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XMUT204 Electronics Design

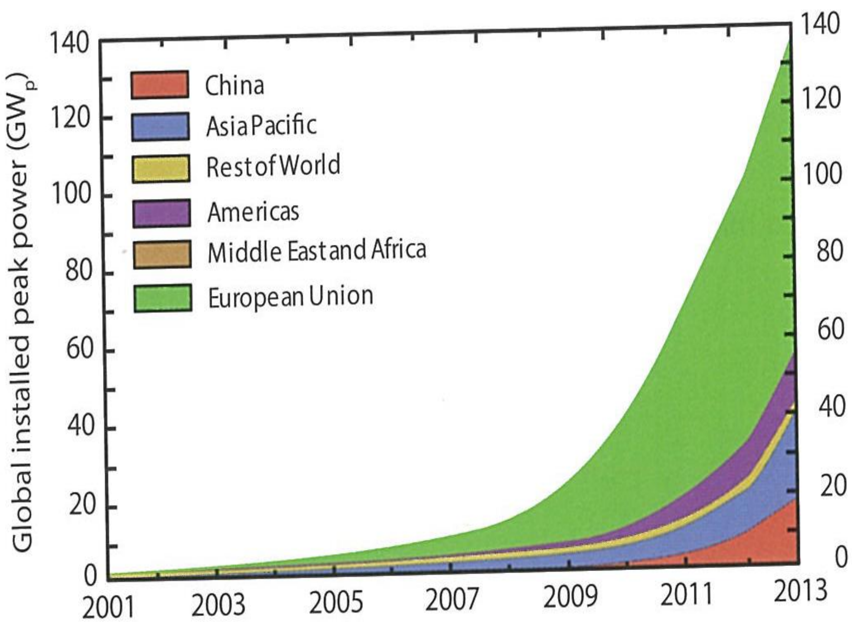
Lecture 2f - Special Purpose Diodes (Solar Cells I)

Overview

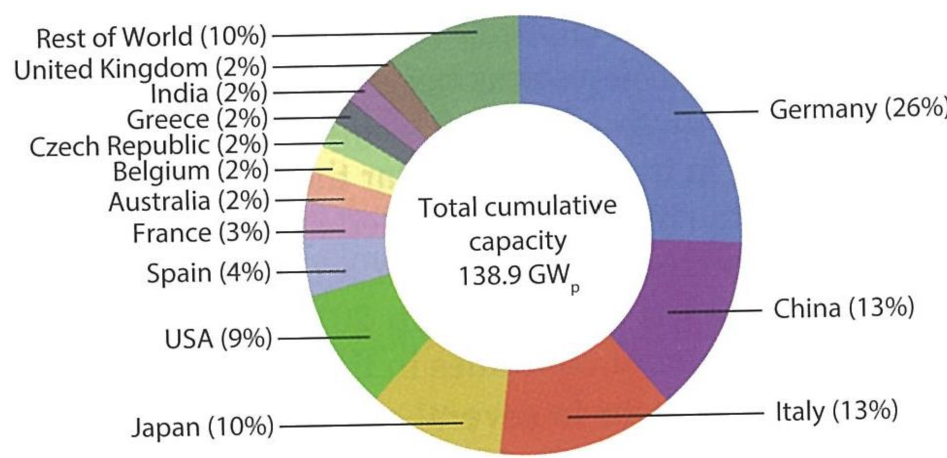
- Demands for solar cells
- Characteristics of solar cells
- Construction of solar cells
- Operation of solar cells
- Conversion of energy in solar cells
- Design of solar cells

An exponential world-wide growth in solar photovoltaics as a source of renewable energy

- Widespread trend for adoption of solar power systems.
- Incentives - commerce and industry regulations in a given countries.



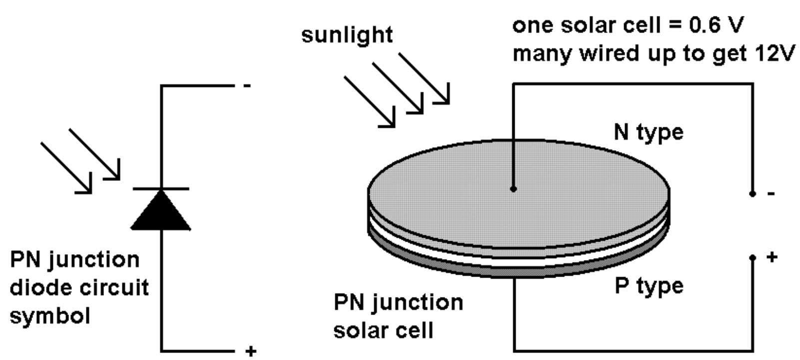
Installed PV capacity across the world per year

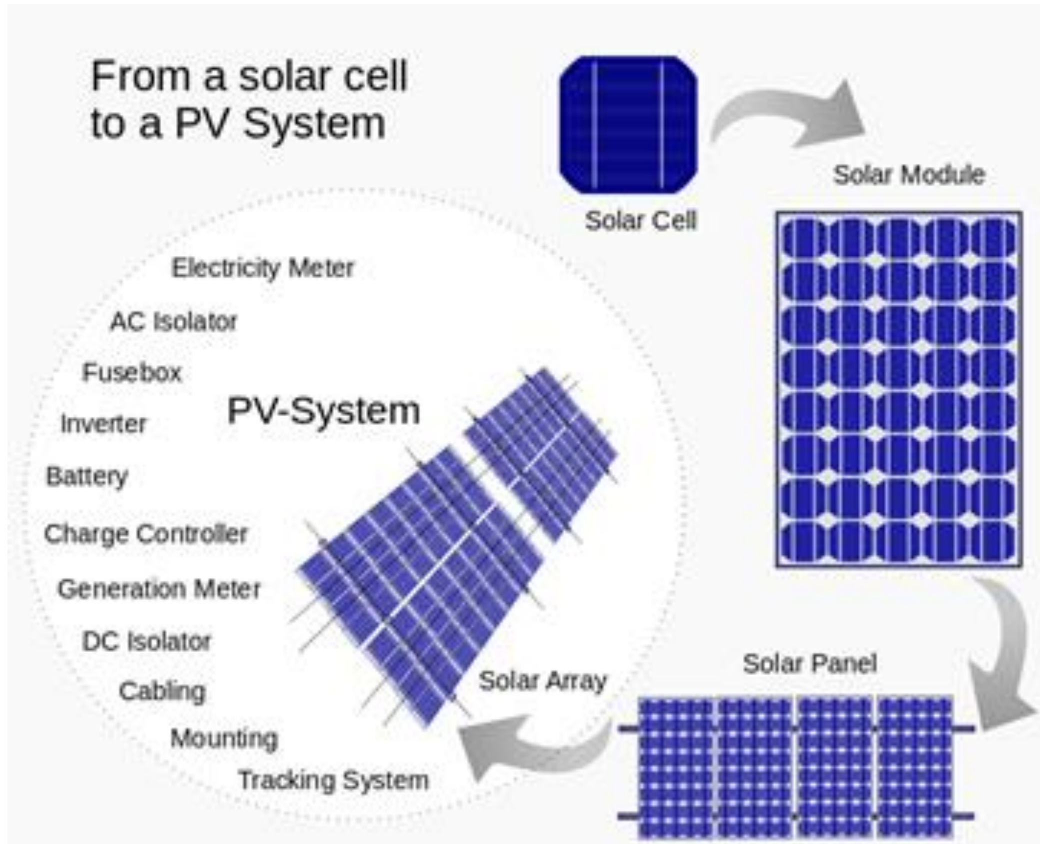


Fraction of PV installations for different countries

Background

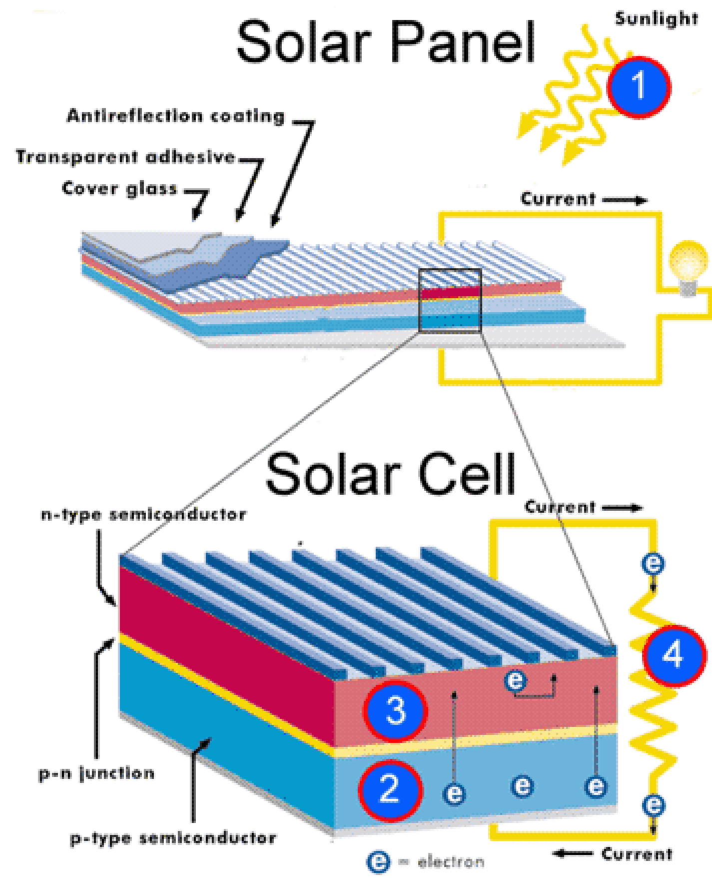
- Use the knowledge on semiconductor properties, p-n junctions and optical absorption - principle of operation of a solar cell.
- Cells are based on the photovoltaic effect - the direct conversion of light into electrical energy.

