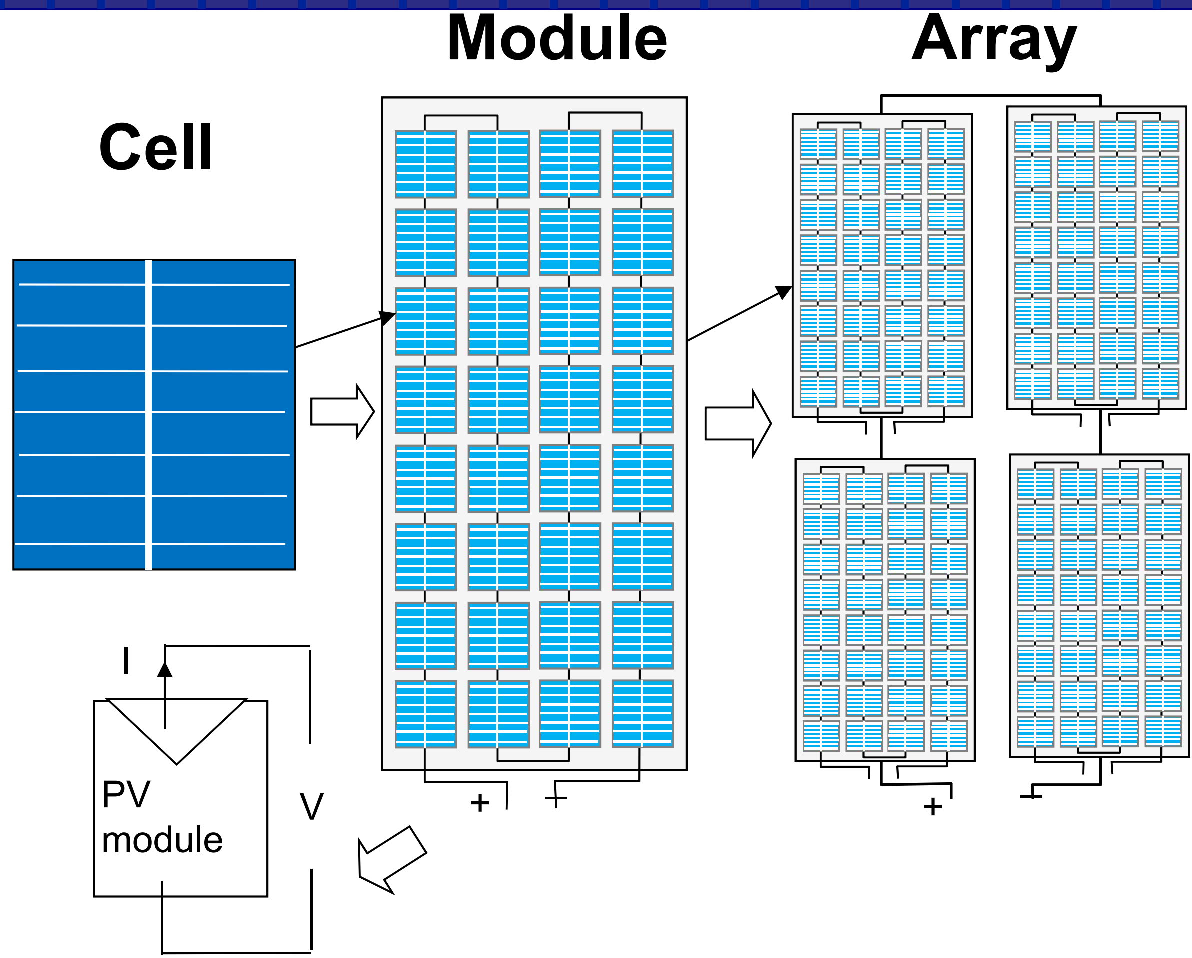
Power output:

- Power output per solar cell can be as small as 0.25 W_p (I= 1000 W/m^2 , Normal cell area- 15 x15=225 cm^2 ,Cell efficiency - 10 to 25%)
- This power is not enough for home lighting, water pumping applications.

