XMUT204 Electronic Design

Note 2f: Special Purpose Diodes (Solar Cells I)

1. Solar Cells

In renewable energy topic, solar panel system is one of its key systems worth for studying.

1.1. Demands for Solar Cells

There is an exponential worldwide growth in solar photovoltaics (PV) as a source of renewable energy. As shown in the diagram below, you could observe an upward trend for installation of PV around the world.

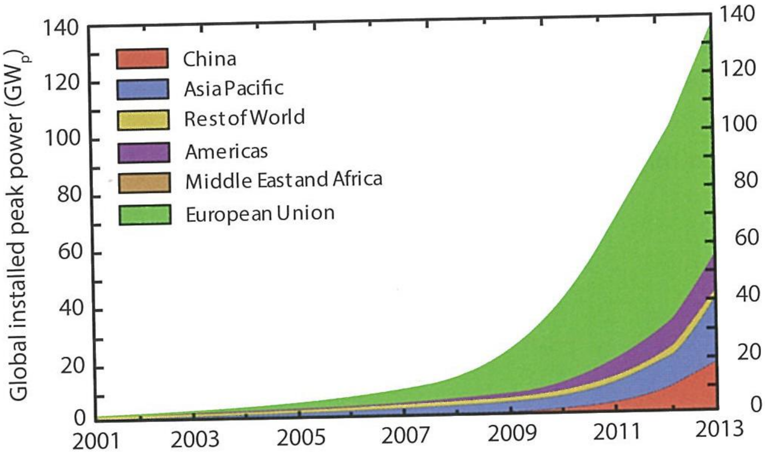


Figure 1: Installed PV capacity across the world per year

These demands become the reasons why solar cells are an important topic to study. But, at the same time, its uptake by societies around the world is still struggling to become the energy of choice as shown in the graph below.

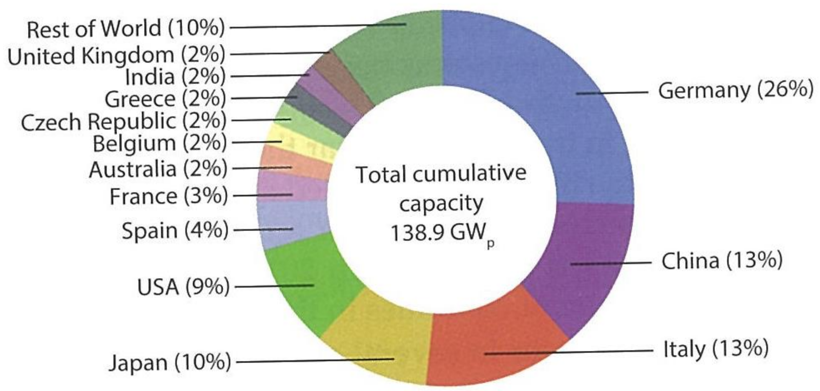


Figure 2: Fraction of PV installations for different countries

We will now use the knowledge of the previous sections on semiconductor properties, p-n junctions and optical absorption to understand the principle of operation of a solar cell.

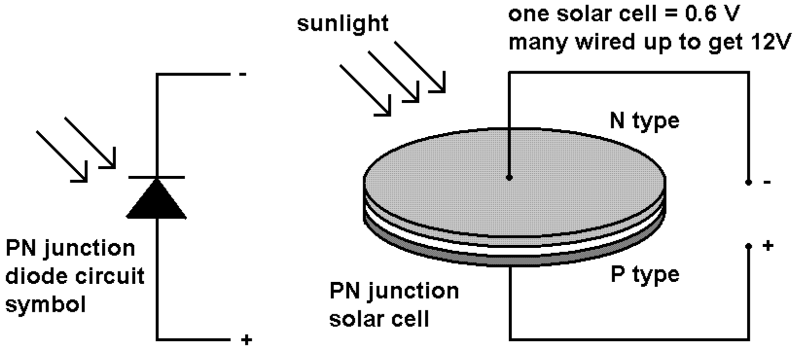


Figure 3: Photovoltaic effect in solar cells

These cells are based on the photovoltaic effect, i.e. the direct conversion of light into electrical energy.