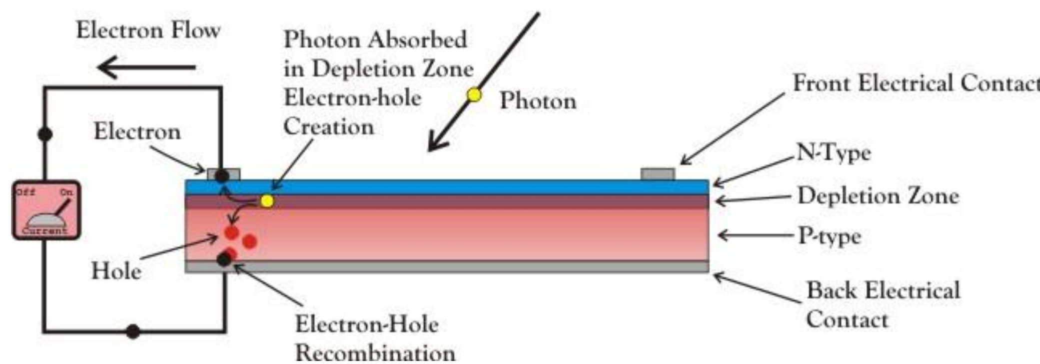




Construction of PV units

- Solar Panel:
  - Coating
  - Cover
  - Frame
- Solar Cell:
  - N-type semiconductor
  - P-N junction
  - P-type semiconductor
  - Metal contacts



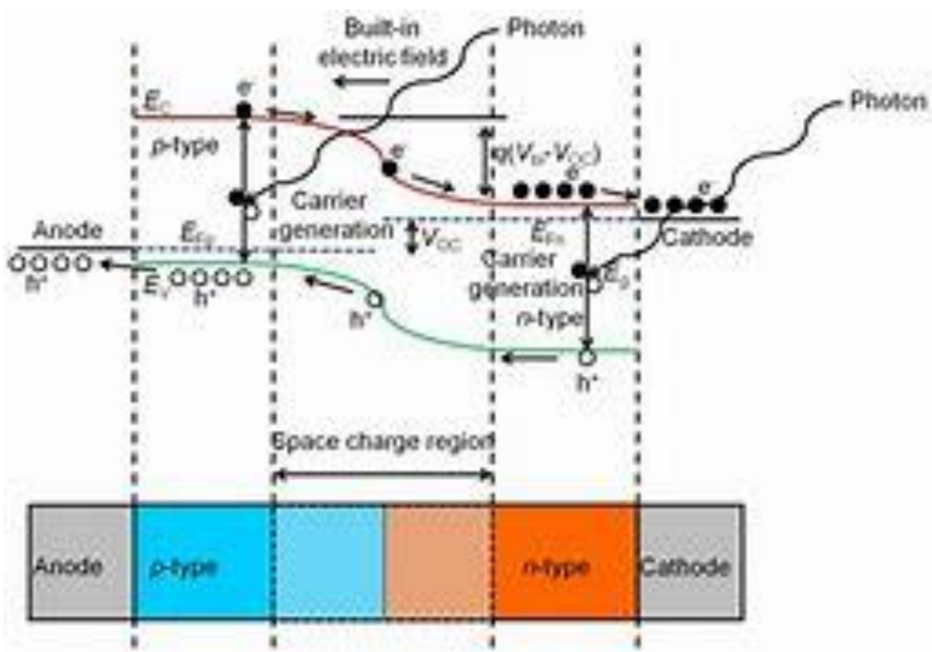


To utilise this effect in a semiconductor, three steps to take place:

1. The generation of e–h$^+$ pairs - light with an energy greater than the bandgap is incident on the material.

2. Separating the e–h$^+$ pairs to prevent them from recombining – the built-in electric field of a p-n junction is ideal for this purpose.

3. Extracting these carriers from the semiconductor and using them to connect to an external circuit – achieved by metal contact on the semiconductor circuit.



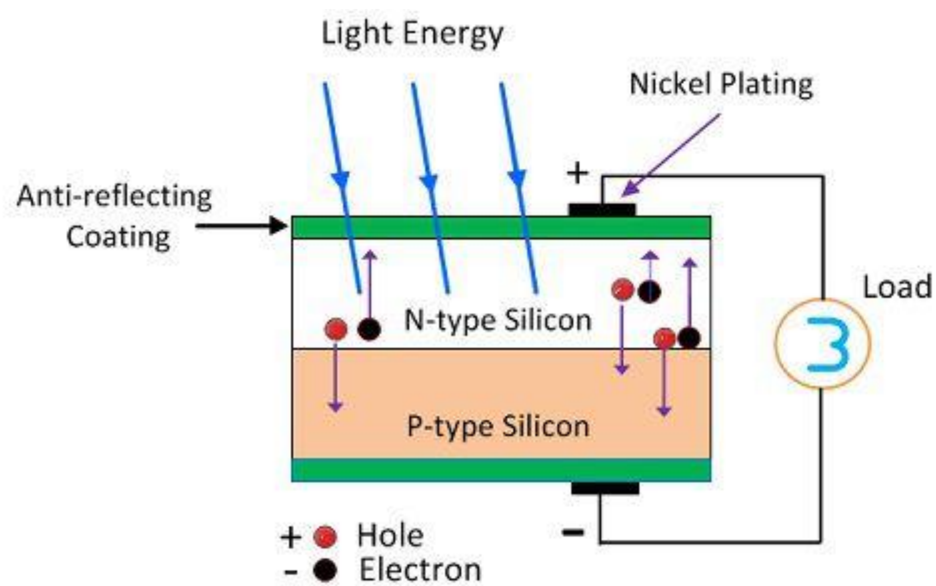
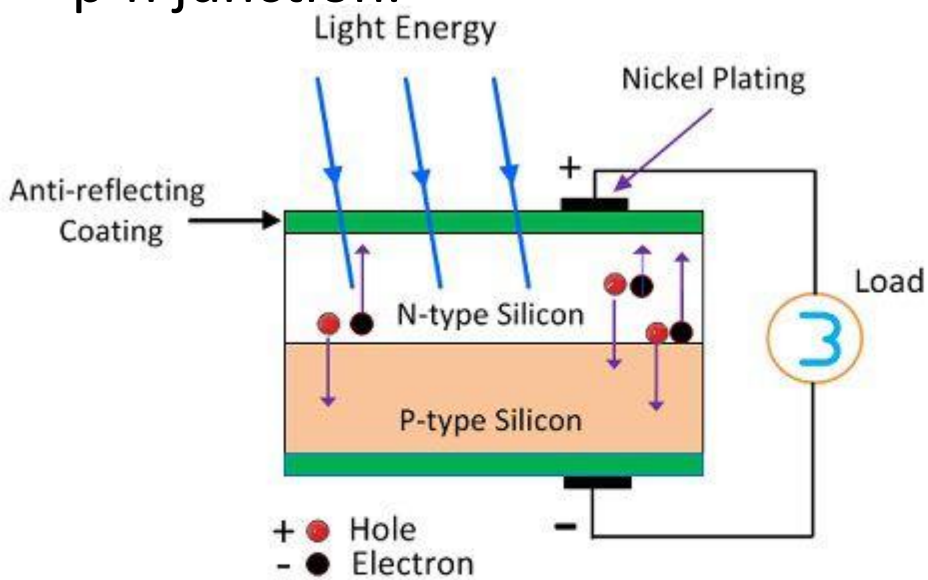
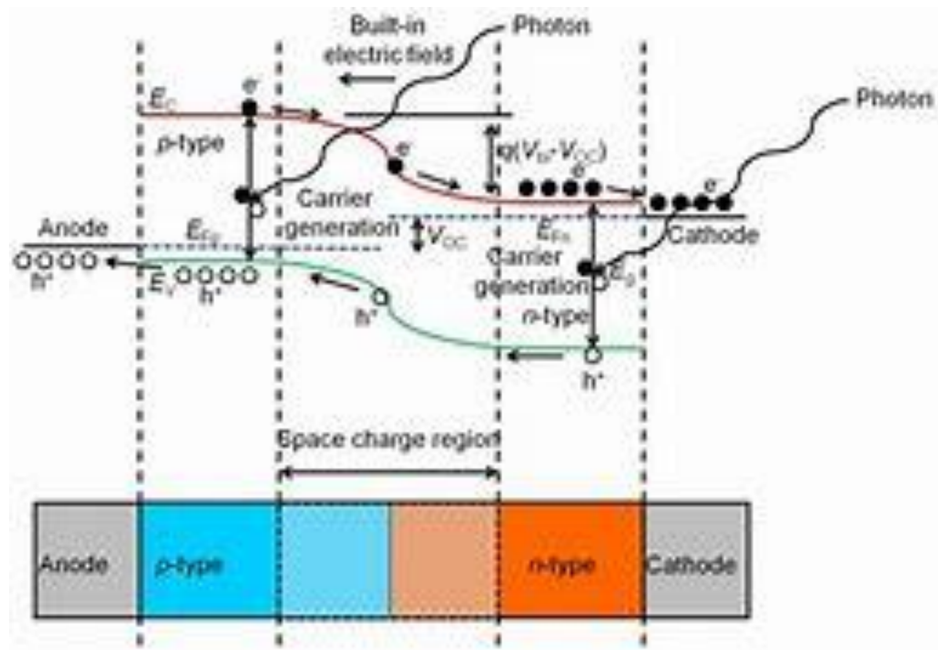
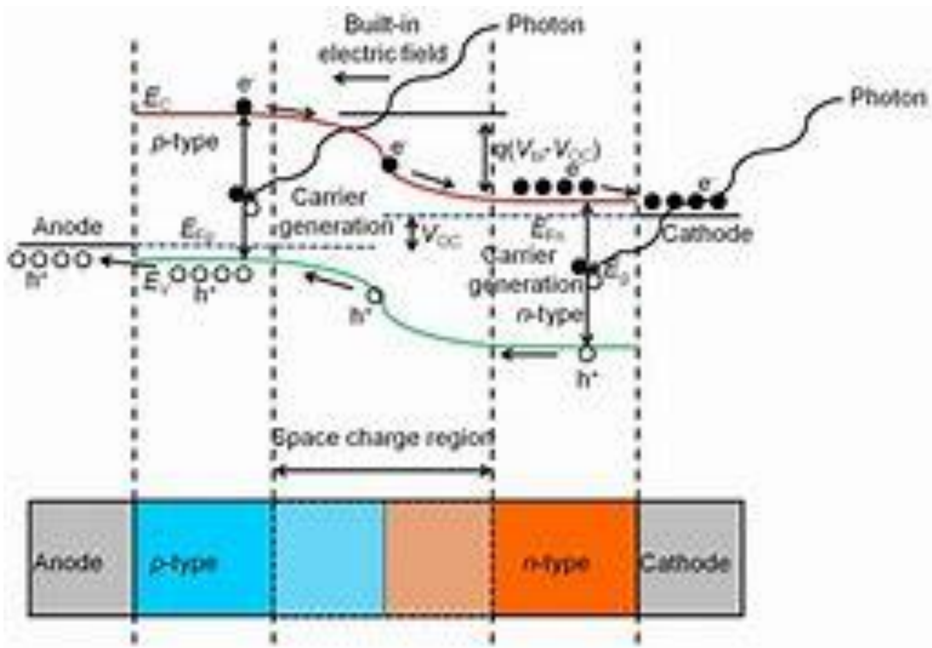


