RENEWABLE ENERGY TECHNOLOGY

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Photo-voltaic conversion of solar radiation

- The word Photovoltaic is a combination of the Greek word for Light and the name of the physicist Allesandro Volta.
- It identifies the direct conversion of sunlight into energy by means of solar cells.
- The conversion process is based on the photoelectric effect.
- The photoelectric effect describes the release of positive and negative charge carriers in a solid state when light strikes its surface.

Solar Cell

- Solar cells are devices that are designed to convert (at least a portion of) available light into electrical energy. They do this without the use of either chemical reactions or moving parts.
- Modern solar cells are based on semiconductor physics - they are basically just P-N junction photodiodes with a very large light-sensitive area. The photovoltaic effect, which causes the cell to convert light directly into electrical energy, occurs in the three energy-conversion layers.
- The first of these three layers necessary for energy conversion in a solar cell is the top junction layer (made of N-type semiconductor). The next layer in the structure is the core of the device; this is the absorber layer (the P-N junction). The last of the energy-conversion layers is the back junction layer (made of P-type semiconductor).

Photons

- **Photon:** A quantum of electromagnetic energy having both particle and wave properties.
- A photon has no electric charge or mass but posses momentum, energy and spin.
- All electromagnetic radiation, in vacuum, moves at the speed of light ($c = 3 \times 10^8$ m/s). The speed of the photons changes when they pass through different media, such as water, glass and air.
- In a metal, the atoms are anchored to fixed sites by the electrostatic forces due to all the other atoms. The outermost orbital electrons of the atoms are almost free, and move through the metal when an electric field is applied.
- It is known that if one shines a beam of light on a clean surface of a metal, electrons can escape from the metal surface and can be detected as electric current - **photoelectric effect.**
- The light has to exceed a certain energy to remove electrons from the metal surface. The number of electrons that escape in a given time rises with the light beam intensity.
- However, the energy with which they escape does not depend on the beam intensity, rather it depends on the frequency of light, v (in Hz). The energy E of each photon is proportional to frequency.

$$E=hv$$

- Where h is Planck's constant that is equal to 6.626 x 10-34 J s.

Semiconductor Materials and Doping

• A few semiconductor materials such as silicon (Si), cadmium sulphide (CdS) and gallium arsenide (GaAs) can be used to fabricate solar cells.

• Semiconductors are divided into two categories-intrinsic (pure) and extrinsic.

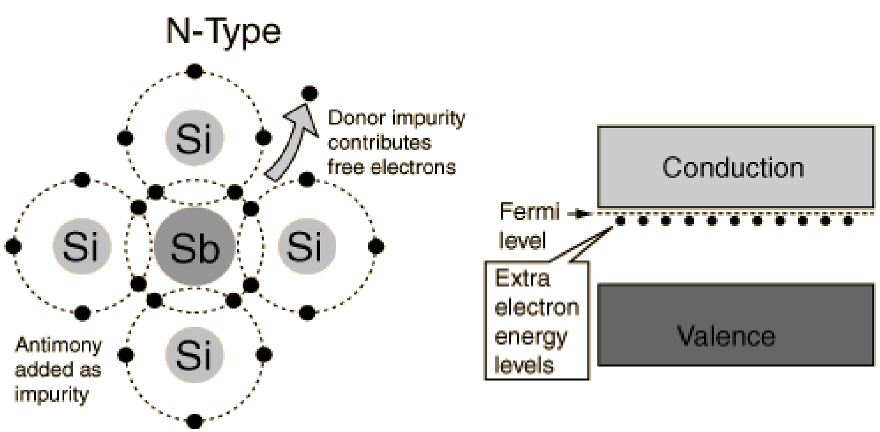
• An intrinsic semiconductor has negligible conductivity, which is of little use.

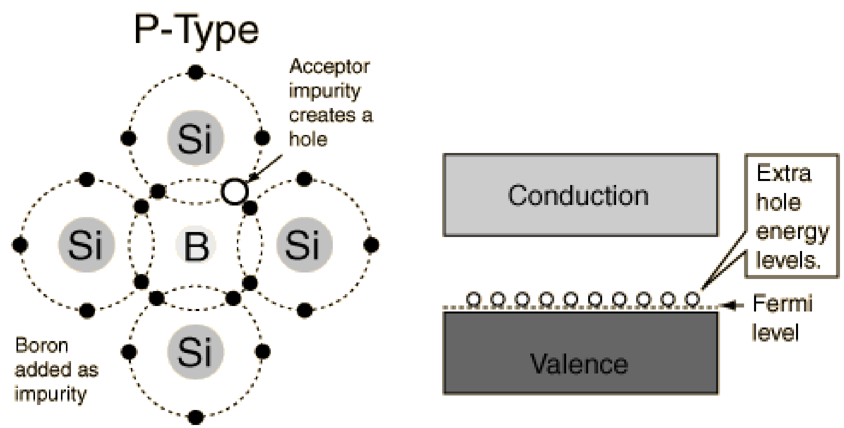
• To increase the conductivity of an intrinsic semiconductor, a controlled quantity of selected impurity atoms is added to it to obtain an extrinsic semiconductor. The process of adding the impurity atoms is called **doping.**

• In a pure semiconductor, electrons can stay in one of the two energy bands-the conduction band and the valence band.

• The conduction band has electrons at a higher energy level and is not fully occupied, while the valence band possesses electrons at a lower energy level but is fully occupied.

• The energy level of the electrons differs between the two bands and this difference is called the band gap energy, Eg.





Fermi Level

- The Fermi energy level, E_f is the energy position within the band gap from where a greater number of carriers, i.e. holes in p-type and electrons in n-type, get excited to become charge carriers.
- For an intrinsic semiconductor, the Fermi level exists at the mid-point of the energy gap.
- It moves closer to E_C (i.e. increases) in n-type semiconductors, similarly in a p-type semiconductor the Fermi level will lie close to E_V.

- In Figure, E_d represents the level of electrons from donor impurities, while in Figure E_a represents the level of excess holes provided by acceptor impurities. Thermal energy kT (k is Boltzmann's constant = 1.38 x 10^{-23} J/K and T is the absolute temperature) provides the energy differences ($E_C – E_d$) and ($E_a – E_v$) to excite the electrons.

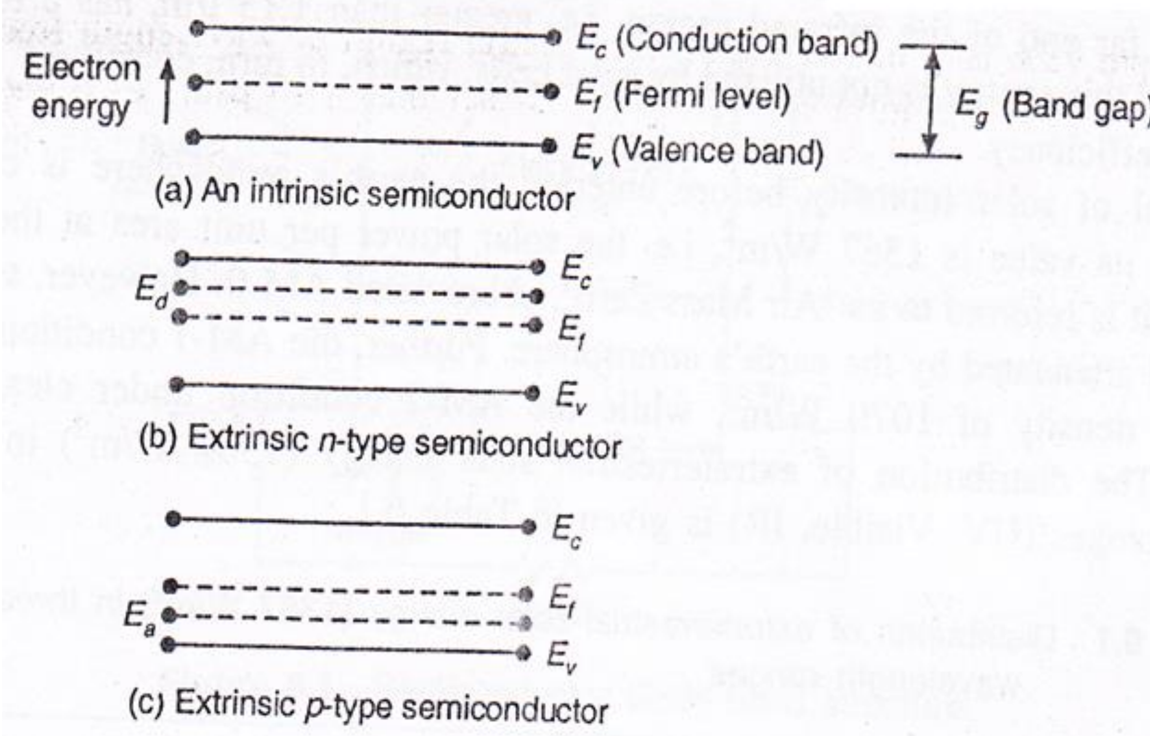
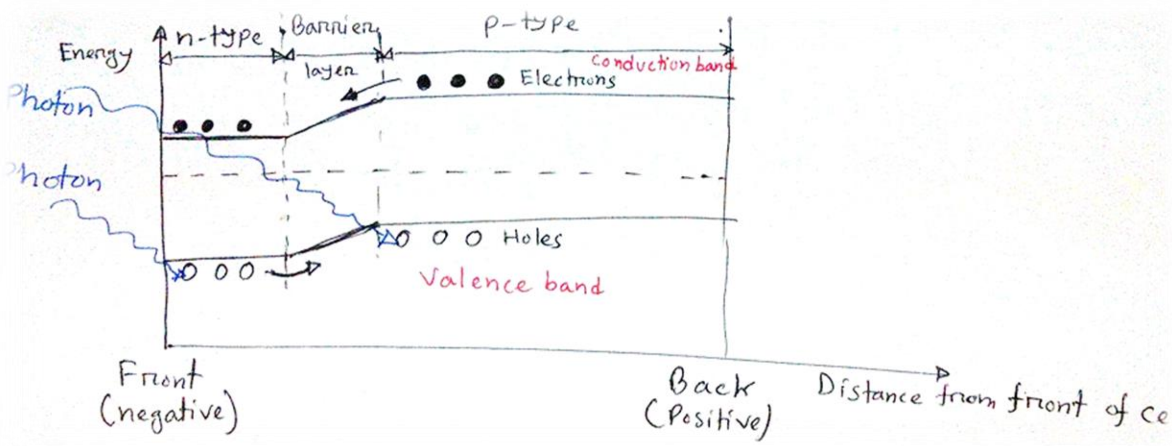


Figure Diagram of energy levels in semiconductors.