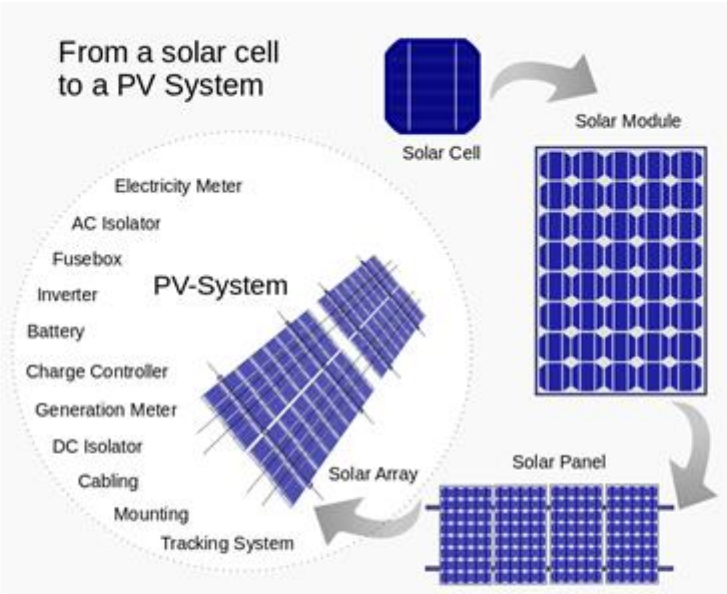


Figure 4: Various forms of solar power system units

In order to utilise this effect in a semiconductor, we need three steps to take place:

a. The generation of e–h^+ pairs as can be achieved when light with an energy greater than the bandgap is incident on the material.

b. A mechanism of 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.

c. A means of extracting these carriers from the semiconductor and using them to perform work in an external circuit – achieved by metal contact on the semiconductor circuit.

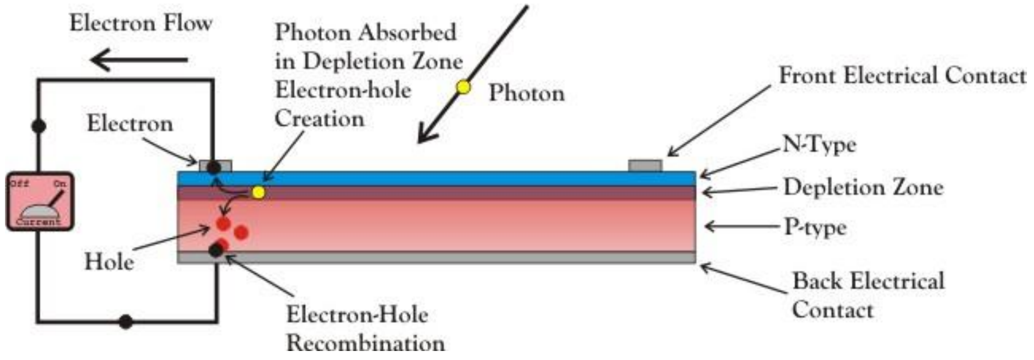


Figure 5: Solar energy generation in solar cells

1.2. Photo-Generation of e-h+ Pairs

Inside the solar cells, light with energy $E = hf > E_g$ will generate e-h+ pairs when incident on a semiconductor. If this generation takes place close to a p-n junction, the built-in field from the junction will sweep carriers across the junction and create a drift current.