PV module Power rating is from 3 W_p to 300 W_p .

Solar PV array

Solar PV array:
- Interconnected solar PV modules.
- Provide power of 100 **W** to several **MW.**

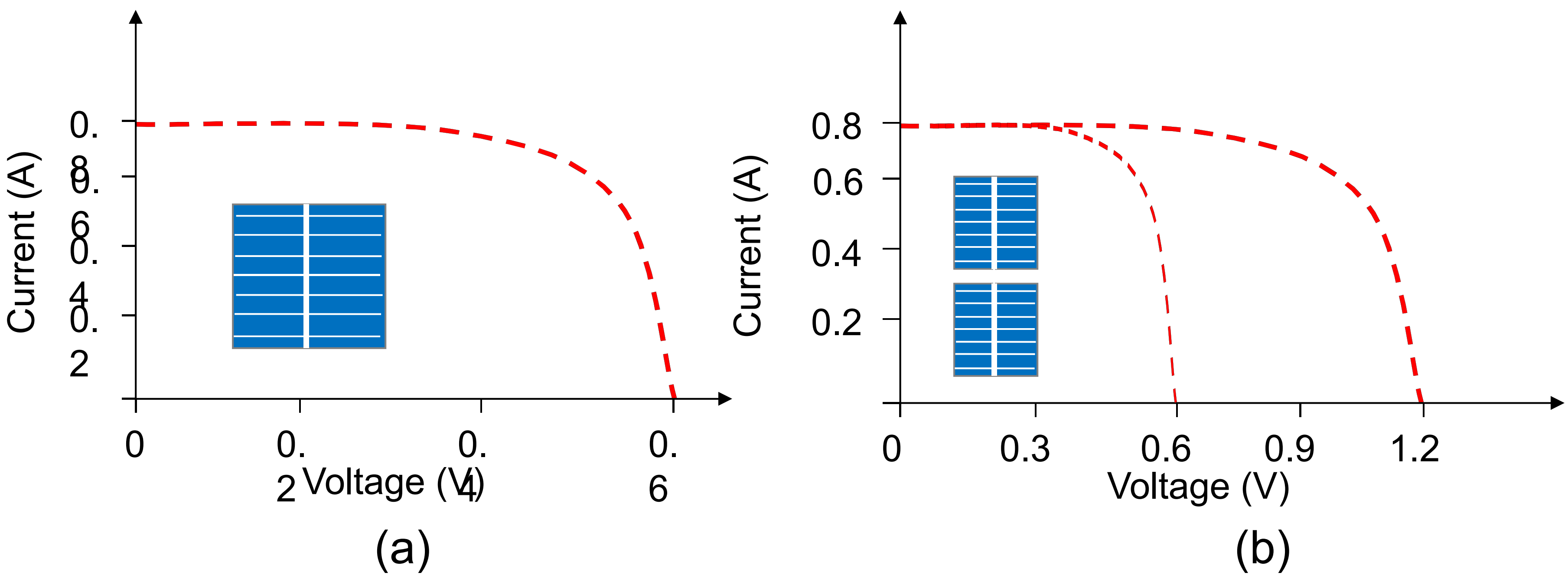


Interconnection of solar cells into solar PV modules and modules into solar PV arrays. Schematic representation of PV module is also shown.

Series and parallel connection of cells

Series connection

•Let us consider a solar cell having V_{oc} of 0.6 V and I_{sc} of 0.8 A.
When two identical cells are connected in series, the V_{oc} of the two cells will be added.
The I_{sc} will be the same as that of a single cell



I-V characteristics of identical solar cells (a) single cell, (b) two cells in series