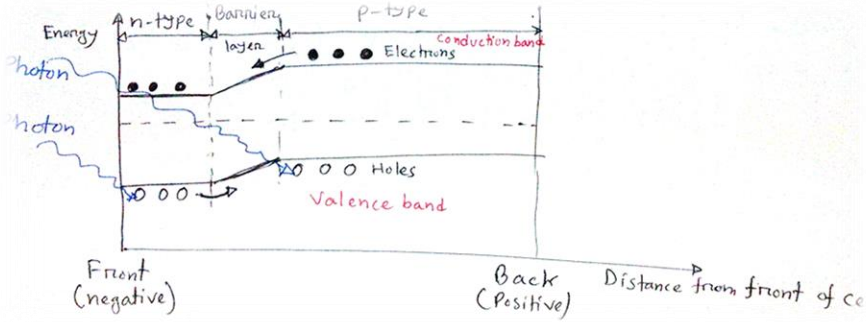
Principle of PV Energy Conversion

- When light falls on the front surface, photons with energy in excess of the energy gap (1.1 eV in crystalline silicon) interact with valance electrons and lift them to the conduction bond.
- This movement leaves behind holes, so each photon is said to generate an “electron-hole pain”. In crystalline silicon, electron-hole generation takes place throughout the thickness of the cell, in concentrations depending on the irradiance and the spectral composition of the light.
- The electrons and holes diffuse through the crystal in an effort to produce an even distribution. Some recombine after a lifetime of the order of one millisecond, neutralizing their charges and giving up energy in the form of heat.
- Others reach the junction before their lifetime has expired. There they are separated by the reverse field, the electrons being accelerated towards the negative contact and the holes towards the positive.
- If the cell is connected to a load, electrons will be pushed from the negative contact through the load to the positive contact, where they will recombine with holes. This constitutes an electric current.
- Another way of looking at the operation of a solar cell is to construct an energy diagram.



Principle of PV Energy Conversion (Contd.)

- In the n-region just below the front surface, the average energy of the charge carriers, called the "Fermi level" is near the top of the forbidden gap, with many electrons in the conduction band and few holes in the valance band.
- The opposite is true in the p-region, where the Fermi level is near the bottom of the forbidden gap.
- The laws of thermodynamics require that the Fermi level must be the same in both regions. SO, to satisfy this requirement, a potential barrier or reverse electric field is setup around the junction.
- Photon generated carriers (electrons and holes) which reach the barrier are separated by it.
- The electrons can be visualized as rolling down towards the negative contact on the front surface and the holes floating upwards and move towards the positive contact.



Photovoltaic Effect

- When a solar cell is illuminated, electron-hole pairs are generated and the electric current obtained I is the difference between the solar light generated current I_{ph} and the diode dark current, I_d.

$$I = I_{ph} - I_d$$

$$I = I_{ph} - I_0\left[e^{\left(eV_d/KT\right)} - 1\right]$$

where I_d is the diode current (A), V_d is the voltage (V) across the diode terminals from p-side to the n-side, Io is the reverse saturation current (A), e is the electron charge (1.602 x 10^{-19}C), k is Boltzmann's constant (1.381 x 10^{-23} J/K) and T is the junction temperature (K).

- **This phenomenon is known as the photovoltaic effect**

Construction of Solar Cell

Solar cells are constructed using various semiconductors. Semiconductors are materials, which become electrically conductive when supplied with light or heat, but which operate as insulators at low temperatures. Semiconductors are tetravalent materials.

Silicon is the most commonly used semiconductor, nowadays, but there are many others

Examples are:

Gallium Arsenide

Germanium

Selenium

Cuprous Oxide

Lead Telluride

Lead Sulfide

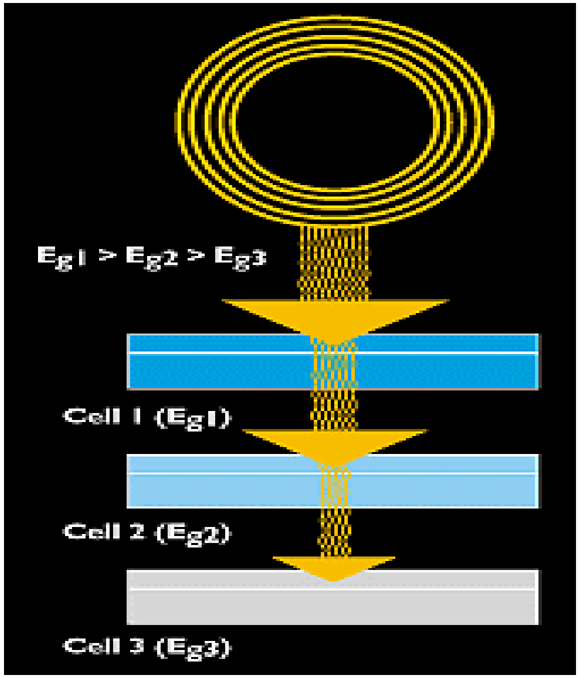
Silicon Carbide

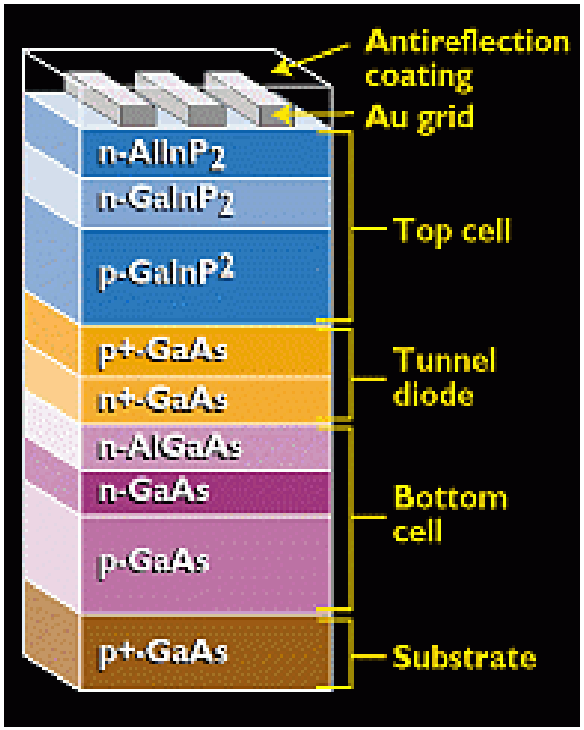
Cadmium Telluride

Indium Gallium Arsenide Nitride

Copper Indium Gallium Selenium

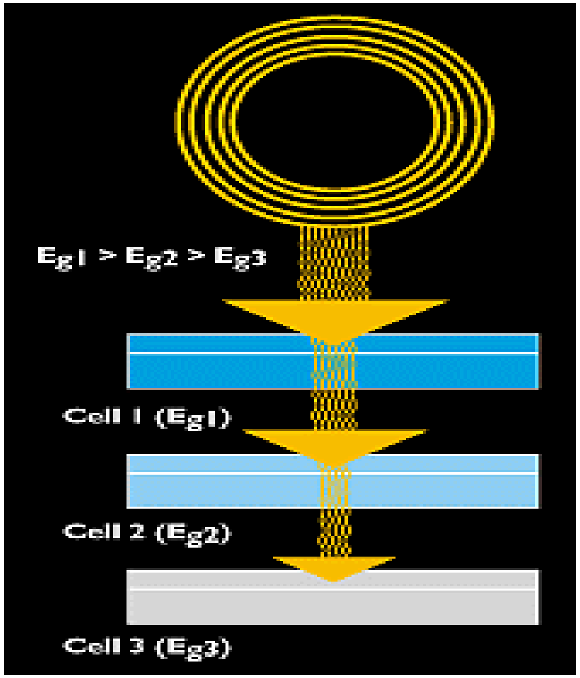
Solar Photovoltaic

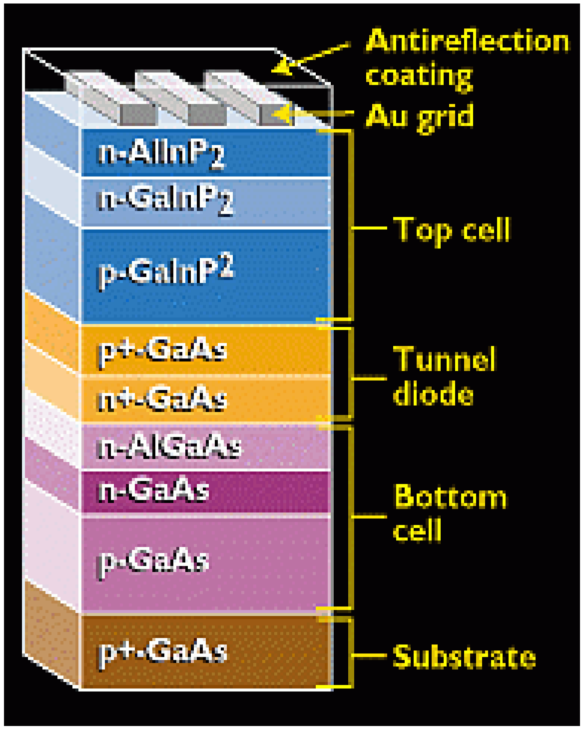




- Today's most common PV devices use a **single junction**, **or interface**, to create an electric field within a **semiconductor.**
- **In a single-junction semi conductor PV cell, only photons whose energy is equal to or greater than the band gap (Eg) of the cell material can free an electron for an electric circuit.**
- In other words, the photovoltaic response of single-junction cells is limited to the portion of the **sun's spectrum whose energy** is above the band gap of the absorbing material, and **lower-energy photons are not used**.