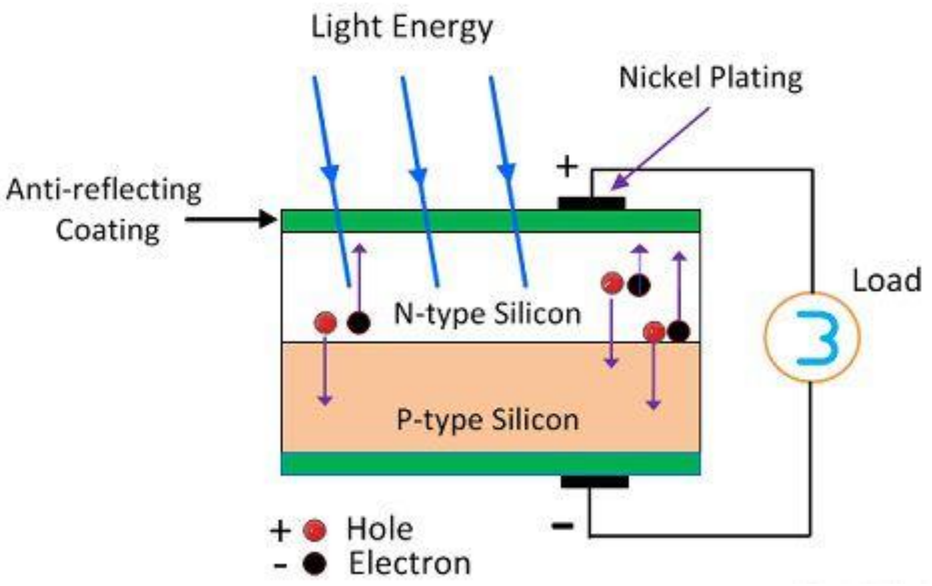


Figure 6: Photo electron processes in solar cells

Assume that the incident radiation creates 10^{15} e-h+ pairs.cm^{-3}. It will thus make no real difference to the majority carrier concentration, but will make a 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, they will be able to diffuse to the junction and swept across the junction by the electric field.

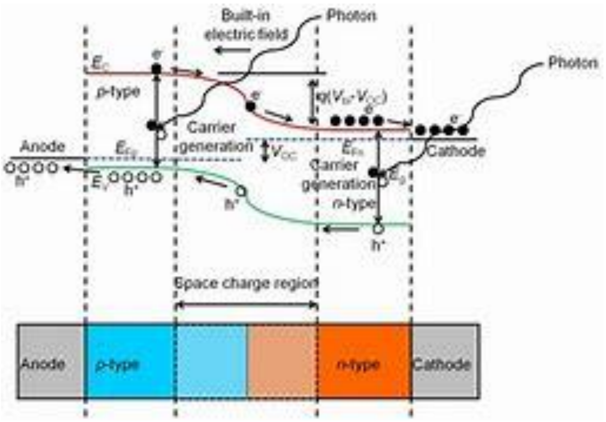


Figure 7: PN junction in the solar cells

We will thus have a drift current of minority carriers across the junction i.e. holes from n to p type and electrons from p to n type.

2. Construction of a Typical Solar Cell

There are two main parts of design construction of PV units e.g. the design of solar panel and the design solar cell. Typically, solar panel consists of the following parts: coating, cover, and frame. Whereas on the other hand the material design of solar cell consists of: N-type semiconductor, P-N junction, P-type semiconductor and Metal contacts.

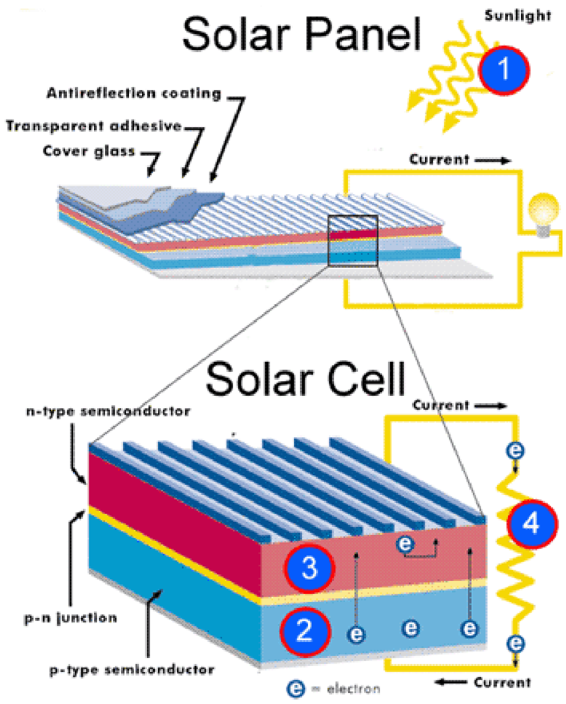
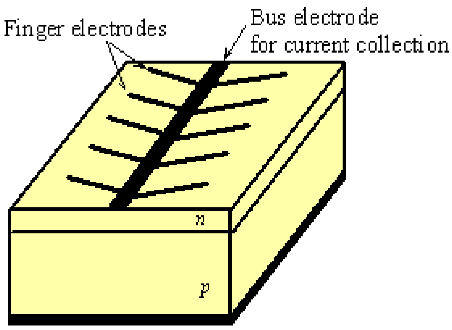