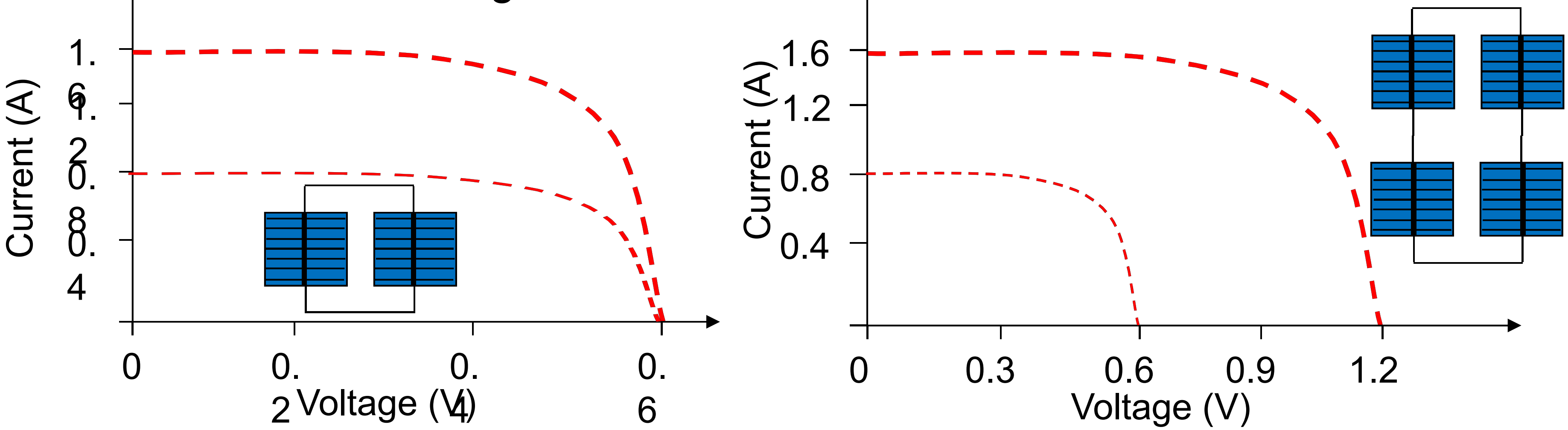
Series and parallel connection of cells

Parallel connection

- I_{sc} the two cells will be **added** .
- V_{oc} of the combination will remain **same** as that of single cell.

Series and Parallel Combination

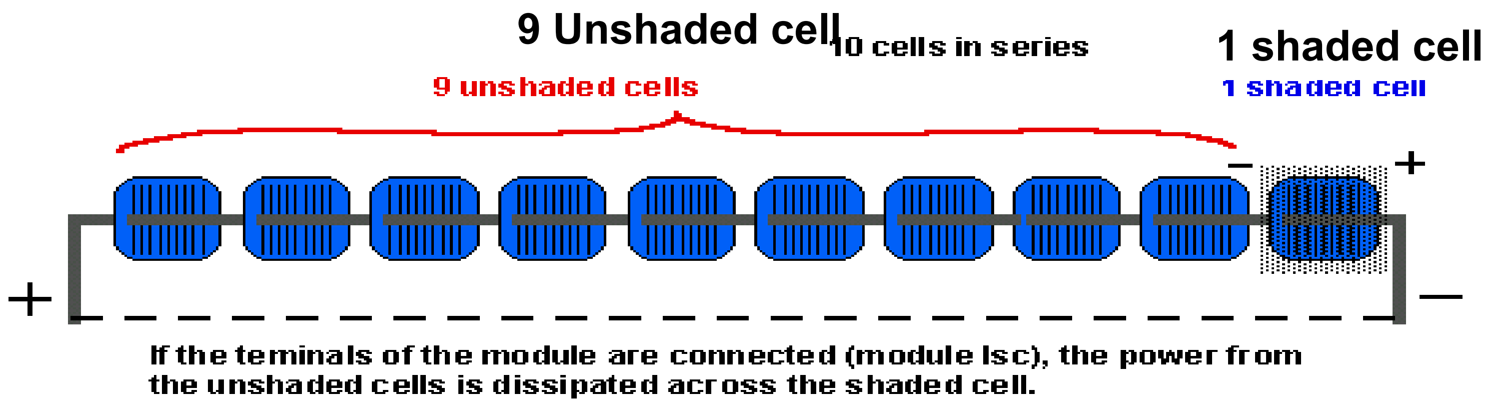
• When more than one series connected cells are connected in parallel,
more current and voltage will obtain



I-V characteristics of identical solar cells (a) two cell connected in parallel
(b) series and parallel combination of cells.