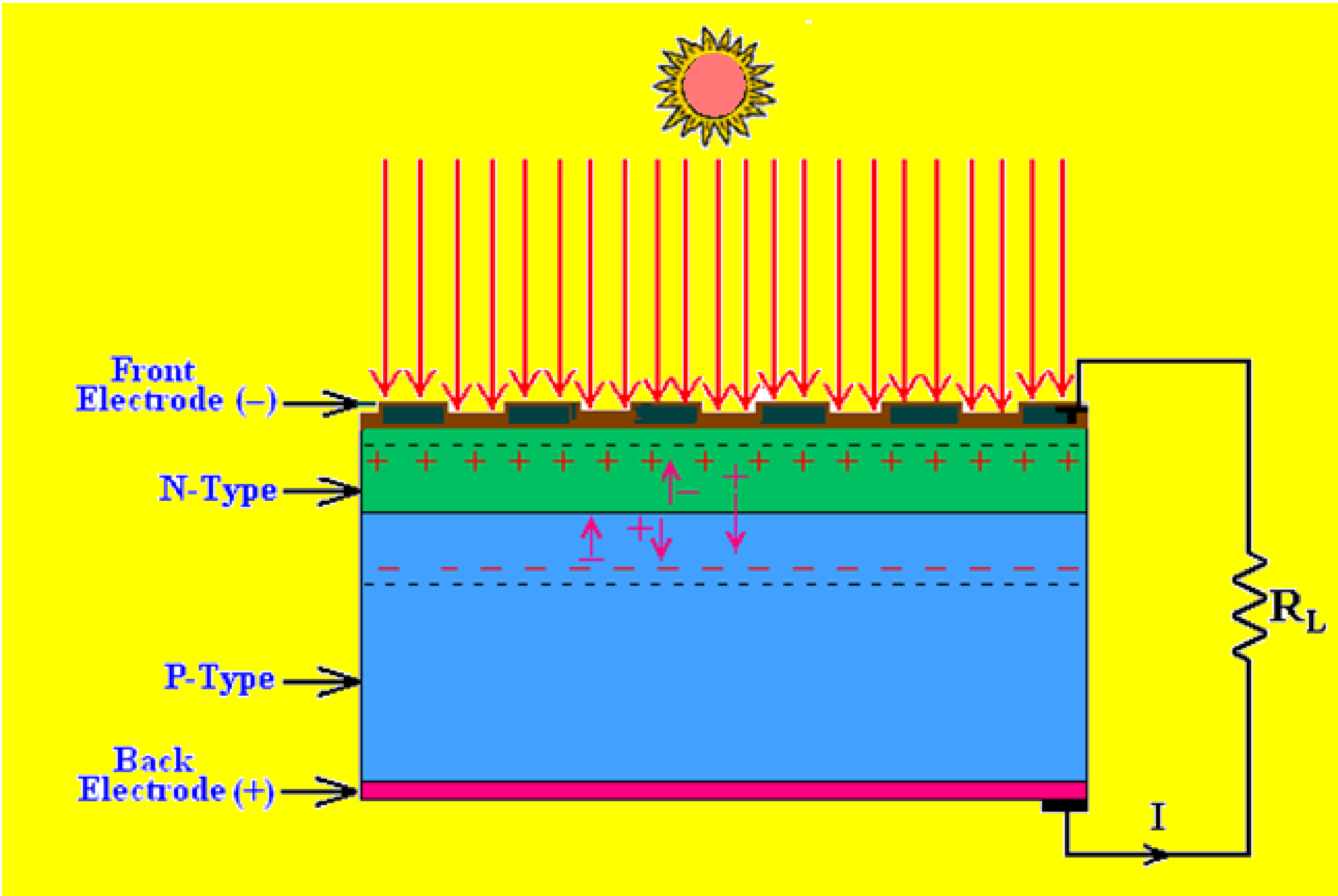
Solar Photovoltaic





- One way to get around this limitation is to use **two (or more) different cells**, with more than one **band gap** and **more than one junction**, to generate a voltage.
- These are referred to as "**Multi-Junction**" cells (also called "cascade" or "tandem" cells).
- Multi-Junction devices can achieve a **higher total conversion efficiency** because they can convert more of the energy spectrum of light to electricity.
- As shown in the left, a Multi-Junction device is a stack of individual single-junction cells in descending order of **band gap (Eg)**.
- The **top cell** captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells.
- Much of today's research in Multi-Junction cells focuses on **Gallium Arsenide** as one (or all) of the component cells. Such cells have reached efficiencies of around 35% under concentrated sunlight.
- Other materials studied for Multi-Junction devices have been Amorphous Silicon and Copper Indium Diselenide.

- Silicon solar cells are approximately 10 cm by 10 cm large.
- A transparent anti-reflection film on the top layer of the cell is used to protect reflection losses from the cell surface.
- A silicon solar cell produces 0.5 V approximately.
- A 100 cm² silicon cell, for example, generates a maximum current of approximately 2 A when projected with solar radiation of 1000 W/m².



Photovoltaic cell

Types of PV Technology

- <u>1st Generation</u>
  - **Monocrystalline**

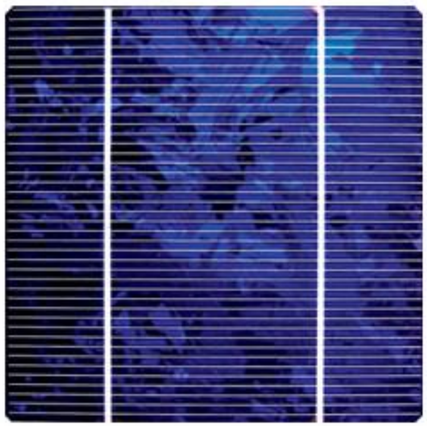
    Cells are cut from single crystals of high purity electronics grade silicon. These cells are about 25 percent efficient at best. Efficiencies may be only about15% or 16% due to the effect of grain boundaries or impurities

  - **Polycrystalline**

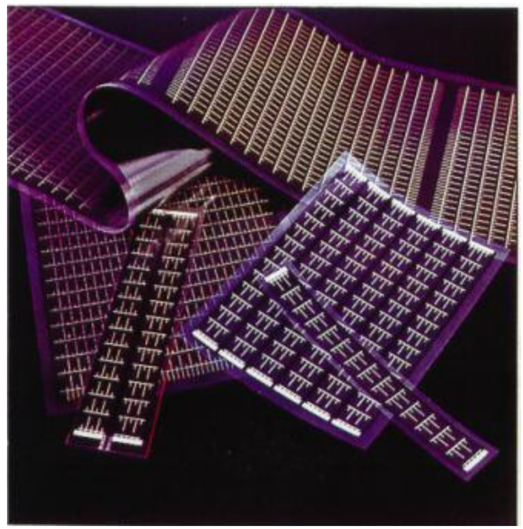
    Made from various crystallites which are melted together. Average efficiencies of around 15%

- <u>2nd Generation</u>
  - **Thin film technology**
    - Amorphous Silicon
    - Copper indium gallium diselenide (CIGS) (max 19.9%)
    - Cadmium telluride (CdTe)
- <u>3rd Generation</u>
  - **Nano PV**

Monocrystalline

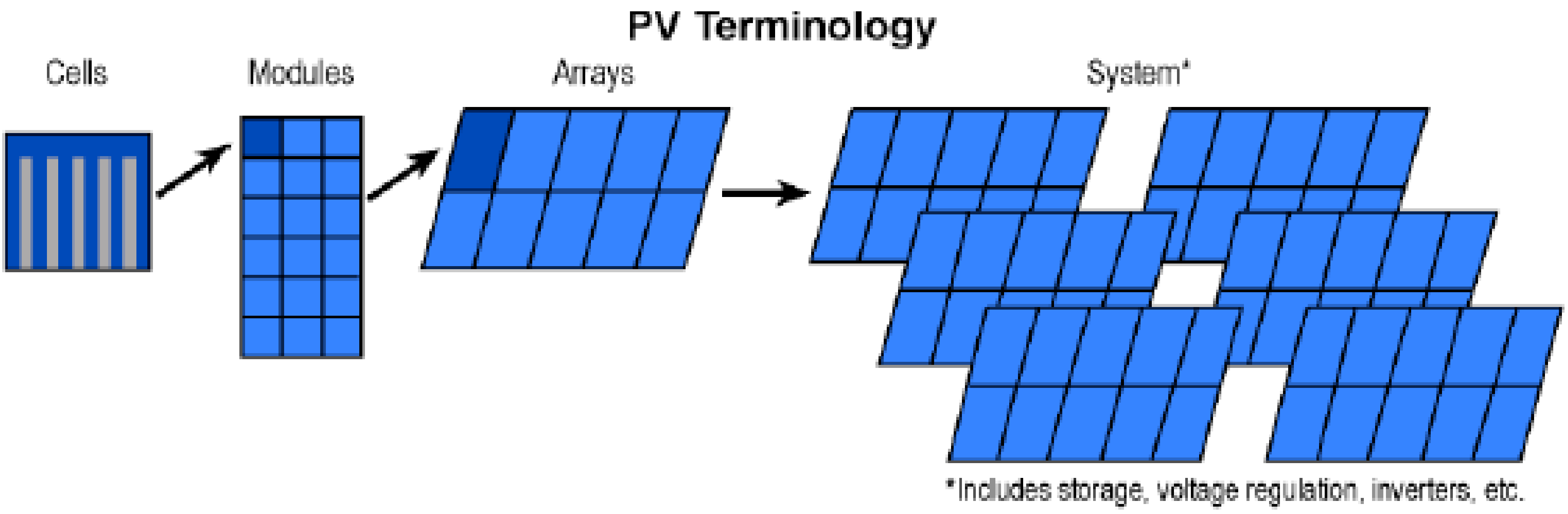


Polycrystalline



Amorphous/thin film

PV Panel


PV Terminology
Cells
Modules
Arrays
System*
*Includes storage, voltage regulation, inverters, etc.