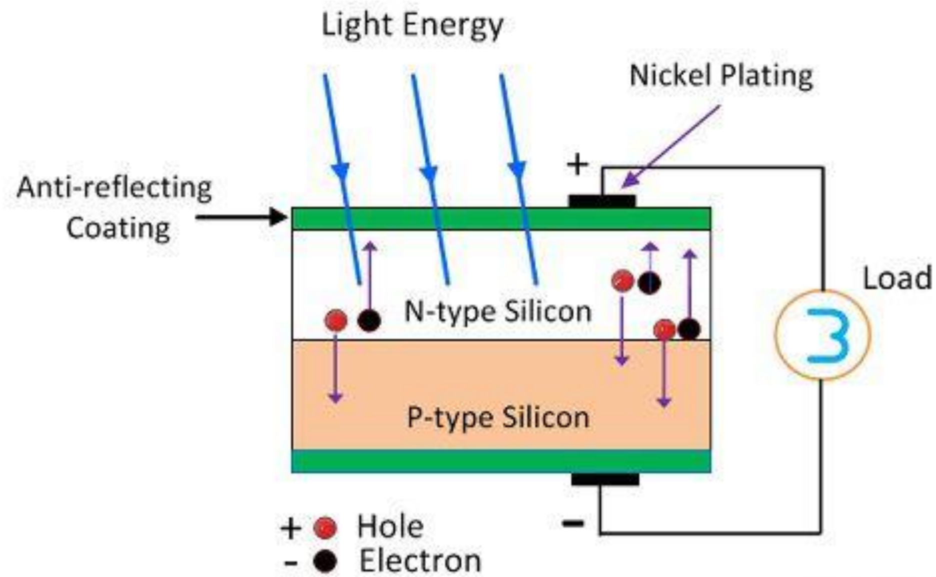
Photo-generation of e-h$^+$ pairs

- Light with energy $E = h\nu > E_g$ -> generate e-h$^+$ pairs when incident on a semiconductor.
- If generation takes place close to a p-n junction -> built in field from the junction will sweep carriers across the junction -> create a drift current.
- Assume that the incident radiation creates 10^{15} e-h+ pairs.cm^{-3} -> no real difference to the majority carrier concentration -> huge difference to the minority carrier concentration on both sides of the p-n junction.





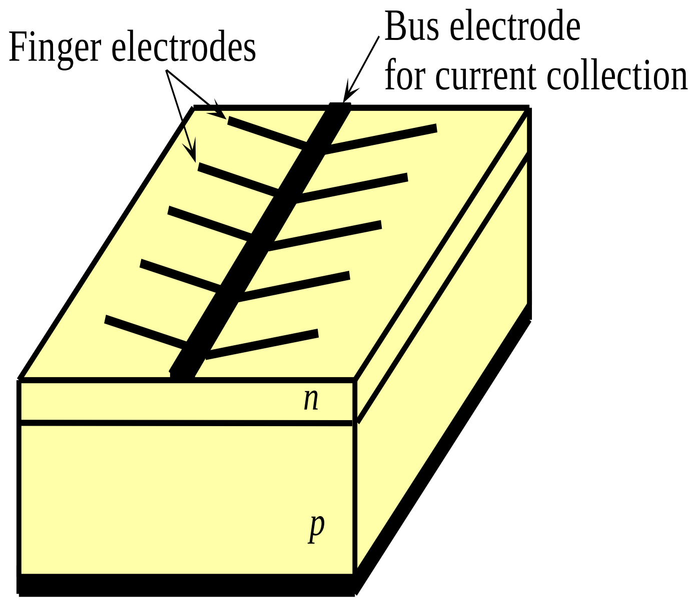


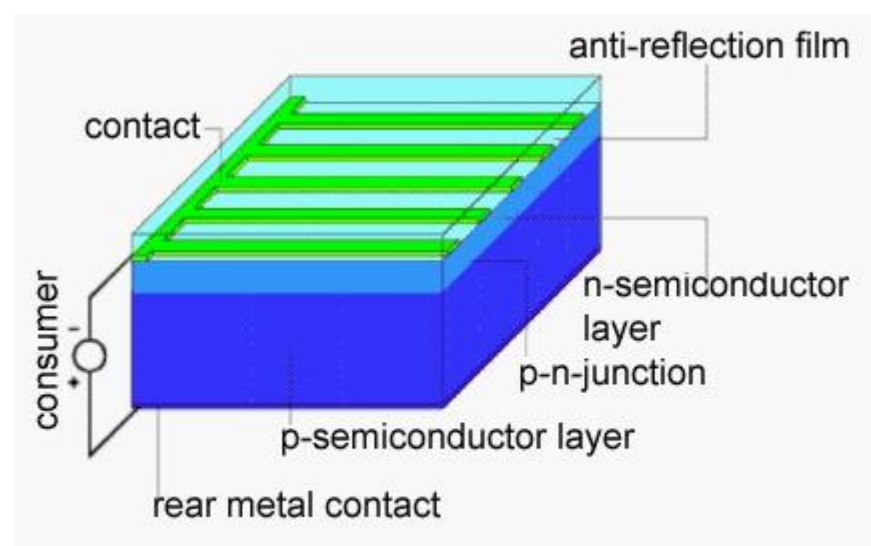


- If these minority carriers are formed within a minority carrier diffusion length from the junction -> diffuse to the junction -> swept across the junction by the electric field.
- Drift current of minority carriers across the junction – holes from n to p type and electrons from p to n type.

Construction of a typical solar cell

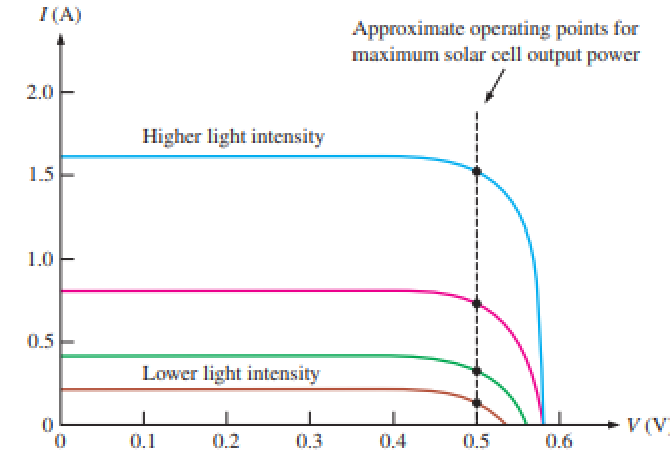
- Electrons and holes extracted from the semiconductor by means of metals contacts deposited on the surface and the carriers can flow in an external circuit with load.
- On the front surface, use a system of grids or finger electrodes plus bus bars.
- On the back surface, use a continuous contact that covers the whole back surface.

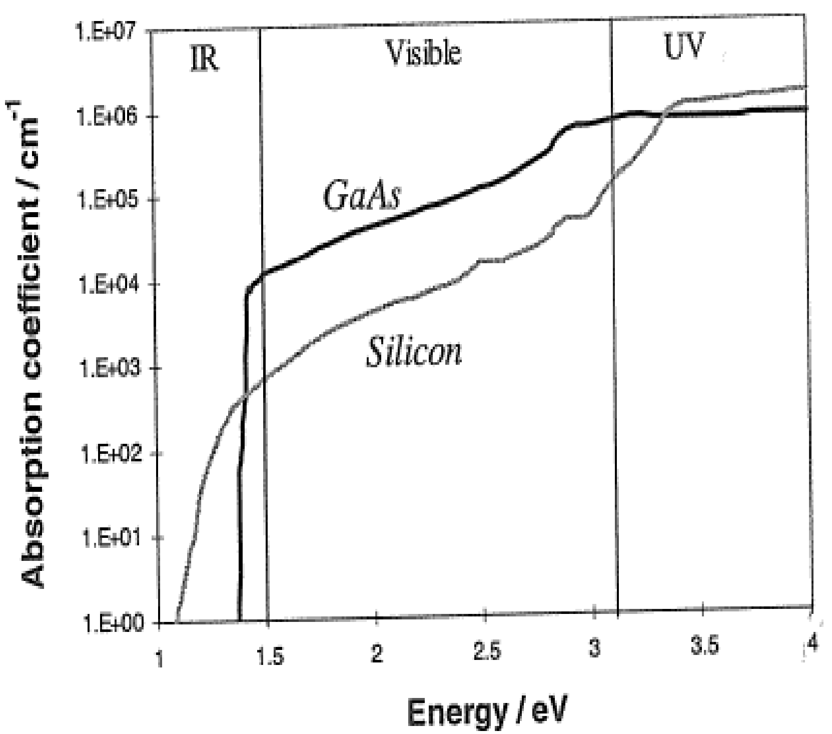




Absorption of light in the cell

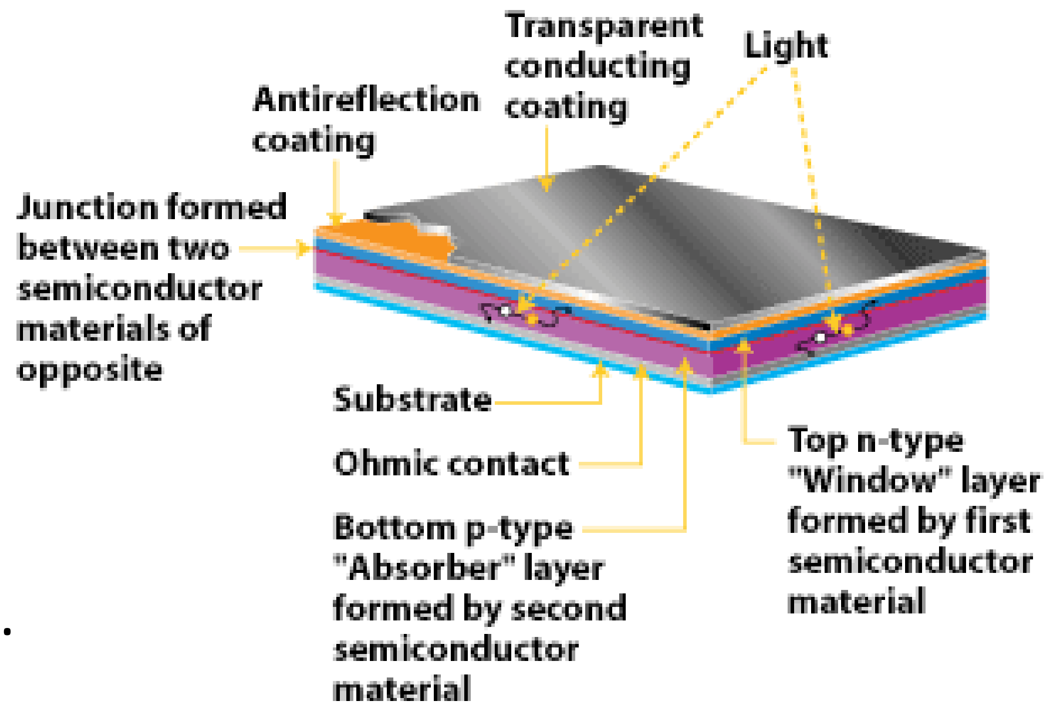
- Assume a Si solar cell -> E_g = 1.1 eV -> need a light with a wavelength shorter than 1.24/1.1 eV = 1.13 µm for electron – hole pair (EHP) formation.
- But, Si has an indirect bandgap and absorption is inefficient – low absorption coefficient for low end (long wavelengths) that increases the photon energy.
- Absorption of light in Si as compared to absorption in GaAs (e.g. 1.4 eV and a direct bandgap material).
- Absorption in GaAs much more efficient.