Figure 8: Designs of solar panel and solar cells

The electrons and holes can then be extracted from the semiconductor by means of metals contacts deposited on the surface and the carriers can flow in an external circuit with load.



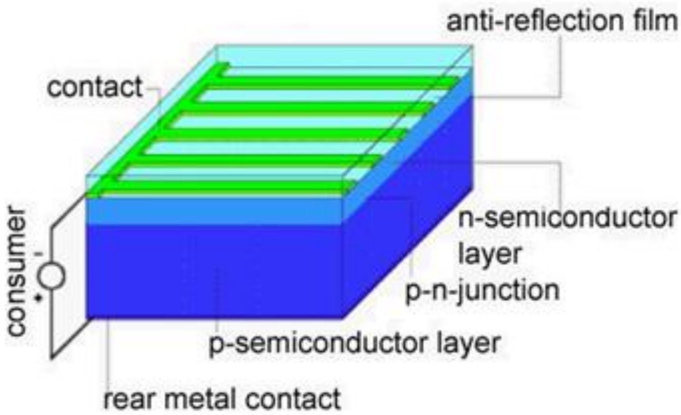


Figure 9: Design construction of metal contacts in solar cells

We use a system of finger electrodes plus bus bars on the front surface. On the back surface, we use a continuous contact that covers the whole back surface.

2.1. Absorption of Light in the Cell

By assuming a Si solar cell i.e. E_g = 1.1 eV, thus, we need 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 i.e. low absorption coefficient for low energies (long wavelengths) that increases as the photon energy increases.

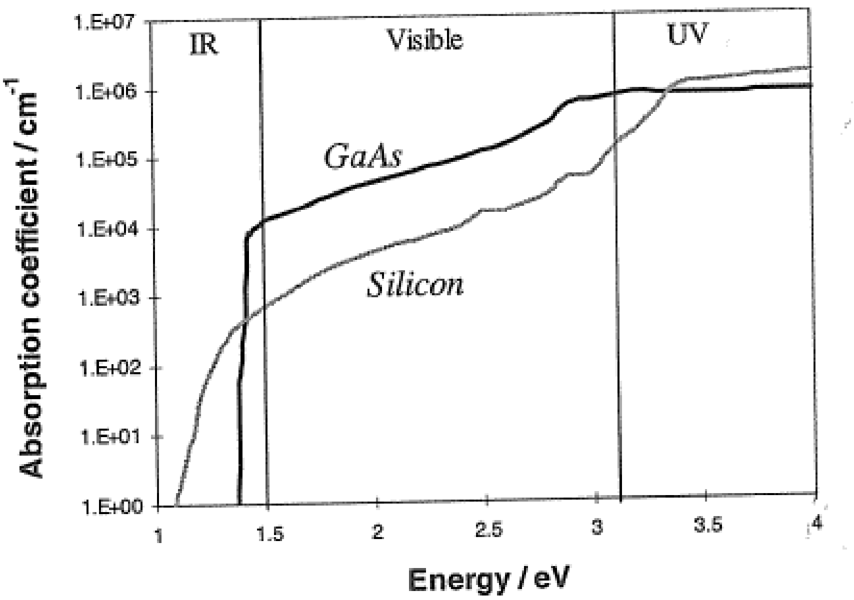


Figure 10: Light energy absorption profiles of Si vs. GaAs

The graph given in the diagram above shows an absorption of light in Si as compared to absorption in GaAs (e.g. it is 1.4 eV and a direct bandgap material). From the graph above, the absorption in GaAs is found to be much more efficient than Si.