Complete Equivalent Circuit of a Solar Cell

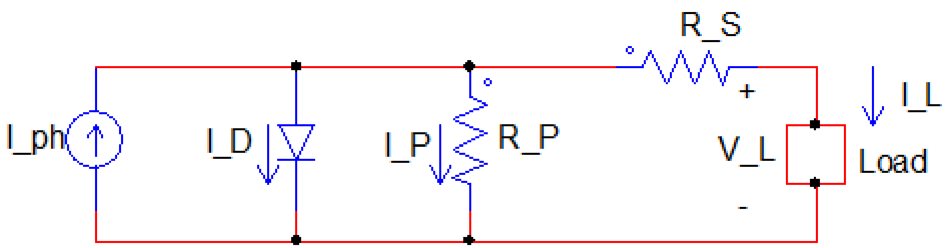
- Recombination path contains some resistance, R_P
- From Si to metal contact, there are some internal resistance, R_S

R_P
- Created in the junction
- Represent the direction of recombination current

R_S
- Created in the contact of cell

$R_P >> R_S$

R_P and R_S affects the shape of the I-V characteristic curve



$$I_L = I_{ph} - I_D - I_p$$

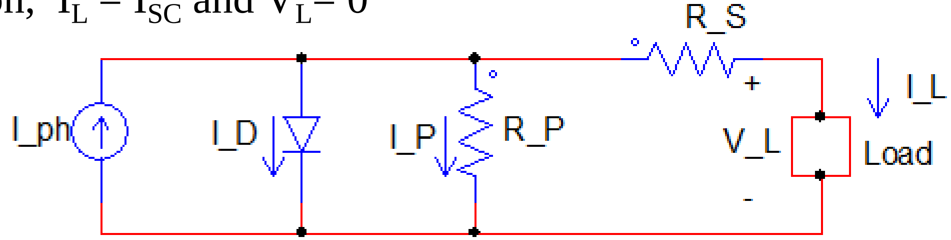
$$I_L = I_{ph} - I_0\left(e^{\frac{qV_D}{KT}} - 1\right) - \frac{V_D}{R_P}$$

$$I_L = I_{ph} - I_0\left(e^{AV_D} - 1\right) - \frac{V_D}{R_P} \qquad \left[A = \frac{q}{KT}\right]$$

$$\boldsymbol{I_L = I_{ph} - I_0\left(e^{A(V_L + I_L R_s)} - 1\right) - \frac{V_L + I_L R_s}{R_P}}$$

Short-circuit Current I_{SC} of a solar cell

- At short-circuit condition, $I_L = I_{SC}$ and $V_L = 0$



$$I_L = I_{SC} = I_{ph} - I_0\left(e^{AI_{SC}R_s} - 1\right) - \frac{I_{SC}R_s}{R_P}$$

$$\mathbf{I_{SC} = I_{ph} - I_0\left(e^{\frac{qI_{SC}R_s}{KT}} - 1\right) - \frac{I_{SC}R_s}{R_P}}$$

Open-circuit Voltage V_{OC} of a solar cell

- At open-circuit condition, $I_L = 0$ and $V_L = V_{OC}$

$$0 = I_{ph} - I_0\left(e^{A\,V_{OC}} - 1\right) - \frac{V_{OC}}{R_P}$$

$$I_0\left(e^{A\,V_{OC}} - 1\right) = I_{ph} - \frac{V_{OC}}{R_P}$$

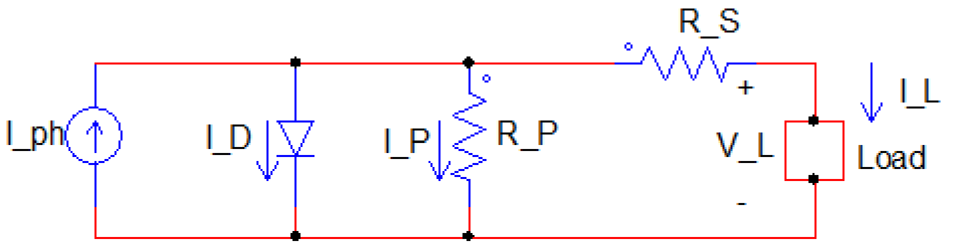
$$\left(e^{A\,V_{OC}} - 1\right) = \frac{I_{ph}}{I_0} - \frac{V_{OC}}{I_0R_P}$$

$$e^{A\,V_{OC}} = \frac{I_{ph}}{I_0} - \frac{V_{OC}}{I_0R_P} + 1$$

$$\boldsymbol{V_{OC} = \frac{KT}{q}\,ln\left(\frac{I_{ph}}{I_0} - \frac{V_{OC}}{I_0R_P} + 1\right)}$$

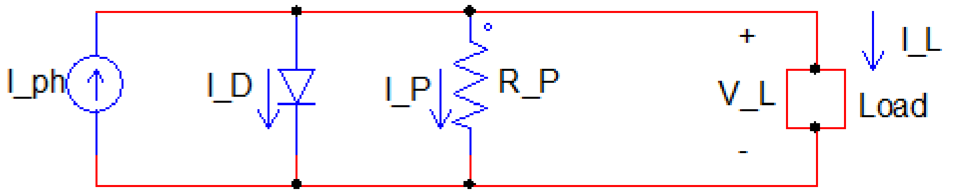
Simplified Equivalent Circuit of a Solar Cell

As $R_P >> R_S$



$$I_L = I_{ph} - I_0\left(e^{A(V_L + I_L R_s)} - 1\right) - \frac{V_L + I_L R_s}{R_P}$$

So, R_S can be neglected for simplification

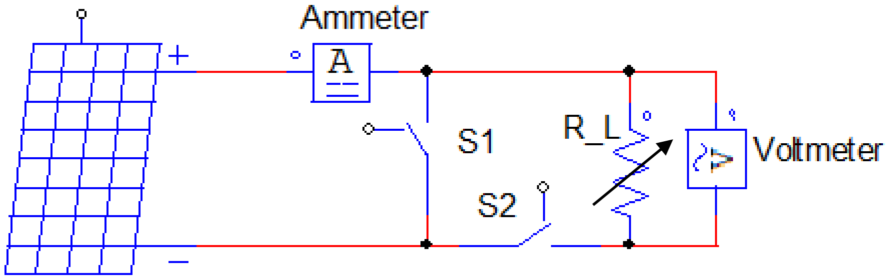


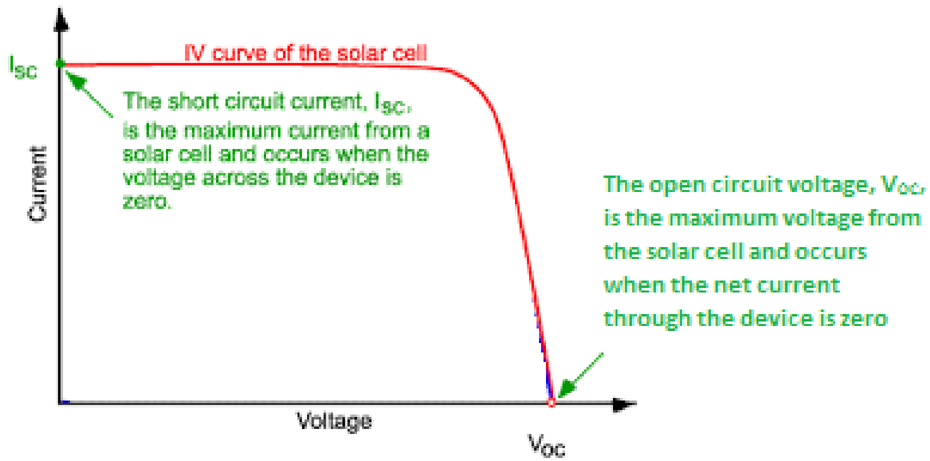
$$I_L = I_{ph} - I_0\left(e^{AV_L} - 1\right) - \frac{V_L}{R_P}$$

Determination of I-V characteristics curve

Method 1:

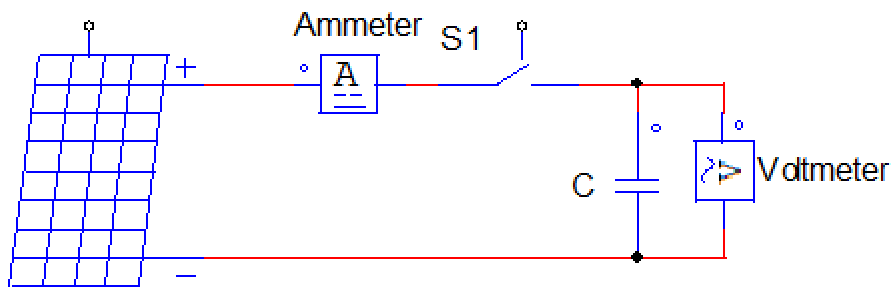
- Initially, S1 and S2 are open, measure open circuit voltage and current. i.e. $I_L = 0$ and $V_L = V_{OC}$
- Close S2 and measure current and voltage using ammeter and voltmeter while varying R_L
- Finally, Close S1 for a short period of time and record voltage and current. This will provide short circuit voltage and current. i.e. $I_L = I_{SC}$ and $V_L = 0$





Method 2:

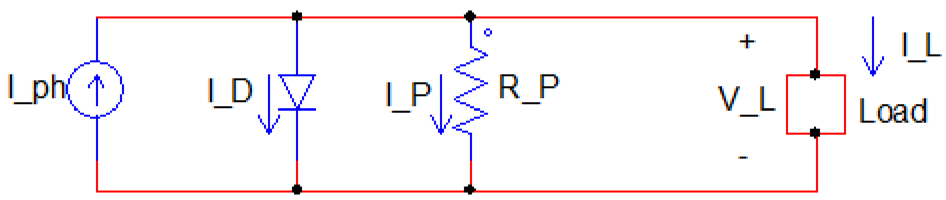
- S1 is closed
- Initially capacitor acts as short circuit path hence I_{SC} can be recorded.
- As the charge of capacitor increases, current decreases

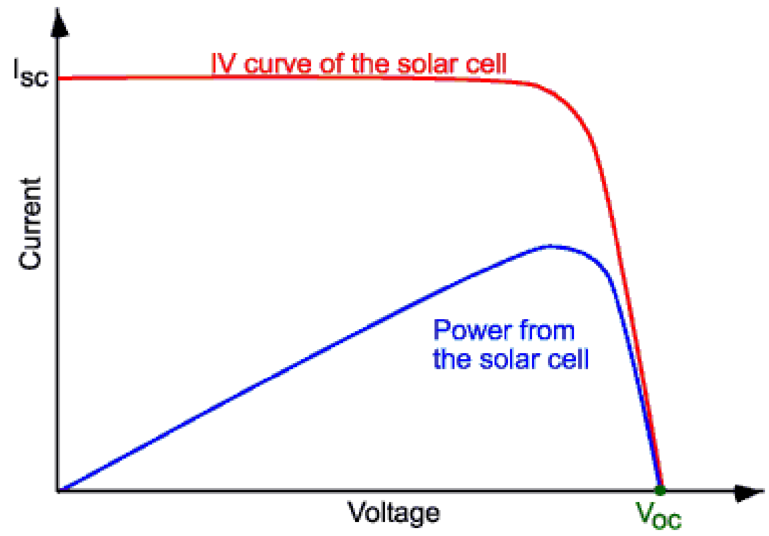


- Continuous data logger is used to record and store the corresponding voltage and current as capacitor's charge increases.
- When capacitor is fully charge, it behaves like open circuit i.e. $V_C = V_{OC}$