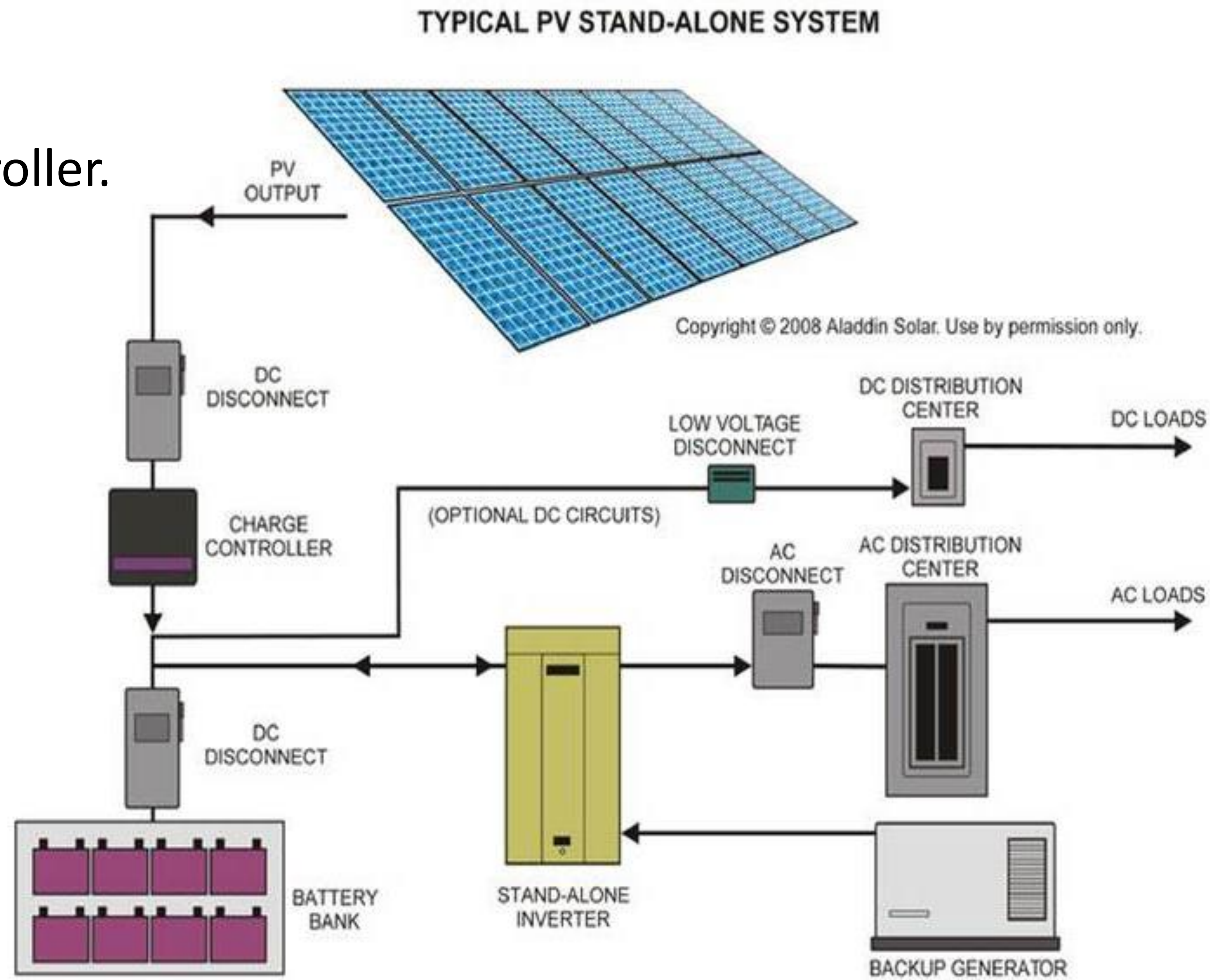
Construction of a typical solar cell

- A thin, heavily doped n-region on illuminated surface side.
- Thicker, moderately doped p-region
- Illumination from the n-side – use only finger contacts (ohmic contacts) on this side to ensure light still penetrates semiconductor.
- Depletion region formed that extend mostly into the p-side.
- Built-in field E_0 due to depletion region.
- Use a thin anti-reflection coating on front surface to reduce reflection and allow maximum light to enter device.

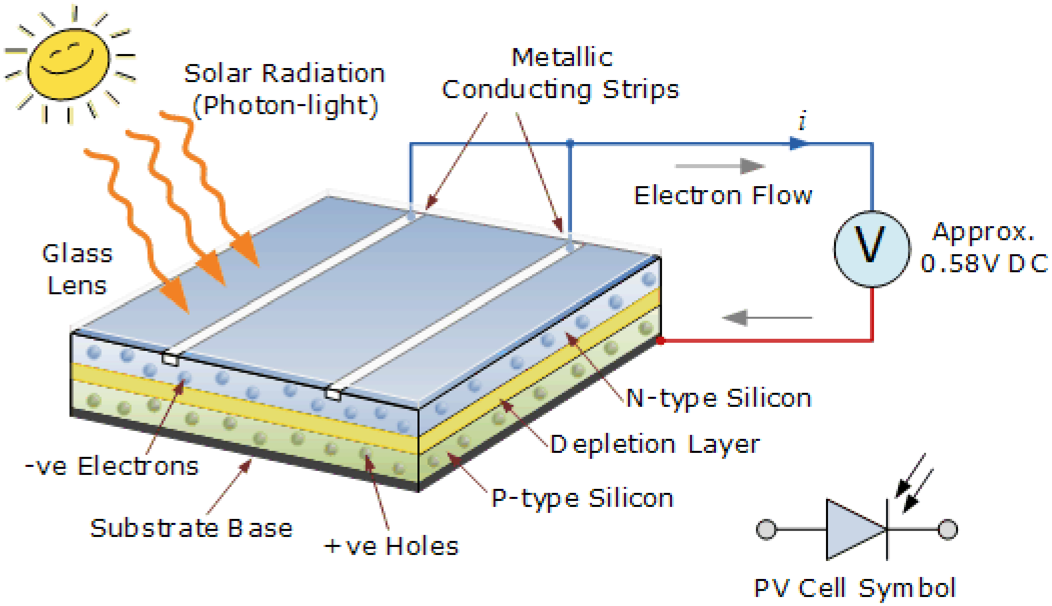


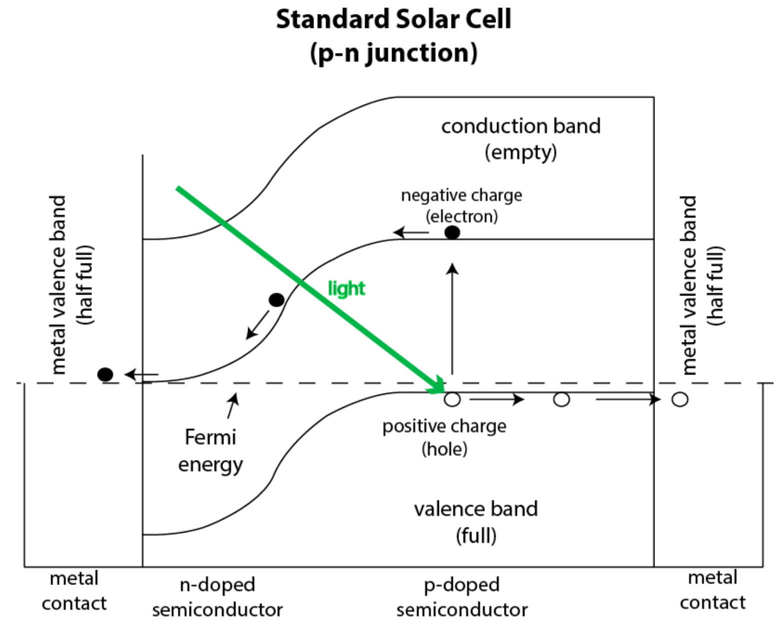
Photovoltaic System

- Solar panel.
- Charge controller.
- Battery.
- Inverter.



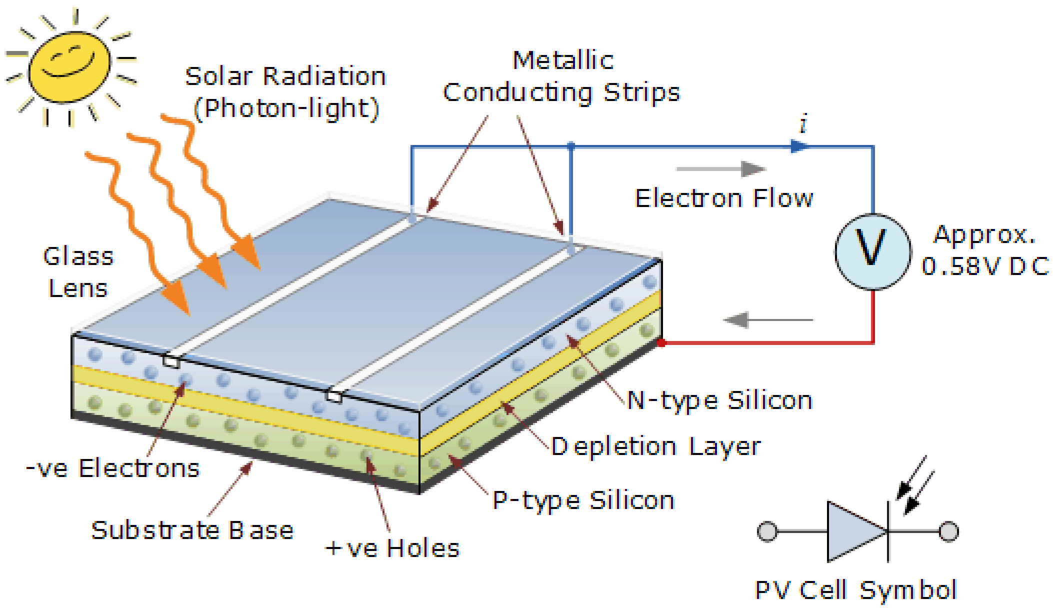
Operation of a solar cell:

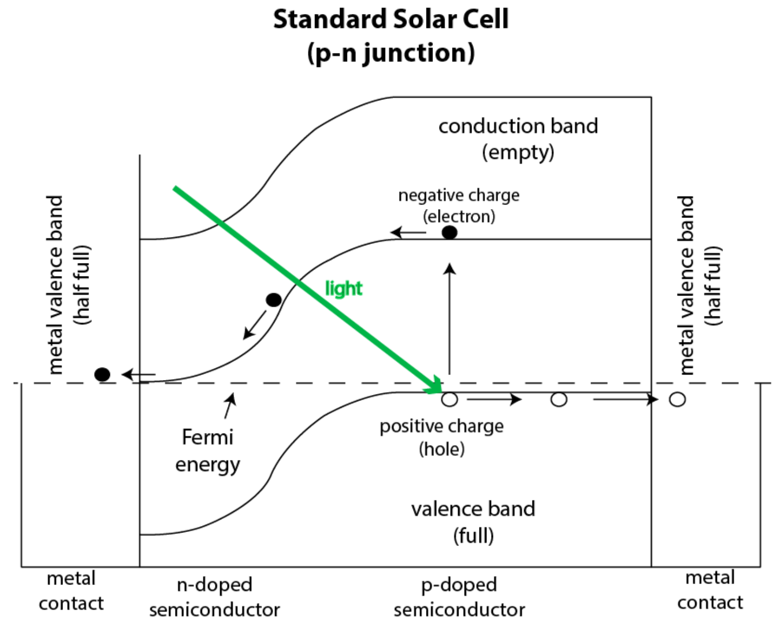




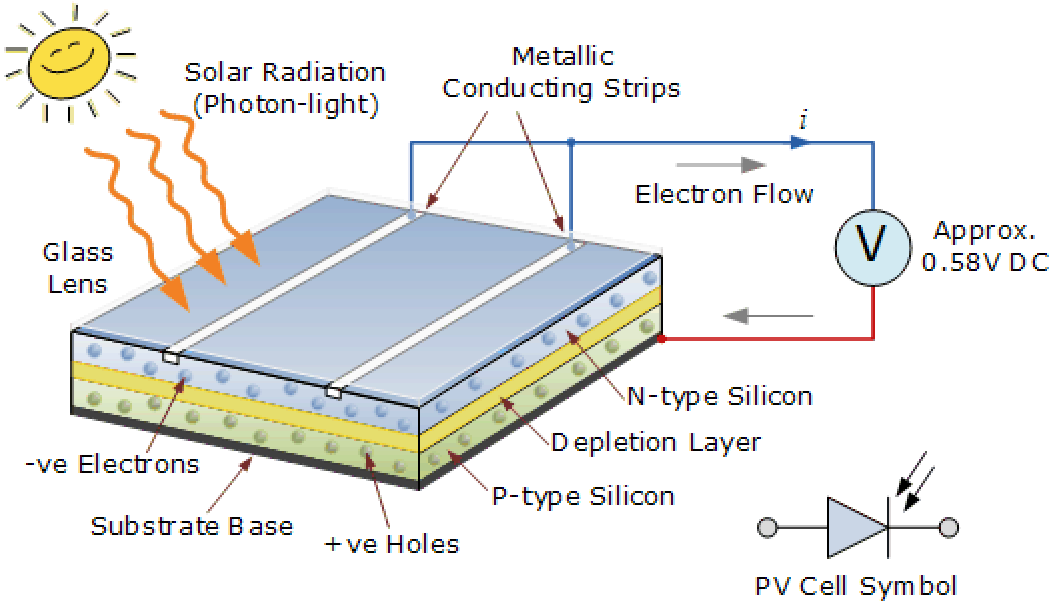
- Light incident from n-side of the device. If the energy of the light is > bandgap of the semiconductor it will lead to electron-hole pair (EHP) generation. An EHP will exists for only a limited time (the minority carrier lifetime) before it recombines.
- As the n-side is very thin, most photons are absorbed in the p-side or in the depletion region and light generated EHPs are then created in these regions.

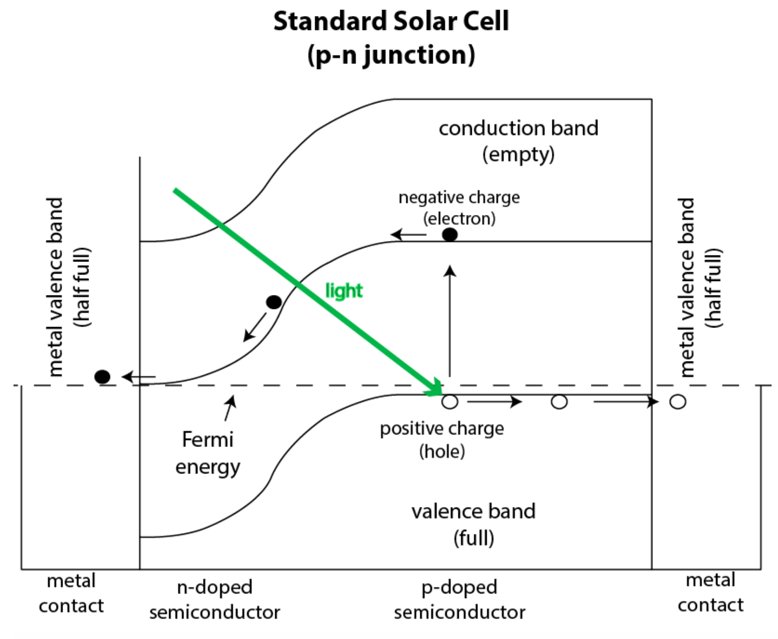
Operation of a solar cell:



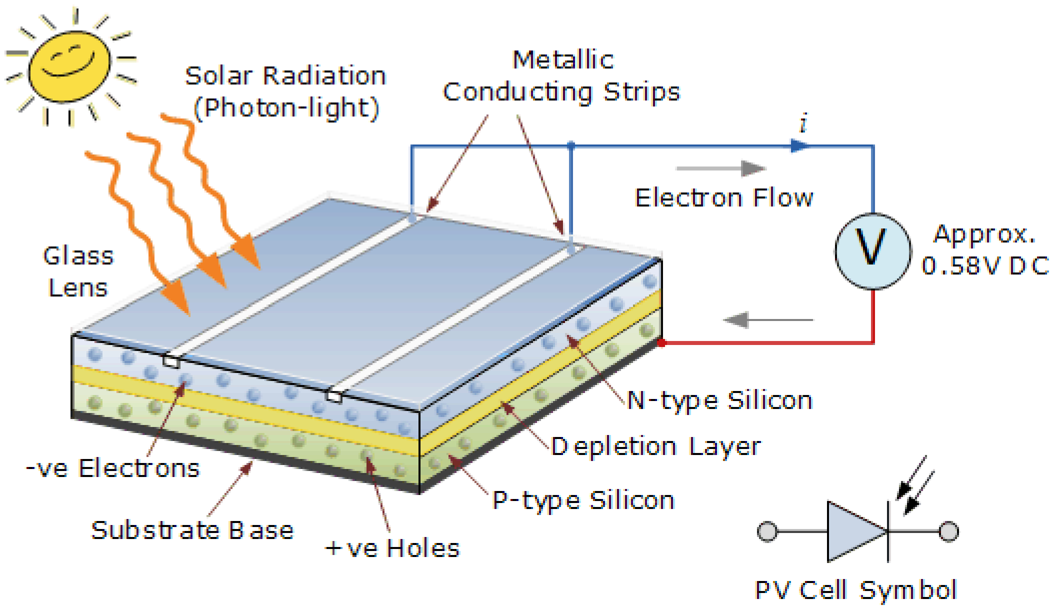


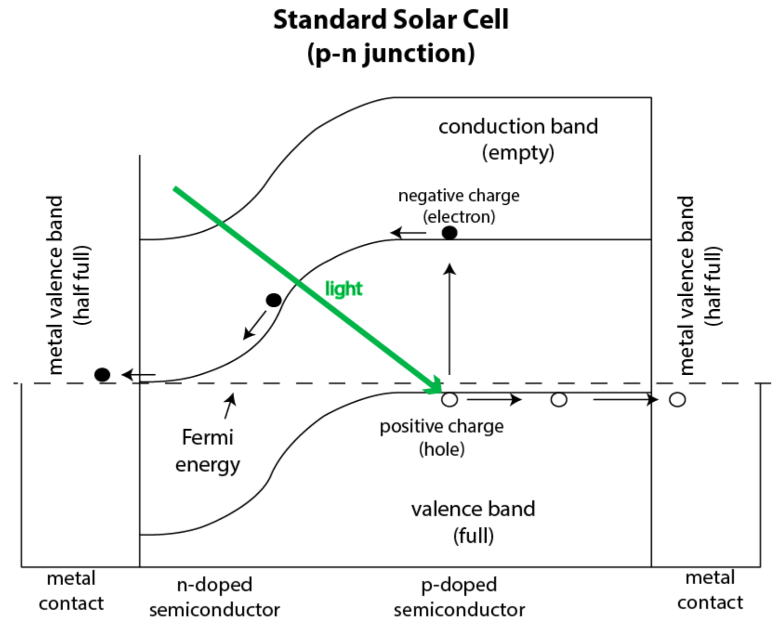
- Any EHPs generated in the depletion region will be separated by the built-in electric field which will drift them apart.
- The electron will drift towards the n-region and will make this region more negative by an amount of charge –e.
- Similarly, holes will drift to the p-side and make this side more positive.





- An open circuit voltage will thus develop over the terminals of the device with the p-side more positive than the n-side.
- If an external load or short is then connected over the terminals, electrons will flow in the external circuit from the n-side to p-side and combine with excess holes at p-side – **a photocurrent.**





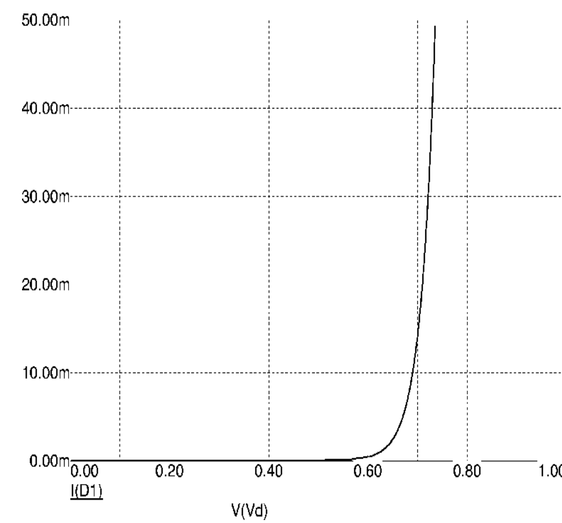
- EHPs that cannot reach the depletion region are lost by recombination and does not contribute to the formation of a voltage – thus need minority carrier diffusion length as long as possible. Diffusion length of minority carrier electrons longer than holes thus the choice of the bulk p-type region.

- In order to absorb long wavelength (~ 1 to 1.1 µm) radiation, the p-side needs to be thick and at same time have a long minority carrier diffusion length. P-side typically 200 to 500 µm thick – much thicker than the diffusion length.