Hot-Spot Heating

Hot-spot heating occurs when there is one low current solar cell in a string of at least several high short-circuit current solar cells



One shaded cell in a string reduces the current through the good cells, causing the good cells to produce **higher voltages that can often reverse bias the bad cell**

→ Power gets dissipated in the "poor" cell

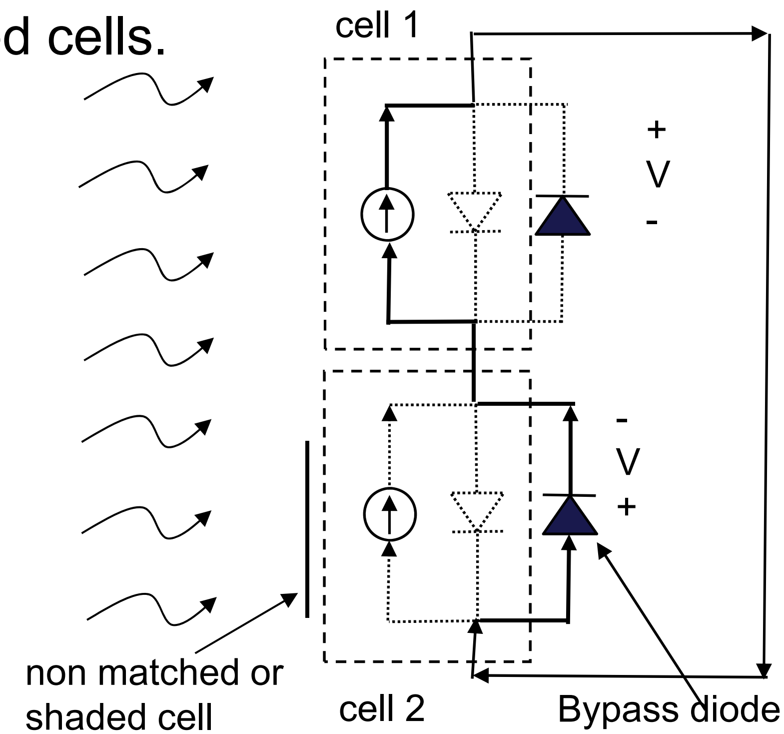
Local overheating, or "hot-spots", leads to destructive effects

→ Cell or glass cracking, melting of solder or degradation of the solar cell.

Bypass diode

Bypass diode is a diode which is used to avoid the destructive effect of hot spots
or local heating in series connected cells.

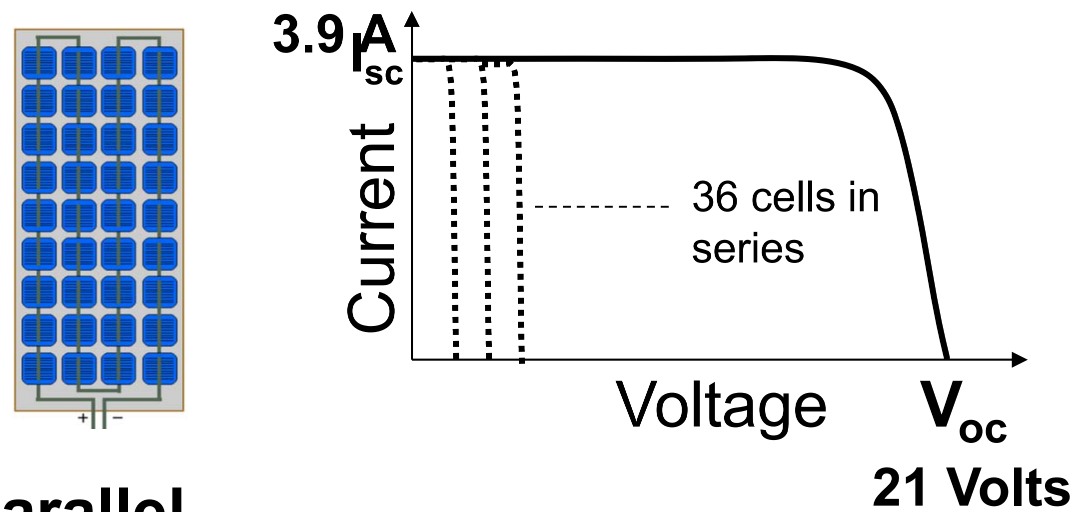
- ❑ Bypass diode, is connected in parallel with solar cells with opposite polarity
- ❑ In normal condition the bypass diode operates in reverse bias condition.
- ❑ If a series connected cell is shaded, reverse bias will appear across it
- ❑ This reverse bias will act as a forward bias for the bypass diode
- ❑ Extra current will be bypassed