Solar radiation must be constant throughout the experiment of both methods

Maximum Power Point (MPP) of a solar cell





$$P_L = V_L I_L$$

$$= V_L\left[I_{ph} - I_0\left(e^{\frac{qV_L}{KT}} - 1\right)\right]$$

$$= V_L I_{ph} - V_L I_0\left(e^{\frac{qV_L}{KT}} - 1\right)$$

$$= V_L I_{ph} - V_L I_0 e^{\frac{qV_L}{KT}} - V_L I_0$$

For maximum Power,

$$\frac{dP_L}{dV_L} = 0 = I_{ph} + I_0 - I_0\left[V_L \times \frac{q}{KT} e^{\frac{qV_{mpp}}{KT}} + e^{\frac{qV_{mpp}}{KT}}\right]$$

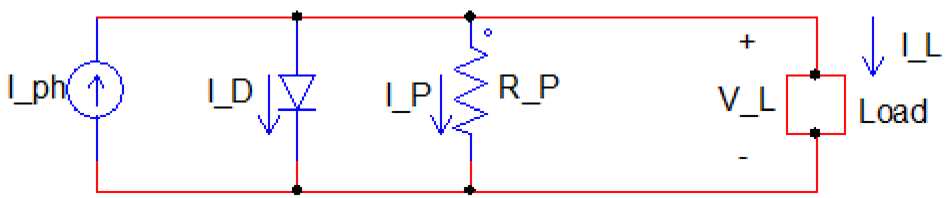
$$0 = I_{ph} + I_0 - I_0 e^{\frac{qV_{mpp}}{KT}}\left[1 + V_{mpp} \times \frac{q}{KT}\right]$$

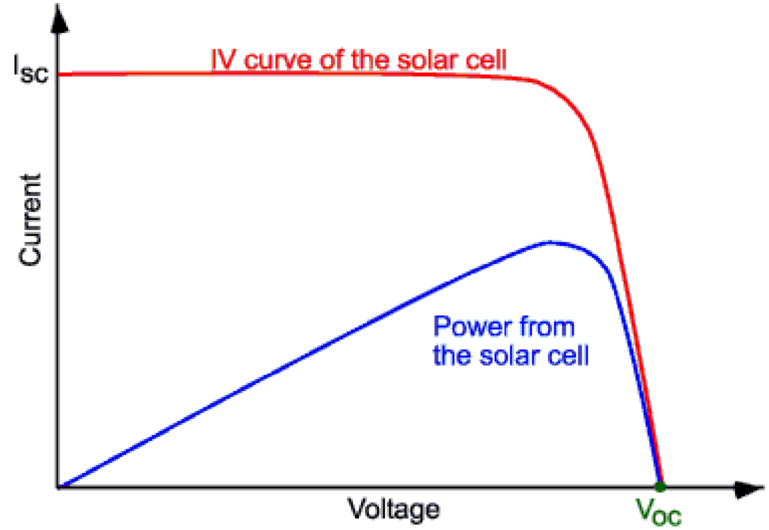
Or, $$I_0 e^{\frac{qV_{mpp}}{KT}}\left[1 + \frac{qV_{mpp}}{KT}\right] = I_{ph} + I_0$$

Or, $$e^{\frac{qV_{mpp}}{KT}}\left[1 + \frac{qV_{mpp}}{KT}\right] = 1 + \frac{I_{ph}}{I_0}$$

$$e^{\frac{qV_{mpp}}{KT}} = \frac{\left[1 + \frac{I_{ph}}{I_0}\right]}{\left[1 + \frac{qV_{mpp}}{KT}\right]}$$

Maximum Power Point (MPP) of a solar cell (Contd.)





Again,

$$I_{mpp} = I_{ph} - I_0\left(e^{\frac{qV_{mpp}}{KT}} - 1\right)$$

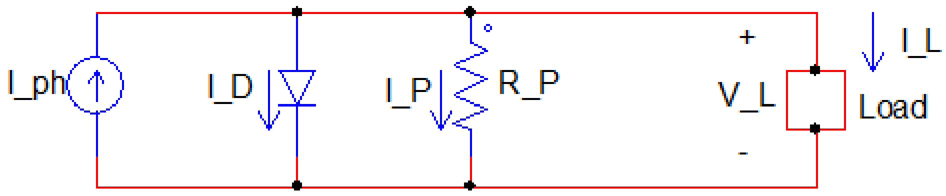
$$= I_{ph} - I_0\left(\frac{\left[1+\frac{\mathrm{I_{ph}}}{\mathrm{I_0}}\right]}{\left[1+\frac{\mathrm{qV_{mpp}}}{\mathrm{KT}}\right]} - 1\right)$$

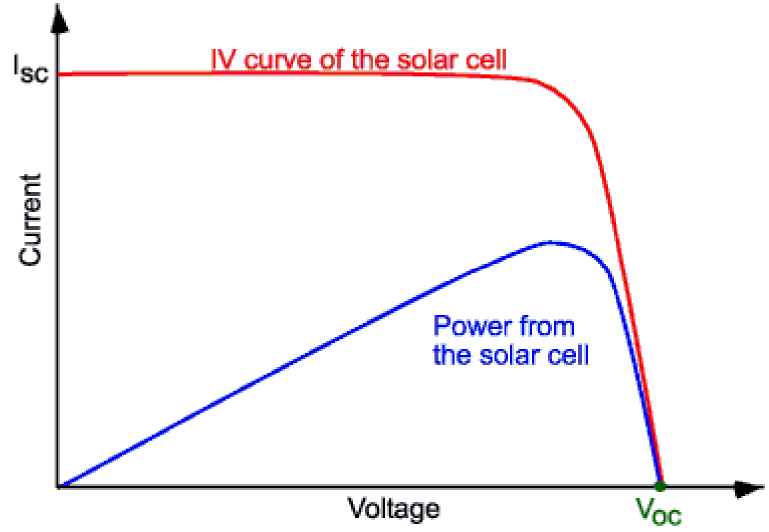
$$= I_{ph} + I_0 - \frac{\mathrm{I_0 + I_{ph}}}{\left[1+\frac{\mathrm{qV_{mpp}}}{\mathrm{KT}}\right]}$$

$$= \left(I_{ph} + I_0\right)\left(1 - \frac{1}{\left[1+\frac{\mathrm{qV_{mpp}}}{\mathrm{KT}}\right]}\right)$$

$$= \left(I_{ph} + I_0\right)\left(1 - \frac{\mathrm{KT}}{KT + \mathrm{qV_{mpp}}}\right)$$

Maximum Power Point (MPP) of a solar cell (Contd.)





$$= (I_{ph} + I_0)\left(\frac{KT + \mathrm{qV_{mpp}} - \mathrm{KT}}{KT + \mathrm{qV_{mpp}}}\right)$$

$$= (I_{ph} + I_0)\left(\frac{\mathrm{qV_{mpp}}}{KT + \mathrm{qV_{mpp}}}\right)$$

$$= (I_{ph} + I_0)\left(\frac{1}{1 + \frac{KT}{\mathrm{qV_{mpp}}}}\right)$$

$$\boxed{I_{mpp} = \left(\frac{I_{ph} + I_0}{1 + \frac{KT}{\mathrm{qV_{mpp}}}}\right)}$$

$$P_{max} = V_{mpp} I_{mpp} = V_{mpp}\left(\frac{I_{ph} + I_0}{1 + \frac{KT}{\mathrm{qV_{mpp}}}}\right)$$

Neglecting I_0,

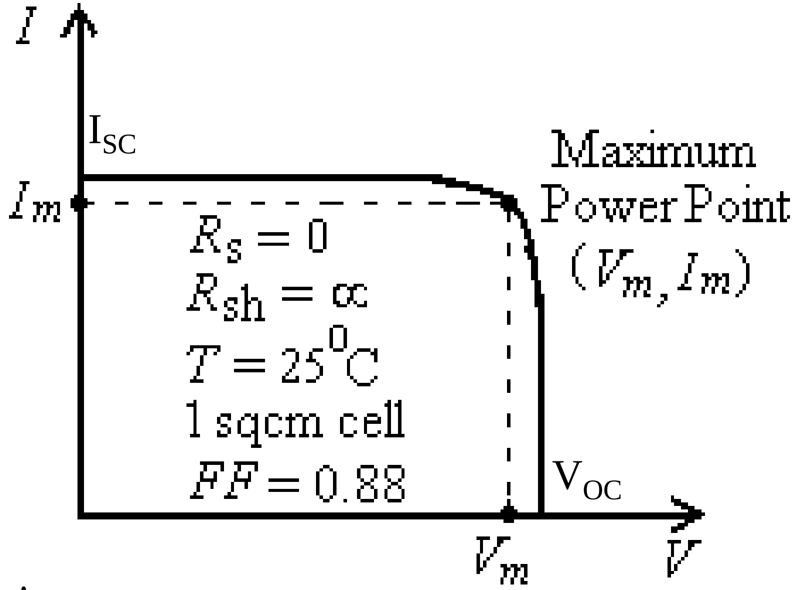
$$P_{max} = \left(\frac{I_{ph} V_{mpp}}{1 + \frac{KT}{\mathrm{qV_{mpp}}}}\right) \Rightarrow \boxed{P_{max} = \left(\frac{q I_{ph} V_{mpp}^2}{\mathrm{qV_{mpp}} + KT}\right)}$$

Fill Factor (FF):

PV cell quality is maximum when the value of "fill factor" approached to unity, where the Fill Factor (FF) is expressed as

$$\text{Fill Factor (FF)} = \frac{\text{Area Enclosed by } V_{mpp} \text{ and } I_{mpp}}{\text{Area Enclosed by } V_{OC} \text{ and } I_{SC}}$$

$$FF = \frac{V_m I_m}{V_{OC} I_{SC}}$$



where V_m = voltage at maximum power point

I_m = current at maximum power point

V_{OC} = open circuit voltage of the cell

I_{SC} = short circuit current of the cell & FF = fill-factor

- A good quality PV panel has fill factor in the range of 0.7 to 0.8

Efficiency of the Cell:

Defined as the ratio of peak power to input solar power.

$$\eta = \frac{V_{mpp} \ \ I_{mpp}}{I\left(\frac{kW}{m^2}\right) A(m^2)}$$

Series Resistance and Shunt Resistance

In practice a cell has series and shunt resistances. The total series resistance and shunt resistance of a cell are denoted by R_S and R_{SH} respectively.