Solar cells – I-V characteristics

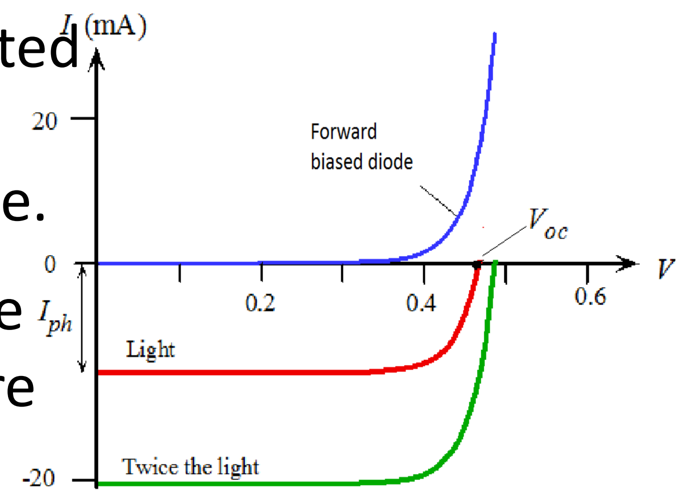
Lets look at the direction of current in in a conventional p-n junction (diode) during forward bias. From section on p-n junctions remember:

- Forward bias decrease the energy hill for electrons flowing from n to p as well as for holes flowing from p to n.
- This increase the diffusion current (majority carriers) flow by forward bias.
- Consider the flow of conventional carriers -> the flow is from p-type to n-type over the junction.
- Thus, define a positive current flow in the device when conventional current (positive charge carriers) flow from the p-side to the n-side.
- The current through an ideal diode is given by: $I_d = I_o \left[exp\left(\frac{eV}{kT}\right) - 1 \right]$



Consider the flow of charge carriers across the p-n junction of a solar cell:

- Generate e-h+ pairs on both sides of the junction -> dominated by the change in concentration of the minority carriers.
- These minority carriers are swept across the p-n junction as a drift current -> positive holes on the n-side flowing to the p-side and similarly negative electrons from the p-side flowing across to the n-side.
- Flow of positive charge carriers is then from n-side to p-side inside the diode -> opposite to direction of what it was in the diode.
- According to our current convention, we thus have a negative current flow in the solar cell and a I-V curve that looks as follows:
- Then, often find the I-V curve of a solar cell plotted with negative current – reflects this change in current direction from conventional biased diode.
- However, just as often the curve is plotted as the inverted with a positive current axis (seems more intuitive!)



Current – voltage behaviour of a solar cell

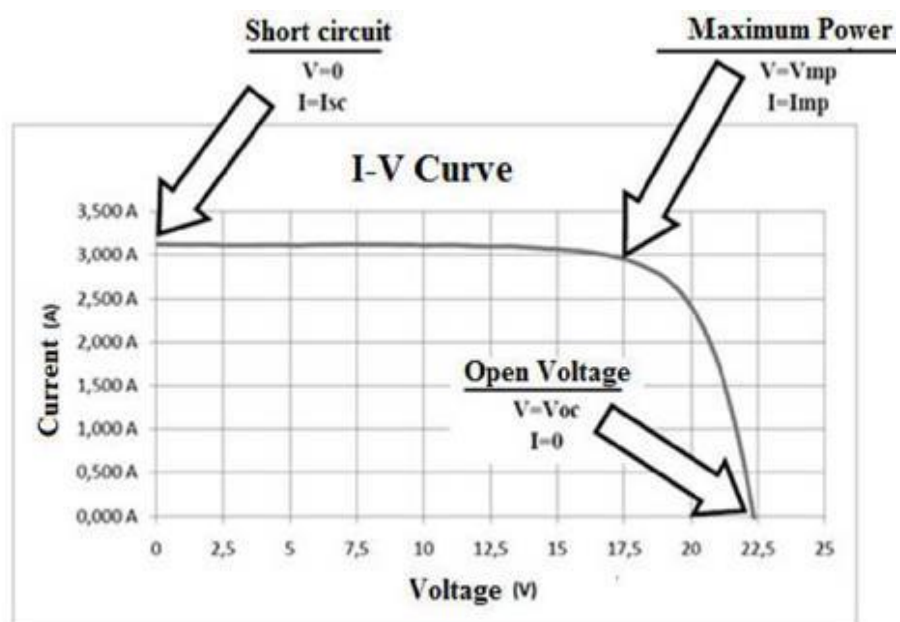
Look at the V-I behaviour of a solar cell as we vary the load resistance connected to the cell.

- Open circuit case ($R_L = \infty$) -> no current flow in the external circuit and the cell voltage is V_{OC}.

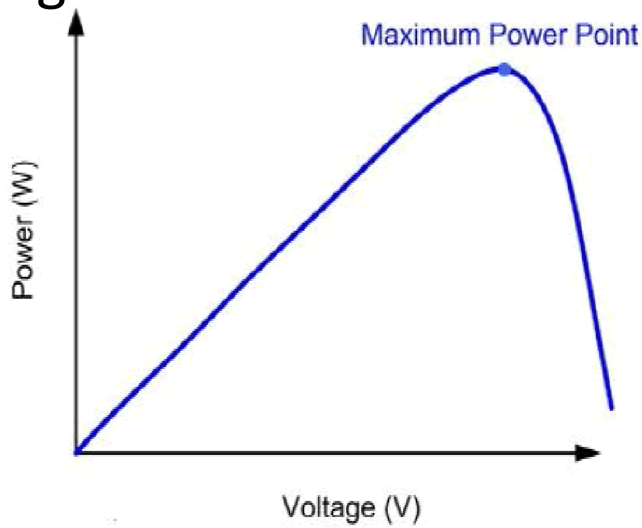
  This value depends on incident light intensity with typical values of 0.5 to 0.7 V observed for C to Si.

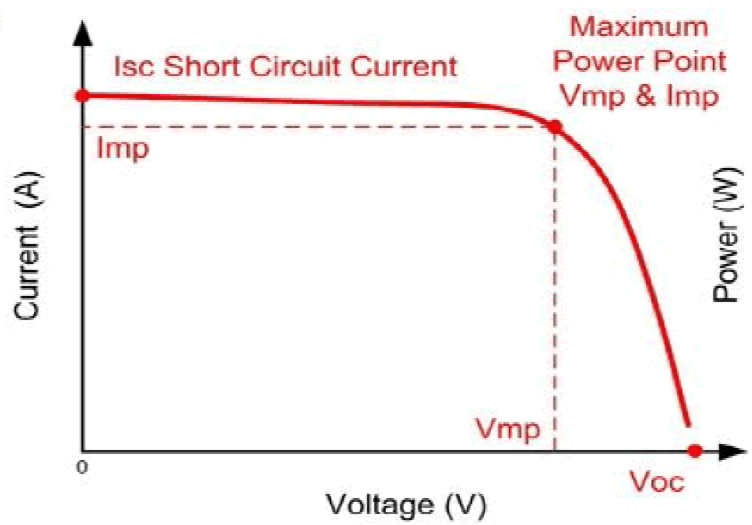
- Short circuit the solar cell ($R_L = 0$) -> all photo generated carriers flow through the external circuit -> no internal build up of charge carriers.

  The voltage measured across the cell would be 0 V, but the maximum possible current would flow in the external circuit.

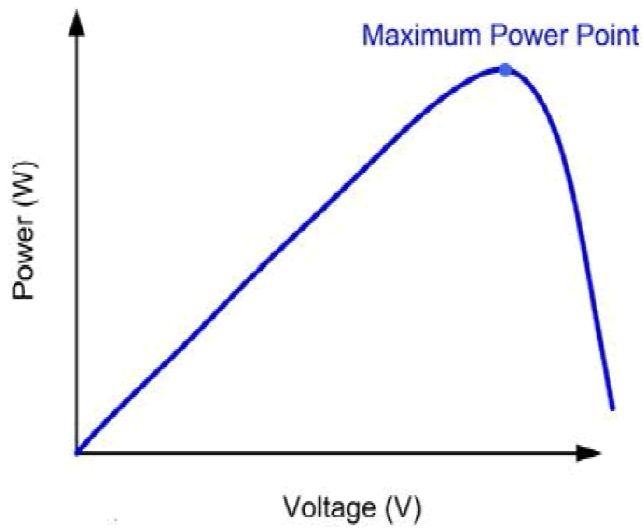


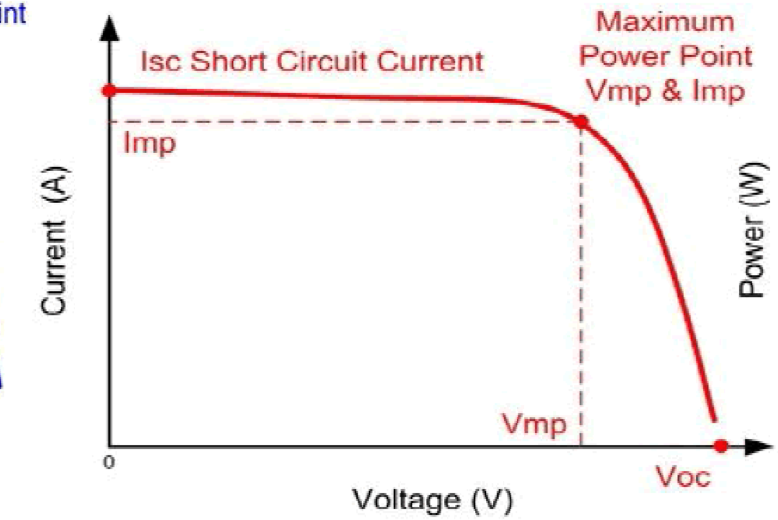
- With addition of a resistive load, the flow of current through the load will produce a voltage drop over the load, which will be equal to the voltage over the solar cell.
- This voltage over the cell will determine the cell "bias" and thus, the majority carrier diffusion current across the cell.
- At high values of R_L, there will be a high voltage drop across the cell and a small current through the load.
- Similarly, with low load resistance, we will have a small voltage over the load, equating to a small voltage over the cell but a high current through the load.



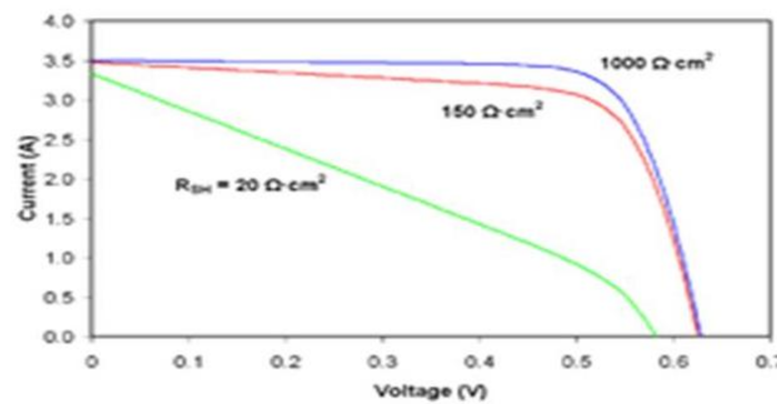


- Both the above two cases leads to relatively poor transfer of electrical power to the load as the power P = VI is relatively low.
- The maximum power is transferred to the load at the “knee” of the V-I curve where P = VI = maximum.