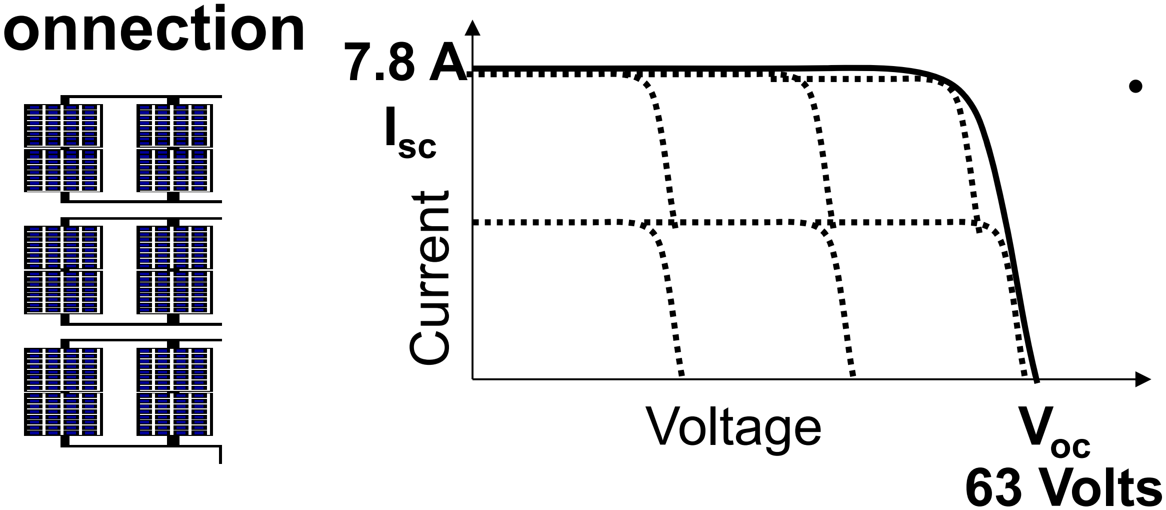
Placing of bypass diode in parallel with cells

Design and Structure of PV modules

Series Connection



Parallel Connection



- **Usually cell in module exhibits identical characteristics**
- Shape of the I-V curve of the module is same as that of cells with change in scale of axis
- I-V relationship for N cell in series and M cell in parallel

I-V relationship of modules

$$I = I_L - [I_o e^{q(V+IR_s)/nkT} - 1]$$

$$V = -IR_s + K\ln\left(\frac{I_L - I + I_o}{I_o}\right)$$

$$V_{mo} = -I_{mo}R_{smo} + K_{mo}\ln\left(\frac{I_{Lmo} - I_{mo} + I_{omo}}{I_{omo}}\right)$$

$$V_{mo} = -I_{mo}N_s R_s + N_s K\ln\left(\frac{I_L - I_{mo} + I_o}{I_o}\right)$$

$$V_{mo} = -I_{mo}\frac{R_s}{N_p} + K\ln\left(\frac{N_{sh}I_L - I_{mo} + N_p I_o}{N_p I_o}\right)$$

$$V_a = -I_a\frac{N_s R_s}{N_p} + N_s K\ln\left(\frac{N_{sh}I_L - I_a + N_p I_o}{N_p I_o}\right)$$