Series resistance: The series resistance consists of

(i) R_1 =Resistance of the bus bar

(ii) R_2 =Resistance of the grid finger

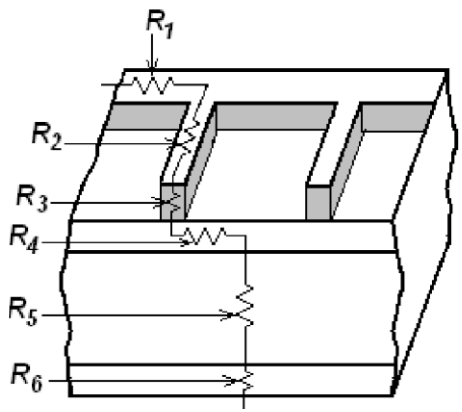
(iii) R_3 =Resistance due to front contact

(iv) R_4 =Resistance of the top or diffuse layer (n-type)

(v) R_5 =Resistance of the base layer (bulk)

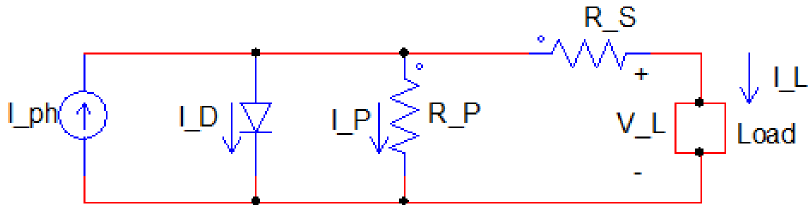
(vi) R_6 =Resistance due to back contact

The different components of the series resistance are shown in following figure.



Series Resistance and Shunt Resistance

Shunt resistance: Besides, the series resistance, the cell may have a shunt resistance R_P due to various leakage paths. The equivalent circuit diagram of a solar cell with series and shunt resistance is given in following figure.



Effect of Series and Shunt resistance on the IV curve

Increase in series resistance R_S causes:

(i) The IV curve of the cell to depart further inward from its rectangular nature as shown in figure below.

(ii) The decrease in power output

(iii) The decrease in fill factor

(iv) The decrease in short-circuit current, I_{SC} as the equation of short circuit is follows

$$\mathbf{I_{SC} = I_{ph} - I_0\left(e^{\frac{qI_{SC}R_s}{KT}} - 1\right) - \frac{I_{SC}R_s}{R_P}}$$

(v) But no effect on open circuit voltage, V_{OC} as the equation of open circuit voltage is follows

$$V_{OC} = \frac{KT}{q}\, ln\left(\frac{I_{ph}}{I_0} - \frac{V_{OC}}{I_0 R_P} + 1\right)$$

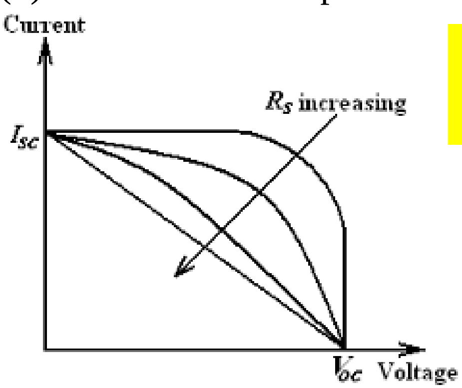


Fig. Effect of increase in series resistance

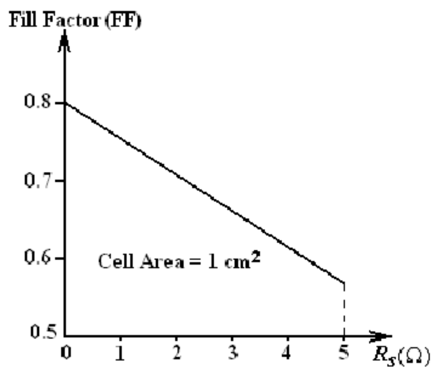


Fig. Effect of increase of series resistance on Fill Factor (FF)

Effect of Series and Shunt resistance on the IV curve

Decrease in shunt resistance R_P causes:

(i) The IV curve of the cell to depart further inward from its rectangular nature as shown in figure below.

(ii) The decrease in power output

(iii) The decrease in fill factor

(iv) The decrease in open-circuit voltage, V_{OC} as the equation of open circuit voltage is as follows

$$V_{OC} = \frac{KT}{q} \ln\left(\frac{I_{ph}}{I_0} - \frac{V_{OC}}{I_0 R_P} + 1\right)$$

(v) Short circuit current, I_{SC} will also decrease as the equation of short circuit is as follows

$$I_{SC} = I_{ph} - I_0\left(e^{\frac{qI_{SC}R_s}{KT}} - 1\right) - \frac{I_{SC}R_s}{R_P}$$

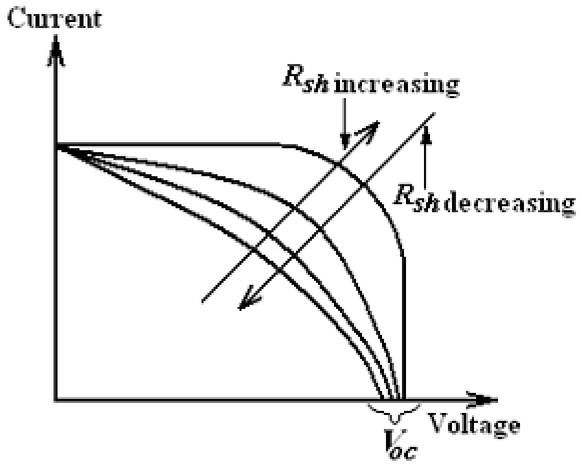


Fig. Effect of increase and decrease in shunt resistance

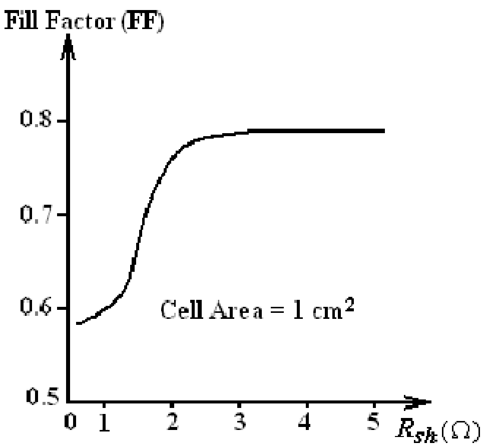


Fig. Effect of increase of shunt resistance on Fill Factor (FF)

Performance of the cell as a function of temperature

Depending upon the efficiency of the cell a fraction of the incident solar energy is converted into electricity. The rest goes to heat the cell and the panel on which cell is mounted. Unless the heat is extracted from the panel, the temperature of the cell would be higher than the ambient temperature.

Therefore, when the cell temperature increases

(i) The short-circuit current I_{SC} is found to be practically constant because the decrease of I_{SC} is not significant.

(ii) The reverse saturation current increases

(iii) The fill factor decreases

(iv) The open circuit voltage decreases

As a result of the change of all parameters with the increase in temperature the efficiency of the cell decreases. The decrease in efficiency with the increase in temperature can be expressed by the equation given below.

$$\eta_C = \eta_{CR}\left\{1 - \beta_T\left(T_C - T_r\right)\right\}$$

Where,

η_C = Efficiency of the cell at reference temperature

T_r = Reference temperature

T_C= Cell temperature

β_r= Fractional decrease of the cell efficiency per unit temperature increase

Performance of the cell as a function of temperature

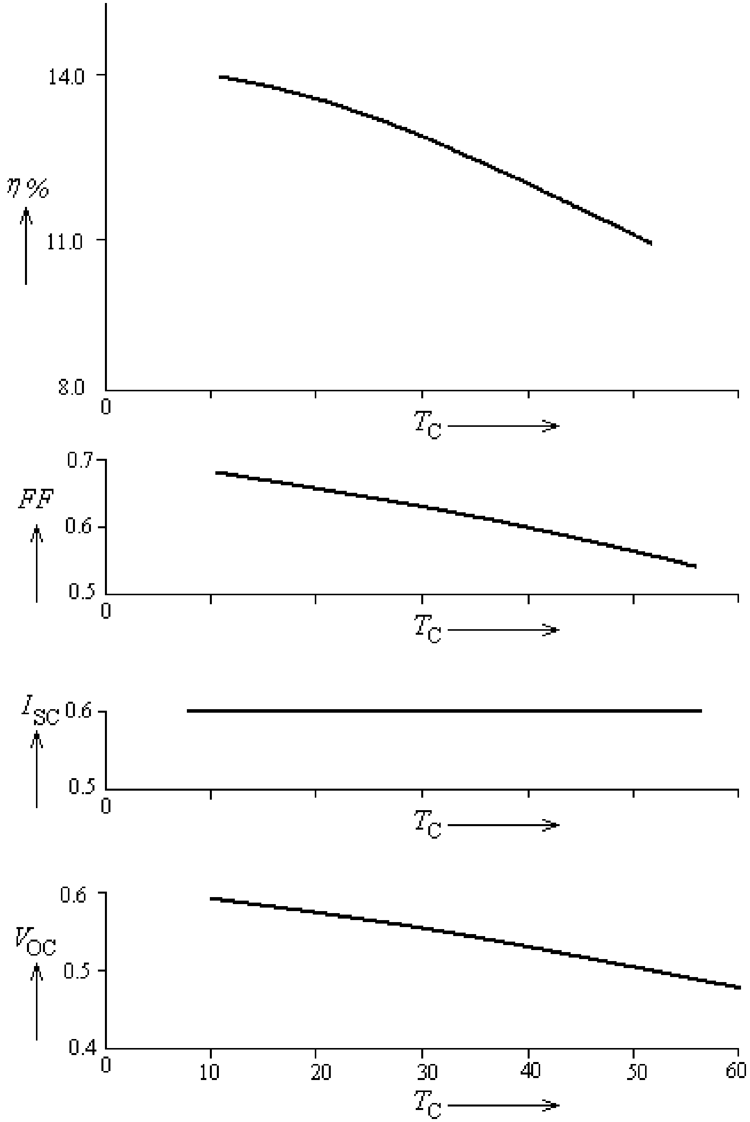


Fig. Variation of V_{OC}, I_{SC}, FF and η_C as a function of cell temperature

For silicon solar cells, efficiency approaches zero as the temperature approaches 270^0C and hence $\beta_r = 0.0041/^0$C

Effect of irradiance on the efficiency

Considering constant cell temperature, irradiance has the following impact :

1. Short circuit current I_{SC} is affected severely with the variation of irradiance. I_{SC} is directly proportional to irradiance i.e. I_{SC} increases with the increase of irradiance. As a result variation of power is abrupt.
2. But there is a small variation of open circuit voltage V_{OC} with the variation of irradiance.
3. Locus of maximum power point (MPP) also varies with irradiance.