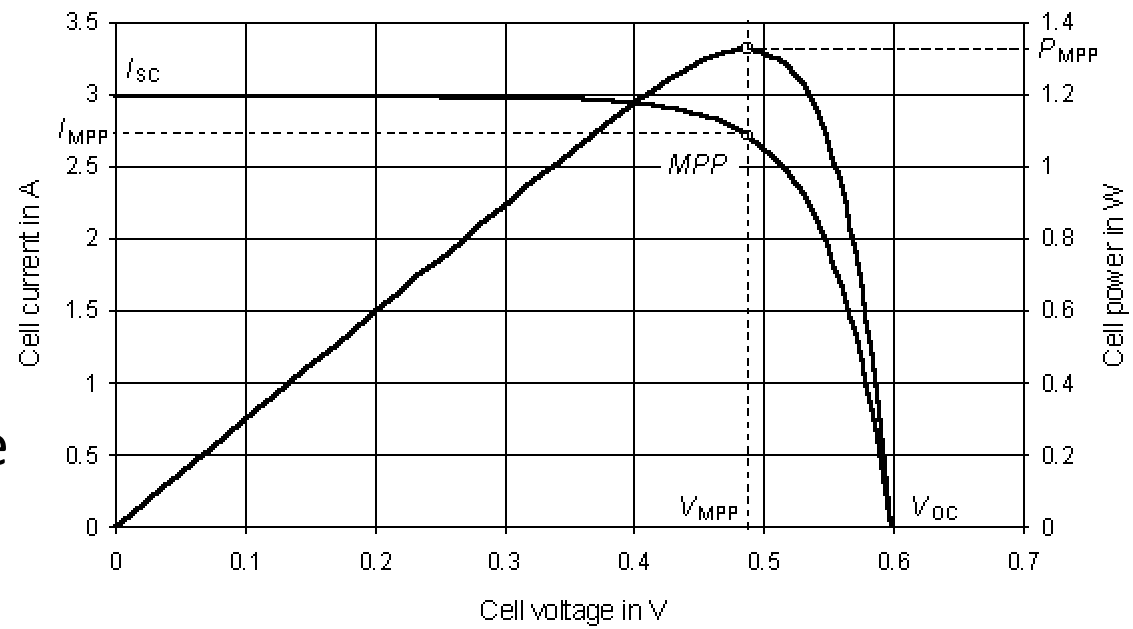
- The value of load connected with the circuit will shape up the curve further e.g. increasing load with sharpen the curve further



- The position of the MPP can be determined from a set of experimental V-I points taken while varying the load resistance.
- This could then also be determined from a load line curve and defines the ideal operating point of the device.
- The power delivered to the load at this point is also represented by the rectangle P = V'I' and will maximised when the area of the rectangle is maximised – $P_{MPP} = V_m \times I_m$
- We can then define the fill factor (FF) as a figure of merit for the cell where:

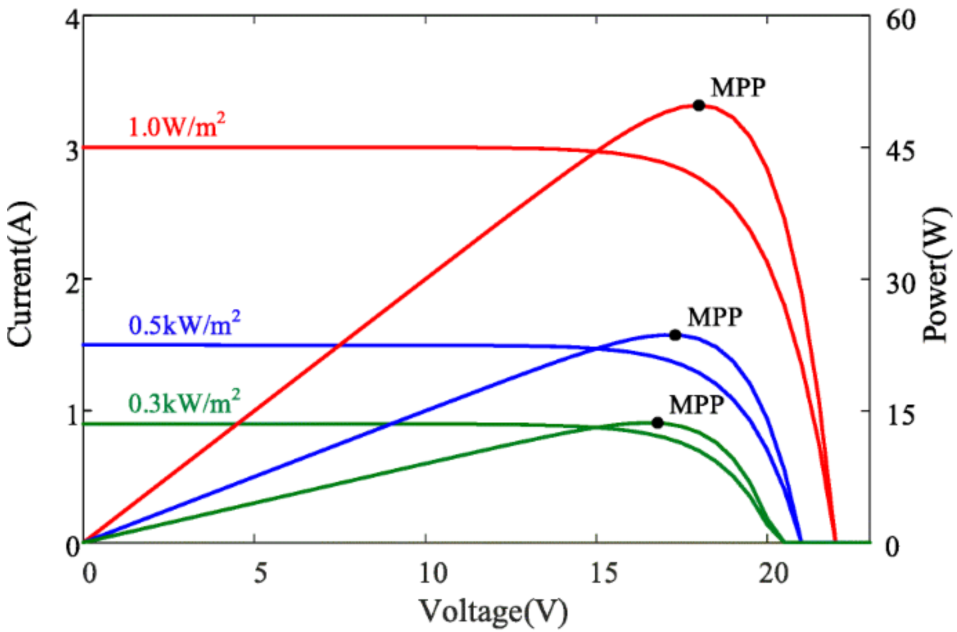
$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

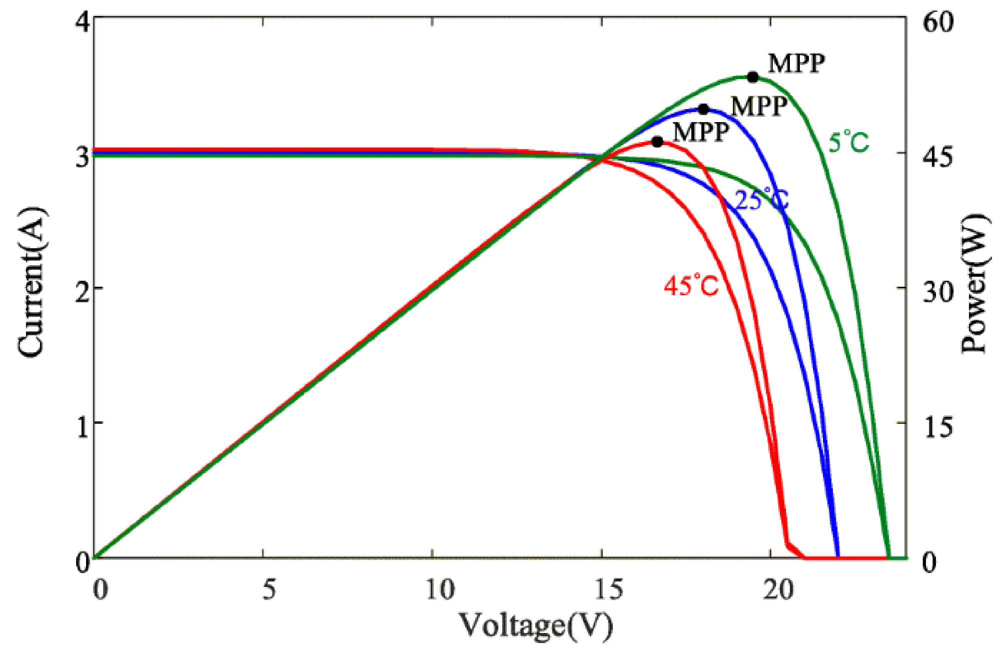
- The MPP will vary depending on the incident light with higher light levels shifting the MPP to lower load resistances.



Example for Tutorial 1 – Characteristics of Solar Cells

1. Installation of solar power systems requires analysis using the Maximum Power Point (MPP) curve graph. Given in the figures below are the MPP graphs of three PV system's irradiance profiles (left) and their temperature conditions (right).





a. Use the MPP curve as given in the top of the figure above to determine the maximum power of a solar cells system when given 0.5 kW/m^2 radiance.

[5 marks]

b. By referring to both graphs given above, describe how operating temperature and irradiance of solar power system affect its performance. [5 marks]

Answer:

a. From the graph, the MPP values of the solar cells system are: (2.5)

$$V_{oc} = 17 \text{ V}$$

And

$$I_{oc} = 1.6 \text{ A}$$

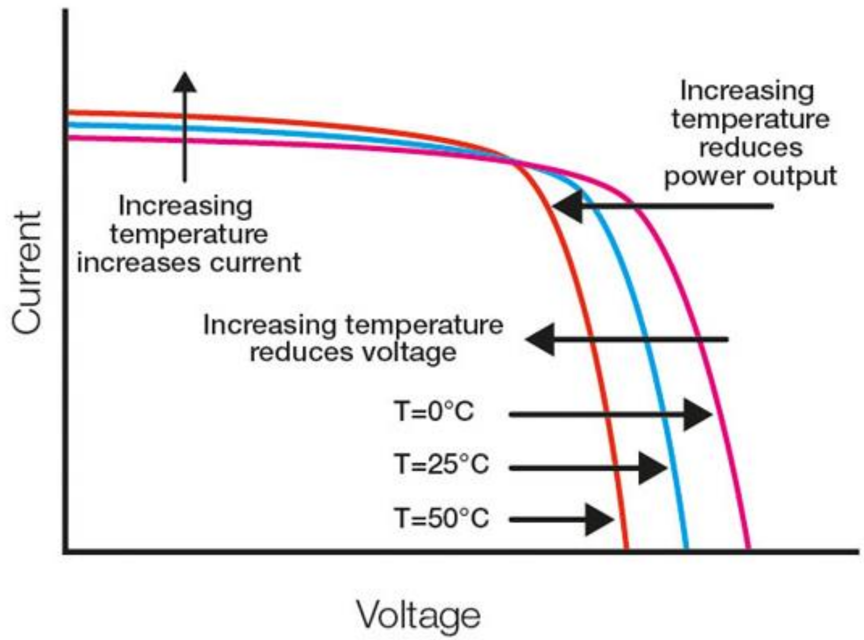
The maximum power of the given solar cells system is: (2.5)