Similar to solar cell, I-V relationship for series connected and parallel connected modules can be written

Fabrication of PV modules

The cells should also be protected from dust, rain, mechanical shock etc. So the PV modules should package by using :

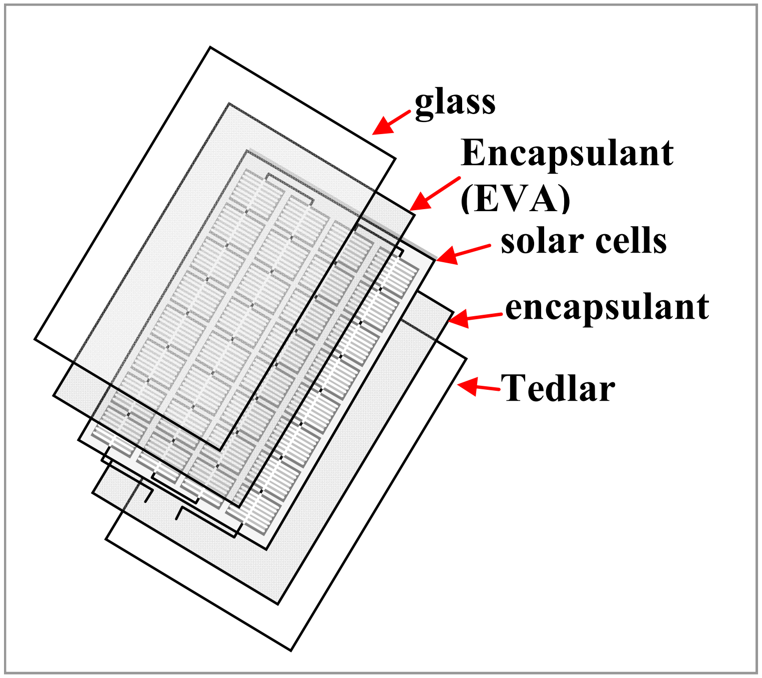
1. **Glass** at the front side
- Low iron content, toughened and textured Glass
- Higher transmitivity (over 90%)

2. **Ethylene vinyl acetate (EVA)** for encapsulation
- High electrical resistivity (10^{14} Ω-cm)
- Very low water absorption ratio
- Good optical transmission

3. **Solar cells** (array)

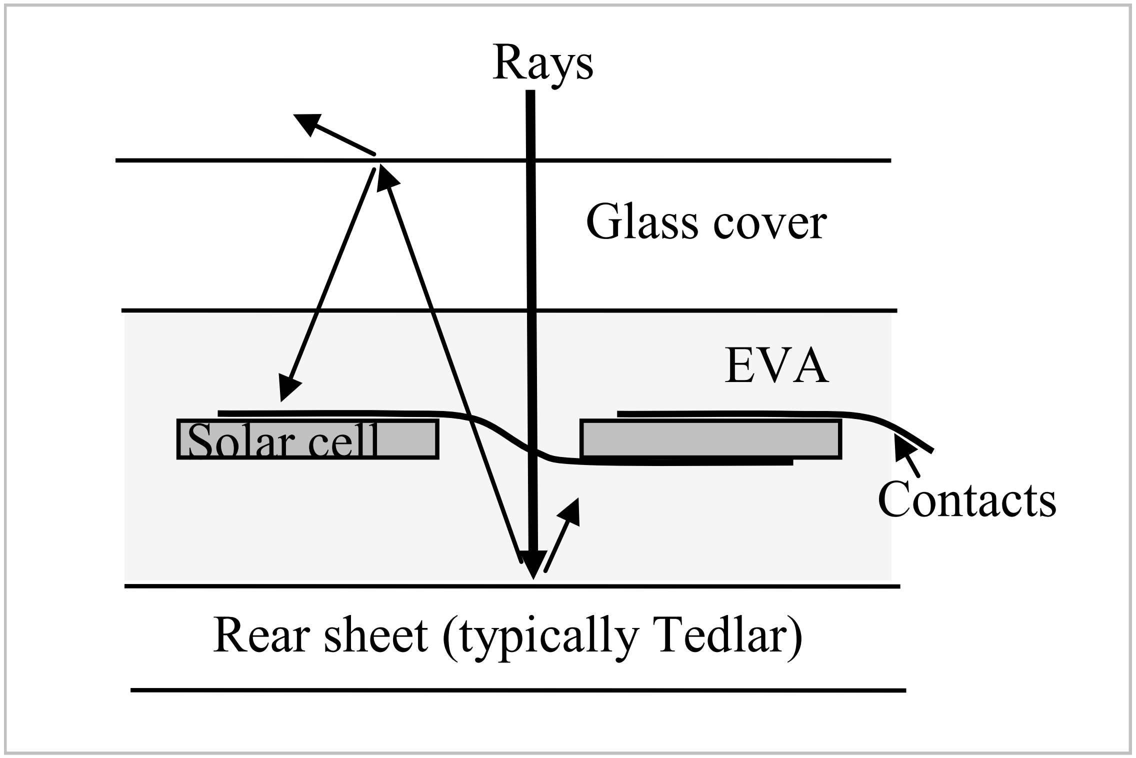
4. **Rear layer** (Tedlar – white colour)
- back reflection of light