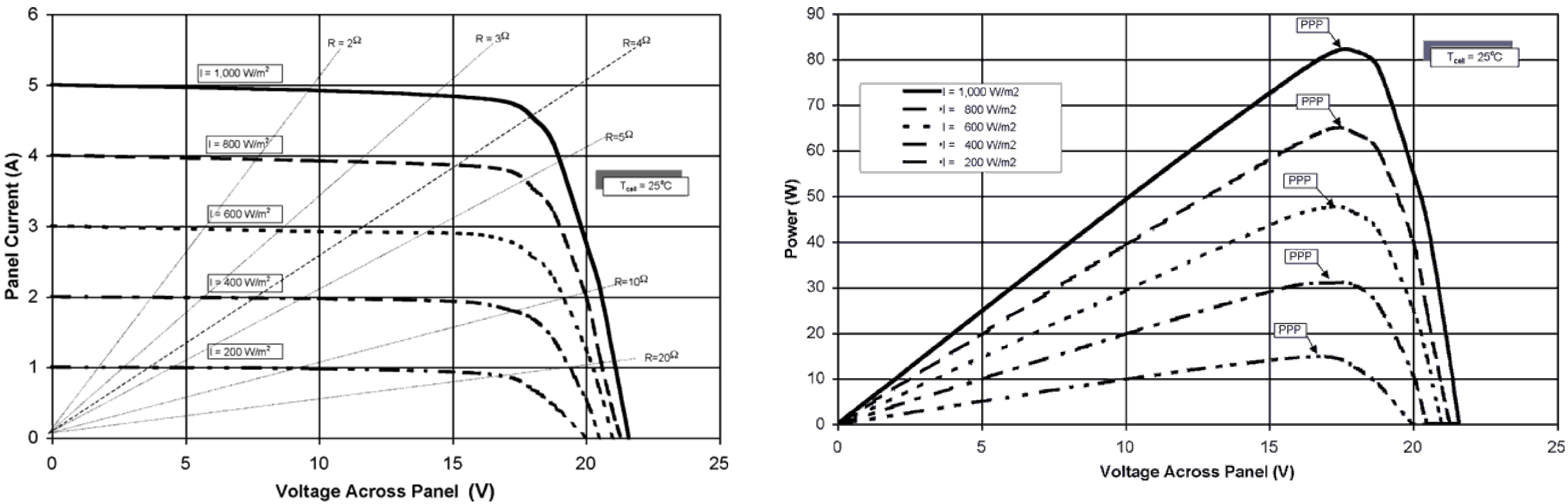


Fig. Variation of V_{OC}, I_{SC}, and locus of MPP with the variation of irradiance

PV Modules and Panels

Series Connection of Cells:

- For two cells connected in series, the current through the two cells is the same. The total voltage produced is the sum of the individual cell voltages.
- Since the current must be the same, a mismatch in current means that the total current from the configuration is equal to the lowest current.

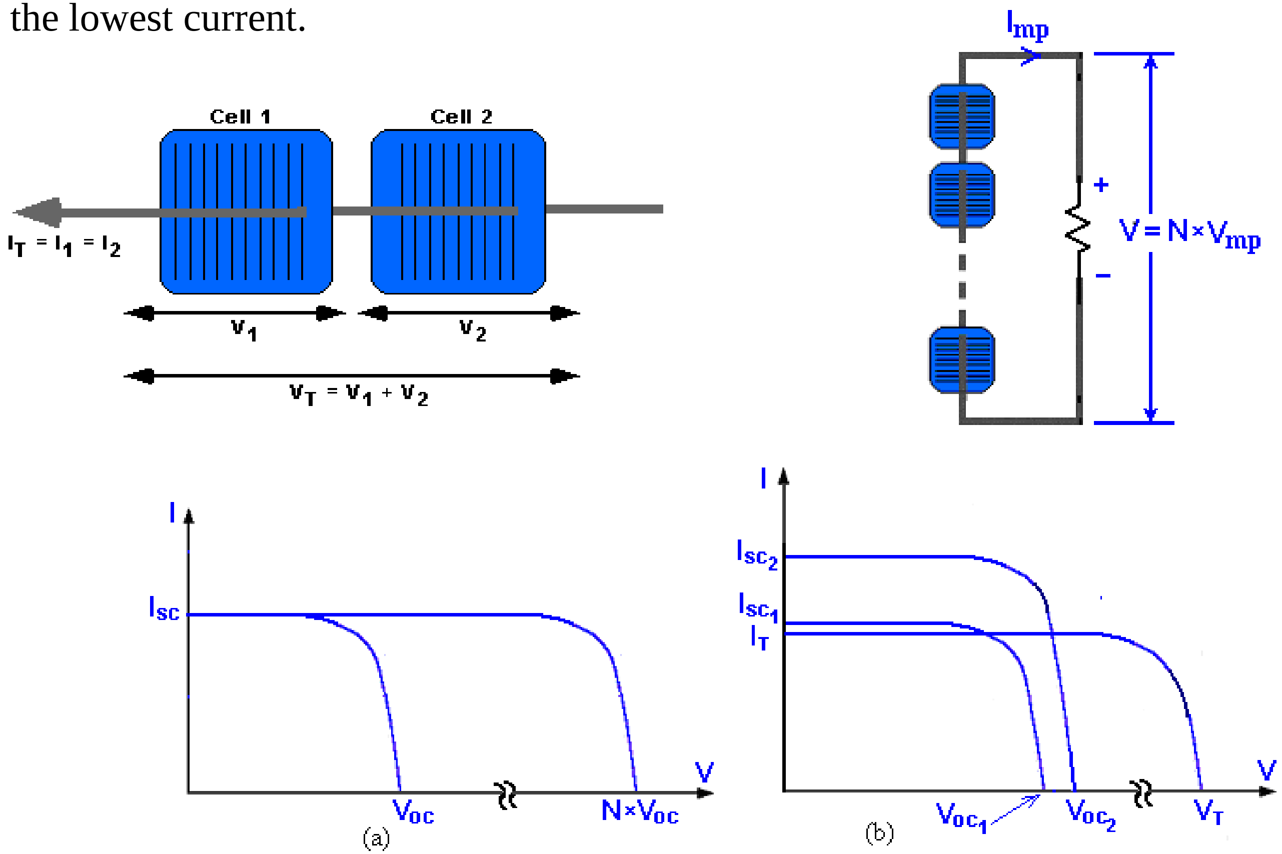


Fig. Solar Cell connected in series

PV Modules and Panels

Parallel Connection of Cells:

- Cells connected in parallel. The voltage across the cell combination is always the same and the total current from the combination is the sum of the currents in the individual cells.