2.2. Construction of a Typical Solar Cell

Solar cell is a thin, heavily doped n-region on illuminated surface side and thicker, moderately doped p-region. Illumination is carried out from the n-side i.e. use only finger contacts (Ohmic contacts) on this side to ensure light still penetrates semiconductor. Depletion region is formed that it extends mostly into the p-side. As a result, we have built-in field E_0 due to depletion region. We use a thin anti-reflection coating on front surface to reduce reflection and allow maximum light to enter device.

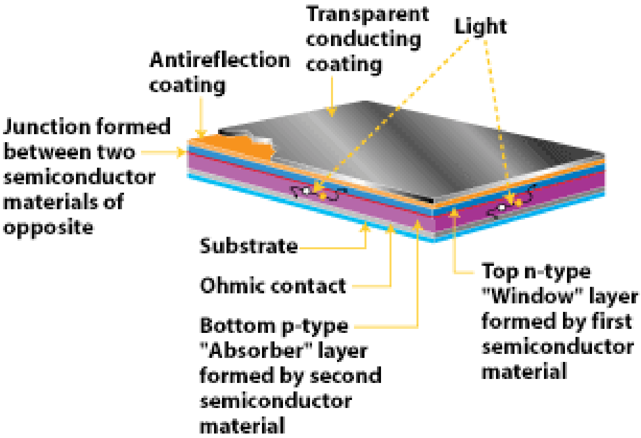


Figure 11: Construction of a solar panel

2.3. Operation of a Solar Cell

In a typical solar cell, light is 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.

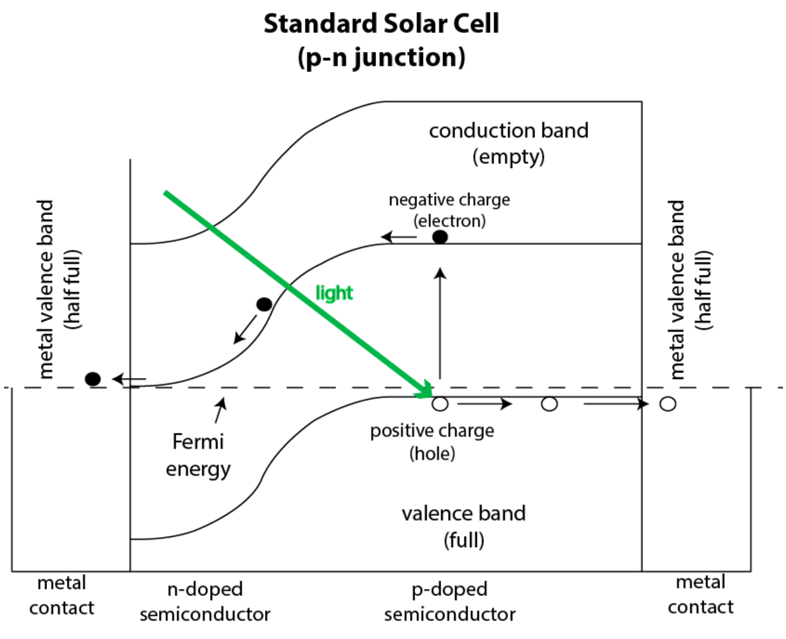


Figure 12: PN materials of solar cells

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.

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.