5. **Outer frame** (**Al**)



Components of Si wafer based PV module.

Module Structure



Flow chart

Fabrication of PV modules

1. Cell sorting
2. Contact soldering at front side (tabbing)
3. Series interconnection of cells (stringing)
4. Preparing lamination assembly
5. Laminate curing and polymerization
6. Module Framing & external connection
7. Module I-V characterization

Flowchart of wafer based PV module fabrication showing steps from cell sorting till PV module characterization.

Packing density of PV modules

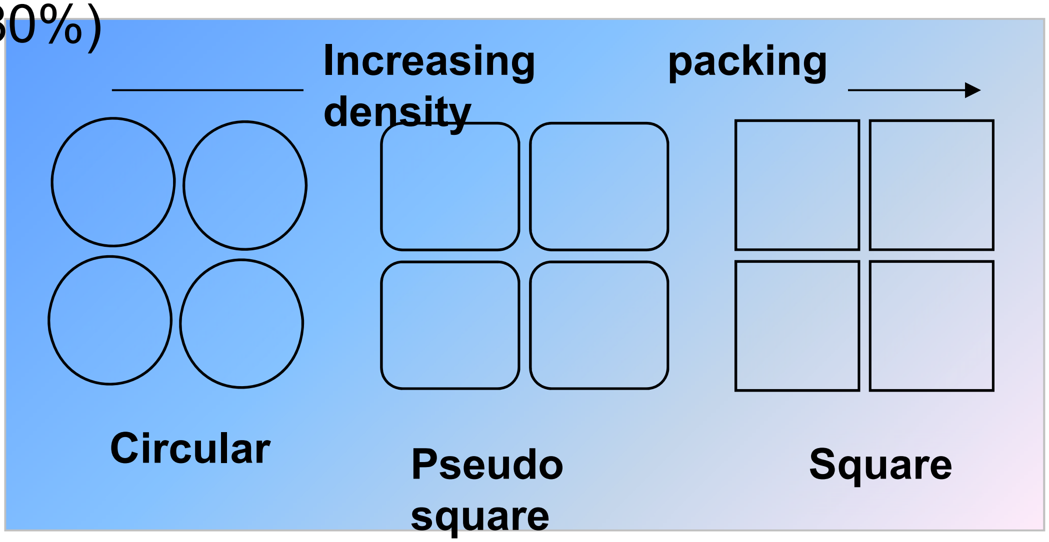
Packing density of a PV module is defined as the percentage of the cell area in the entire module area.

The **packing density** depends on the shape of the solar cells

- Circular solar cell (70%)
- Pseudo-square shaped cell (80%)
- Square solar cells (90%)

Packing density **affects**

- Output power of the module
- Operating temperature



Schematic demonstrating the packing density of cells based on their shape