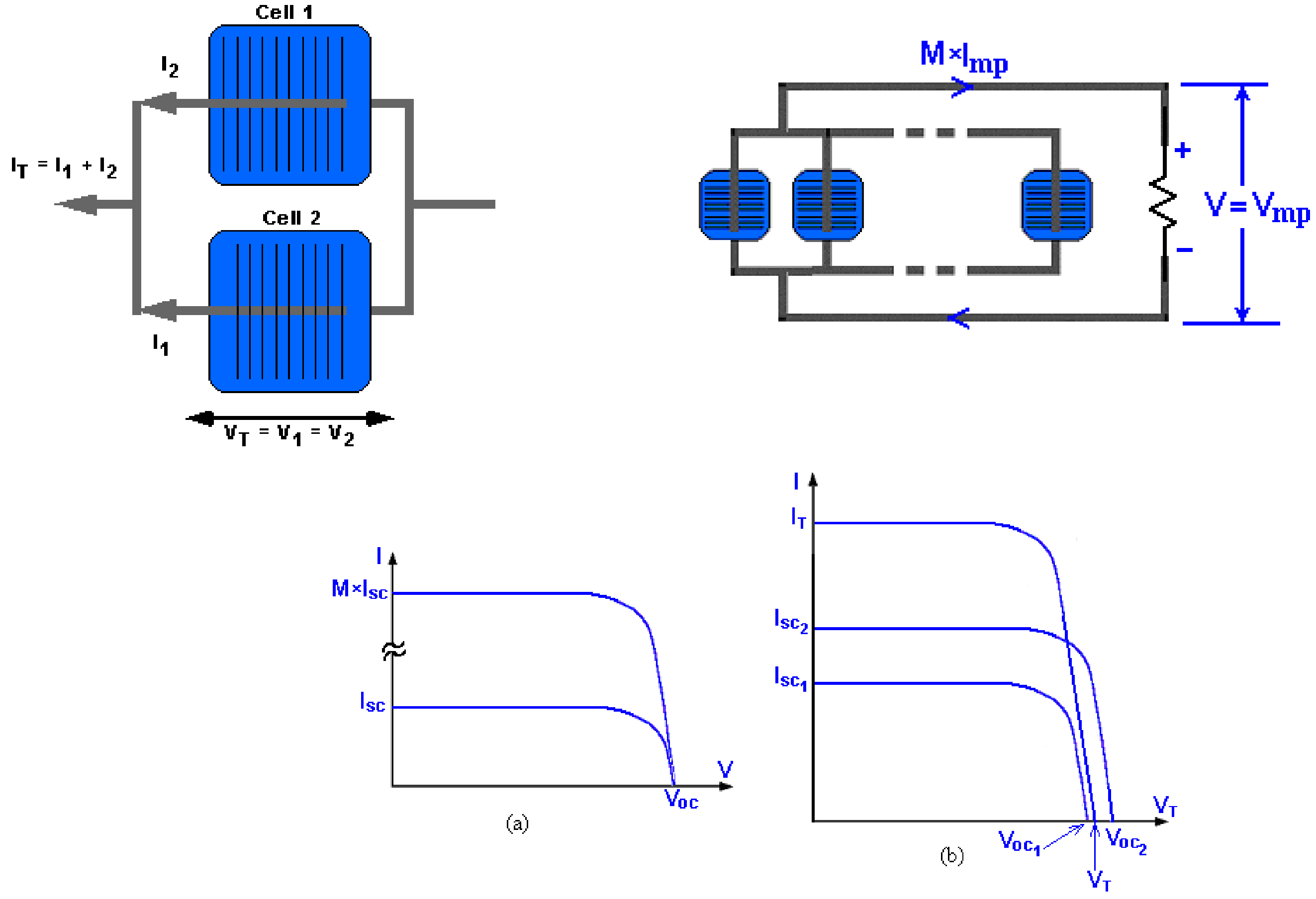
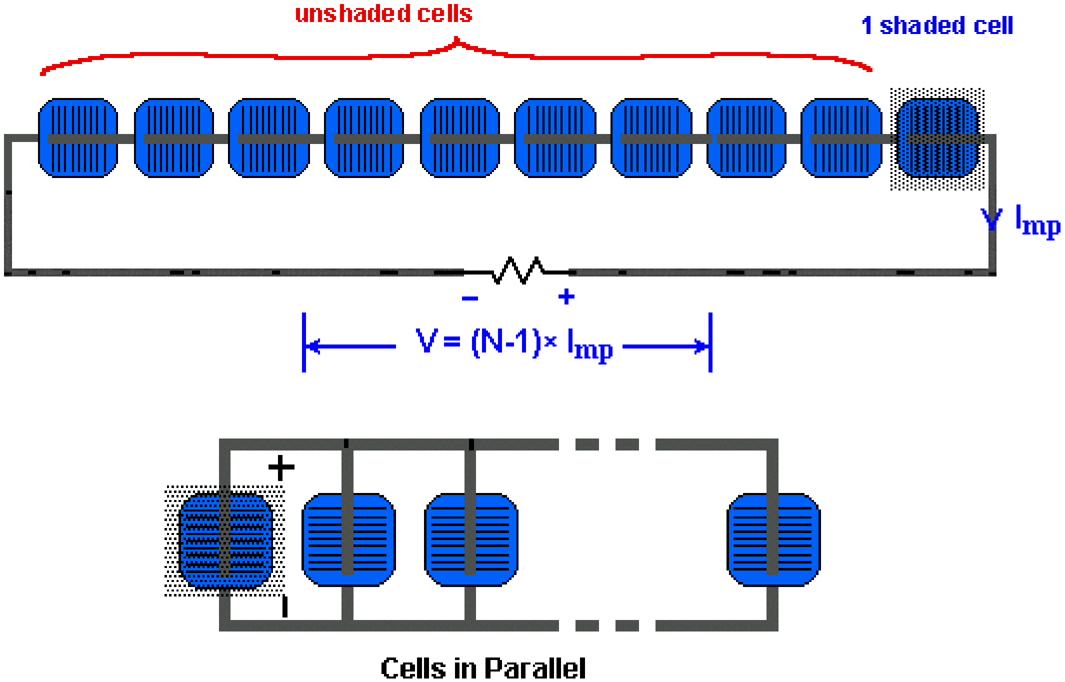


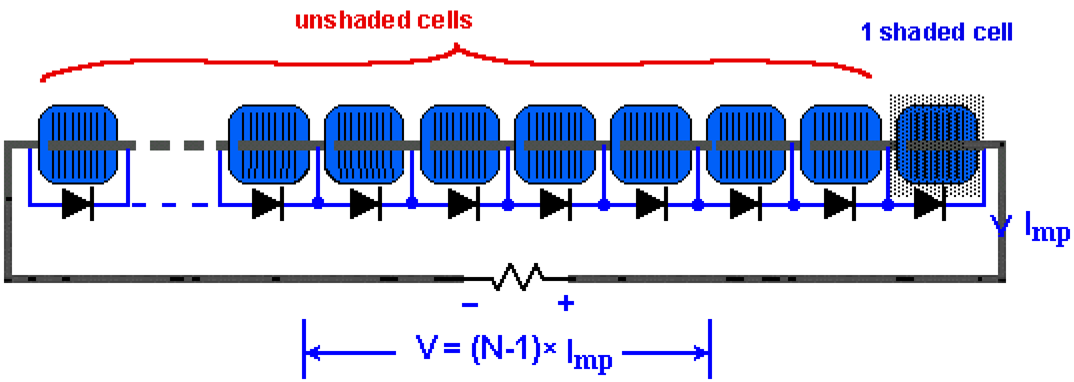
Fig. Solar Cell connected in parallel

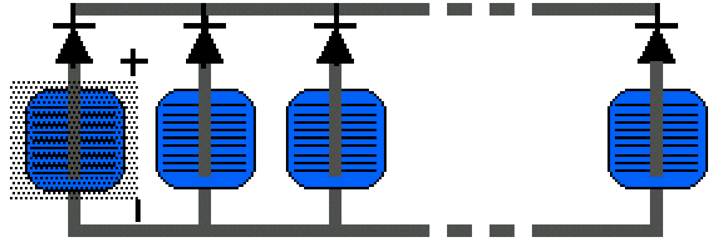
Hot-spot in PV cell

- 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, as shown in the figure below.

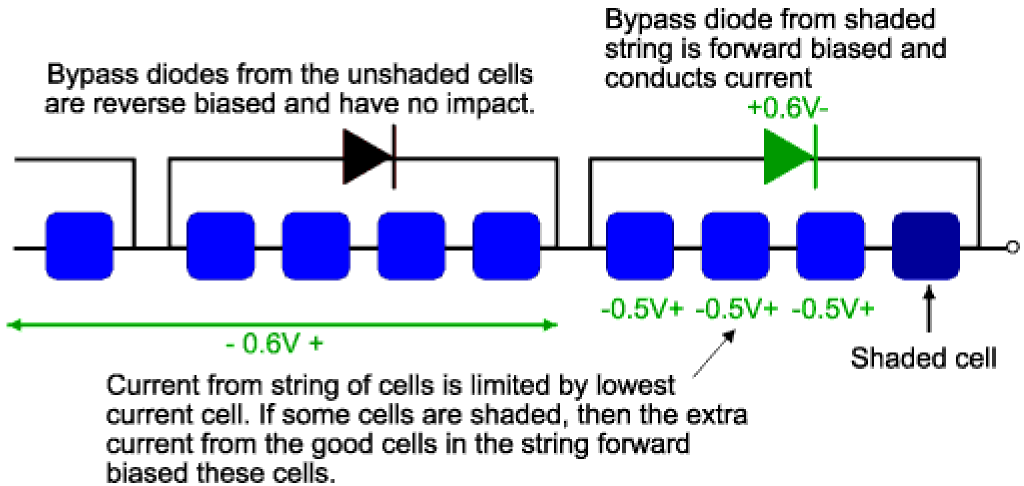


Bypass Diodes



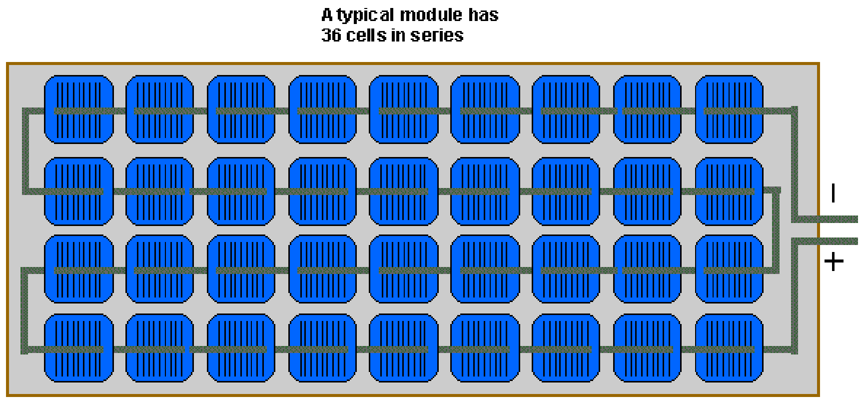


Cells in Parallel



- Bypass diodes across groups of solar cells. The voltage across the unshaded solar cells depends on the degree of shading of the poor cell. In the figure above, 0.5V is arbitrarily shown.

Bypass Diodes



- In a typical module, 36 cells are connected in series to produce a voltage sufficient to charge a 12V battery.
- If all the solar cells in a module have identical electrical characteristics, and they all experience the same insolation and temperature, then all the cells will be operating at exactly the same current and voltage.
- In this case, the IV curve of the PV module has the same shape as that of the individual cells, except that the voltage and current are increased. The equation for the circuit becomes:

$$I_T = M \cdot I_L - M \cdot I_0 \left[\exp\left(\frac{q \frac{V_T}{N}}{nkT} \right) - 1 \right]$$

where:

N = the number of cells in series; M = the number of cells in parallel; I_T = the total current from the circuit;

V_T = the total voltage from the circuit;

I_0 = the saturation current from a single solar cell; I_L = the short-circuit current from a single solar cell;

n = the ideality factor of a single solar cell; and q, k, and T are constants.

The overall IV curve of a set of identical connected solar cells is shown below.

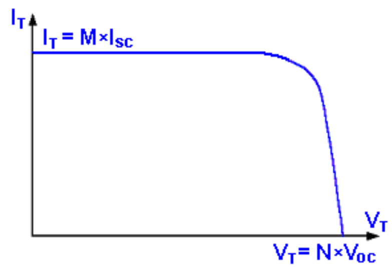


Fig. I-V curve for N cells in series x M cells in parallel

Packing Density

- The packing density of solar cells in a PV module refers to the area of the module that is covered with solar cells compared to that which is blank.
- The packing density affects the output power of the module as well as its operating temperature.
- The packing density depends on the shape of the solar cells used.
- Single crystalline solar cells are round or semi-square, while polycrystalline silicon wafers are usually square. Therefore, if single-crystalline solar cells are not cut squarely, the packing density of a single crystalline module will be lower than that of a polycrystalline module.
- The relative packing density possible with round verses square cells is illustrated below.