$$P_{Max} = V_{oc} I_{oc} = (17 \text{ V})(1.6 \text{ A}) = 27.2 \text{ W}$$

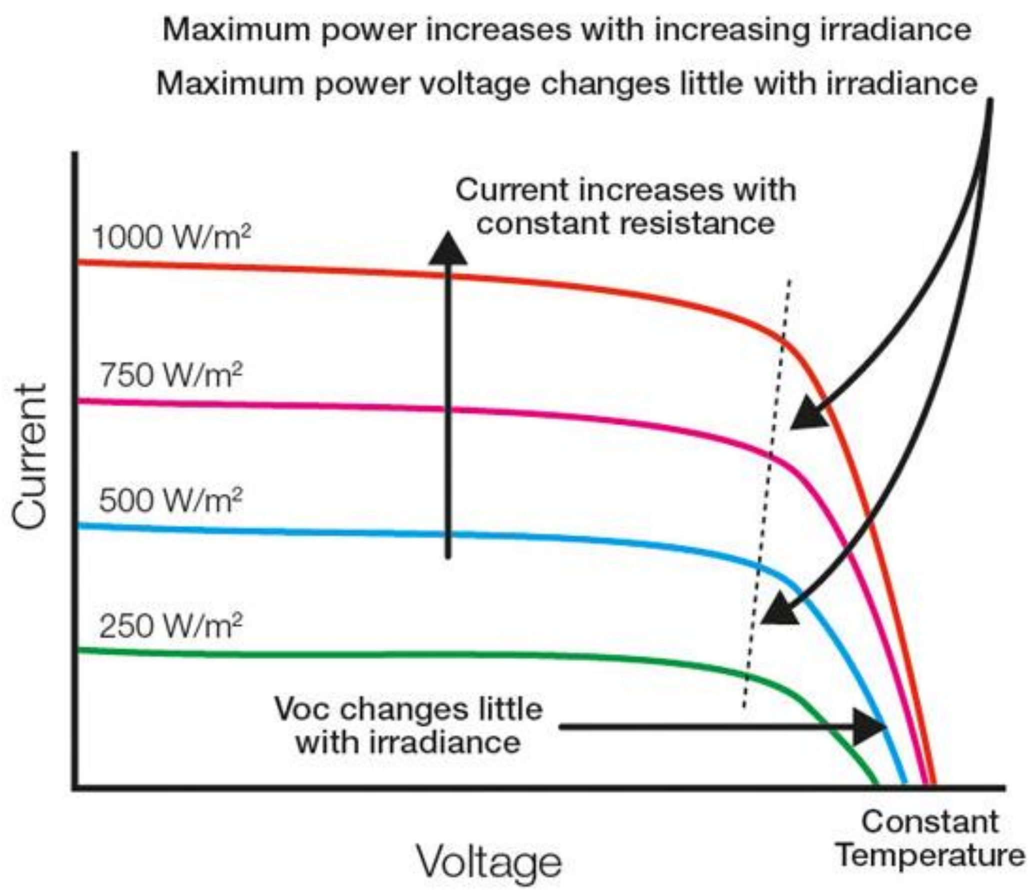
b. The open circuit voltage of a PV module varies with cell temperature.

As the temperature increases, due to environmental changes or heat generated by internal power dissipation during energy production, the open circuit voltage (V_{oc}) decreases.

This in turn reduces the power output.



In the same way, irradiance will also affect module performance, with a reduction of sunlight resulting primarily in a reduction in current and consequentially a reduced power output.



2. Consider the cell that drives a load of 3 Ω. The cell has an area of 3 x 3 cm and is illuminated with light of intensity 700 $W.m^{-2}$.

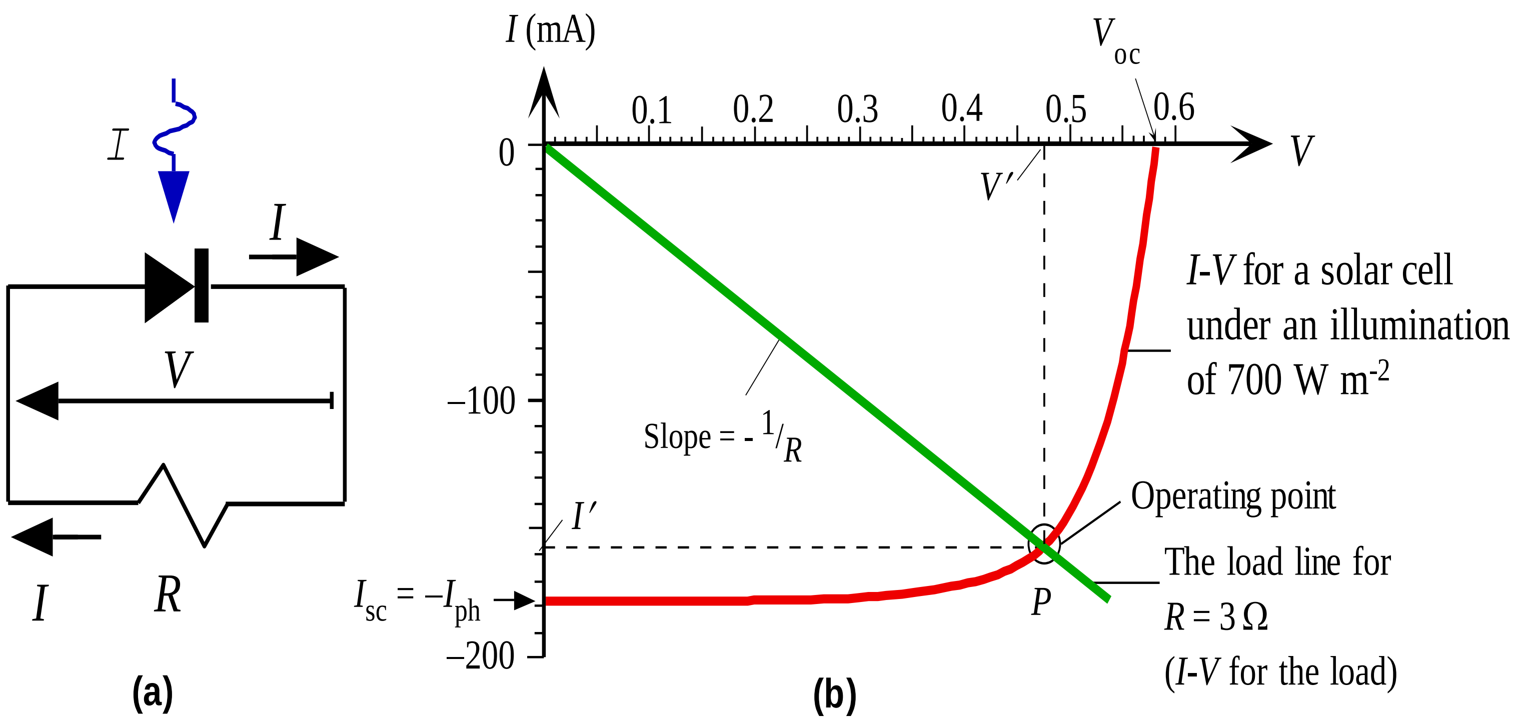
For a given solar cell panel, find:

a. The current and voltage in the circuit. [2 marks]

b. The power delivered to the load. [2 marks]

c. The efficiency of the solar cell. [2 marks]

d. The fill-factor of the solar cell. [2 marks]



Answer

a. From the load line, we have I' = 157 mA and V' = 0.475 V approximately.

b. The power delivered to the load is:

$$P_{out} = I'V'$$

= (157 mA)(0.475 V) = 74.6 mW

c. The incident power (P_{in}) is:

P_{in} = (light intensity)(area)

= (700 W.m^{-2})(0.03 m)^2 = 0.63 W

So, the efficiency of the solar cell is:

$$\eta = \left(\frac{P_{out}}{P_{in}}\right) \times 100$$

= (0.0746/0.63) x 100 = 11.8%

d. The maximum power point of the cell is obtained when:

$$P = I_{sc}V_{oc}$$

= (178 mA)(0.58 V) = 103.24 mW

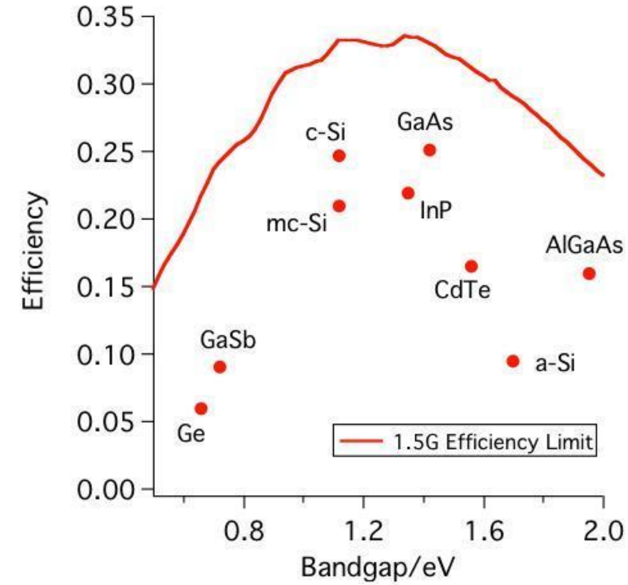
The fill factor of the solar cells is:

$$FF = \frac{I'V'}{I_{sc}V_{oc}}$$

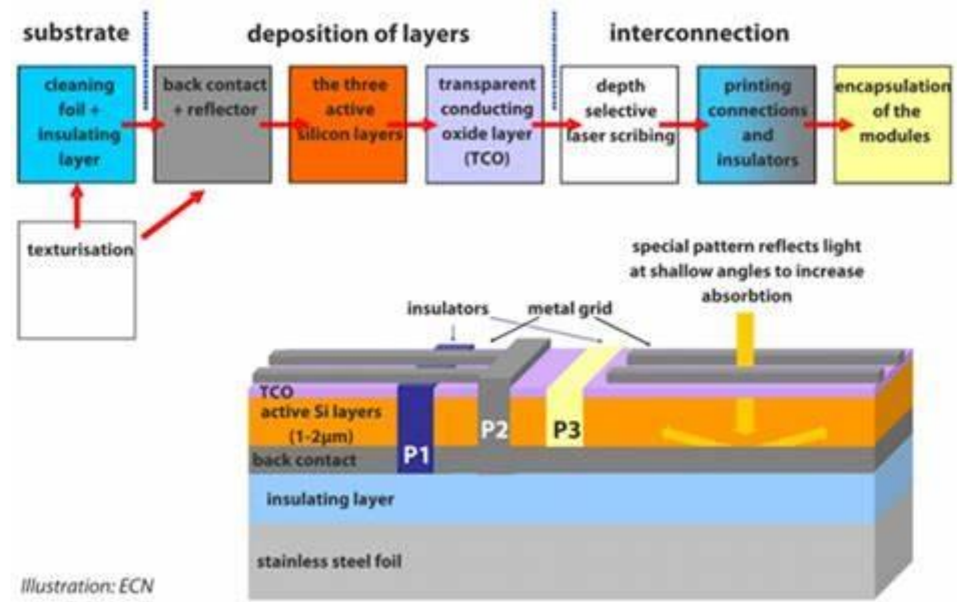
= 74.6 mW /103.24 mW = 0.72 or 72%

- Solar Cell Materials:
  a. Single crystal silicon.
  b. Polycrystalline silicon.
  c. Amorphous silicon.
  d. CdTe, $CuInSe_2$, GaAs, etc.
  e. Organic (plastic) solar cells.

(a. and b.: 1st generation PV)



- Silicon a poor light-to-electrical converter due to the indirect bandgap – typical efficiency ~ 15% in commercial cells
- So, why do we use it for solar cells?
- Are there not many more efficient materials ?



Solar cell efficiency as monitored by the National Renewable Energy Laboratory (USA)