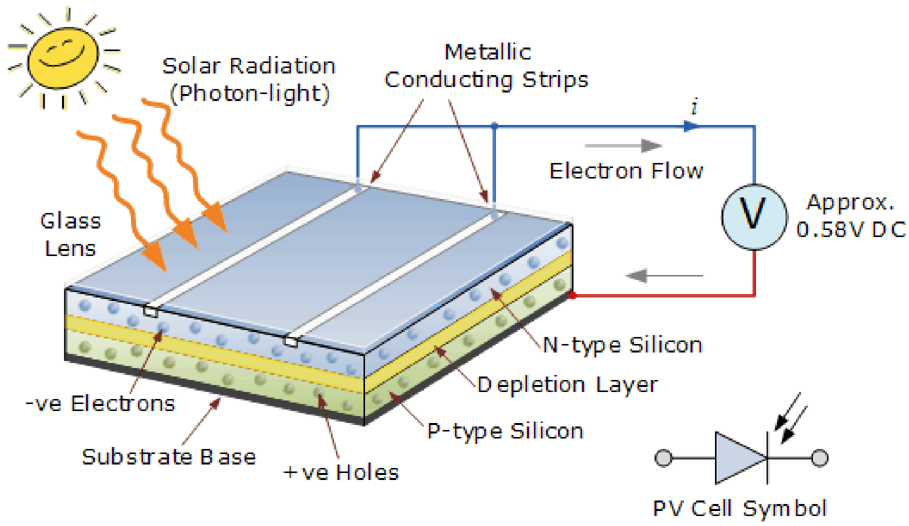


Figure 13: Solar cell – electricity conversion process

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 i.e. **a photocurrent.** In this process electrical work will be performed.

EHPs that cannot reach the depletion region are lost by recombination and does not contribute to the formation of a voltage i.e. 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 i.e. much thicker than the diffusion length.

3. Solar Cell Characteristics

In this section, we will look into the properties and behaviour of solar cells such as I-V characteristics and maximum power point (MPP) conditions.

3.1. Solar Cells – I-V Characteristics

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

a. Forward bias decrease the energy hill for electrons flowing from n to p as well as for holes flowing from p to n

b. We will thus increase the diffusion current (majority carriers) flow by forward bias.

c. If we consider the flow of conventional carriers, the flow is from p-type to n-type over the junction and we sketch the I-V curve as below.

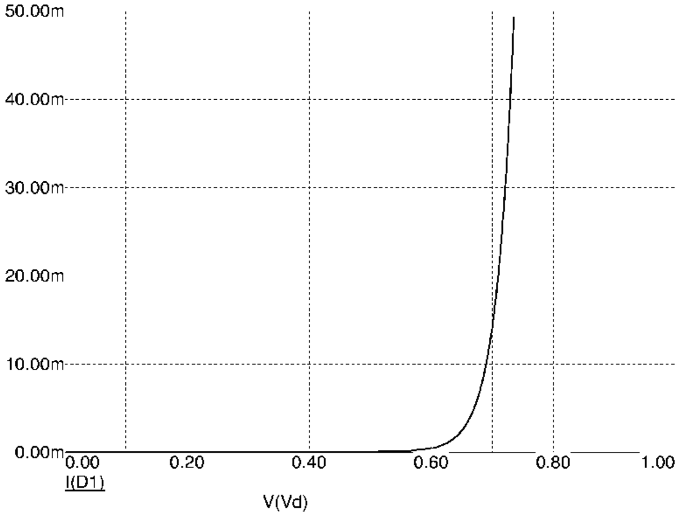


Figure 14: V-I characteristics curve of a conventional diode

Thus, if we 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 the following equation:

$$I_d = I_o\left[e\left(\frac{eV}{kT}\right) - 1\right]$$

If we consider the flow of charge carriers across the p-n junction of a solar cell, this generates e-h+ pairs on both sides of the junction, but this process is 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.

The flow of positive charge carriers is then from n-side to p-side inside the diode. Thus, it is 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:

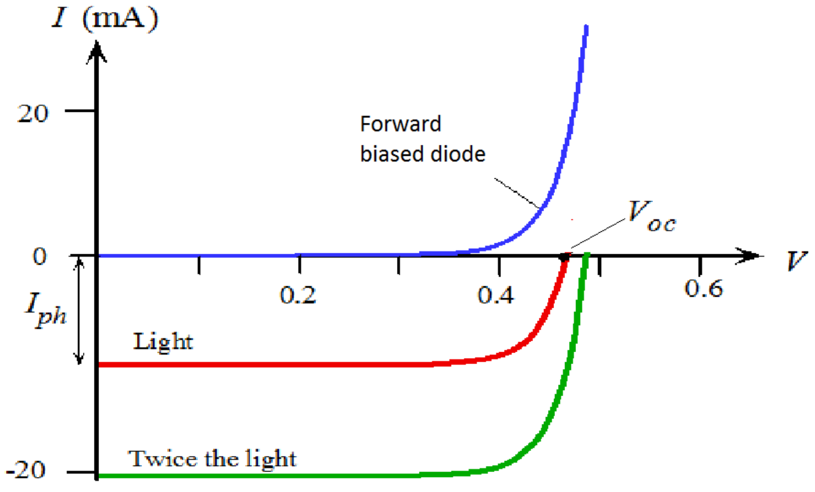


Figure 15: Influence of light intensity or power in solar cell characteristics

Then, often find the I-V curve of a solar cell plotted with negative current i.e. it 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!)

3.2. Current – Voltage Behaviour of a Solar Cell

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

In the open circuit case ($R_L = \infty$), we have the case as previously discussed, where there is 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-Si.

In the other extreme case, we would short circuit the solar cell ($R_L = 0$). All photo generated carriers would thus flow through the external circuit and there would be 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.

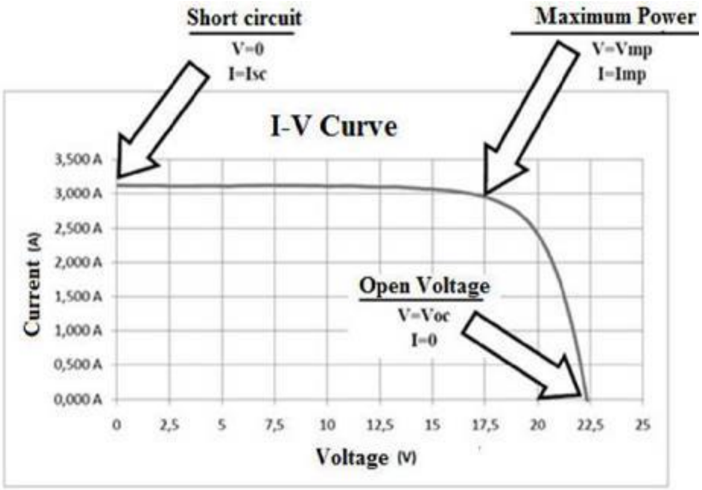


Figure 16: Extreme points in V-I characteristics curve of solar cells

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 lead 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 $P = VI = \text{maximum}$.

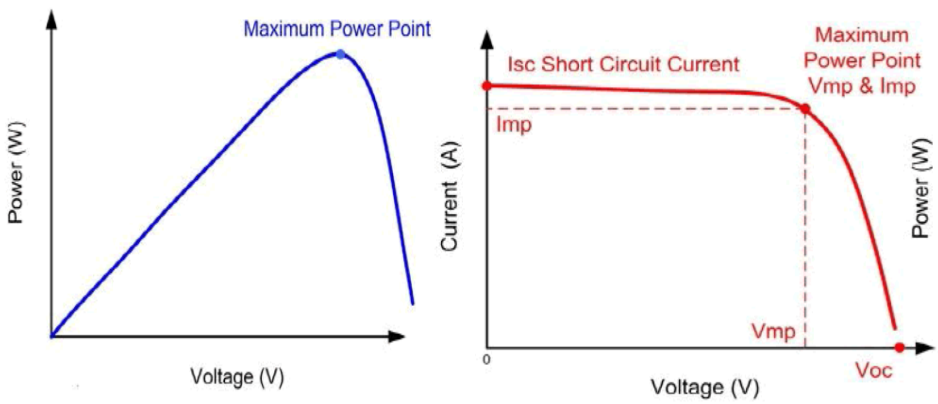


Figure 17: MPP and solar cell characteristics curve

The position of the MPP can be determined from a set of experimental V-I points taken while varying the load resistance. This can 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 – $P_{MPP} = V_m I_m$.

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.

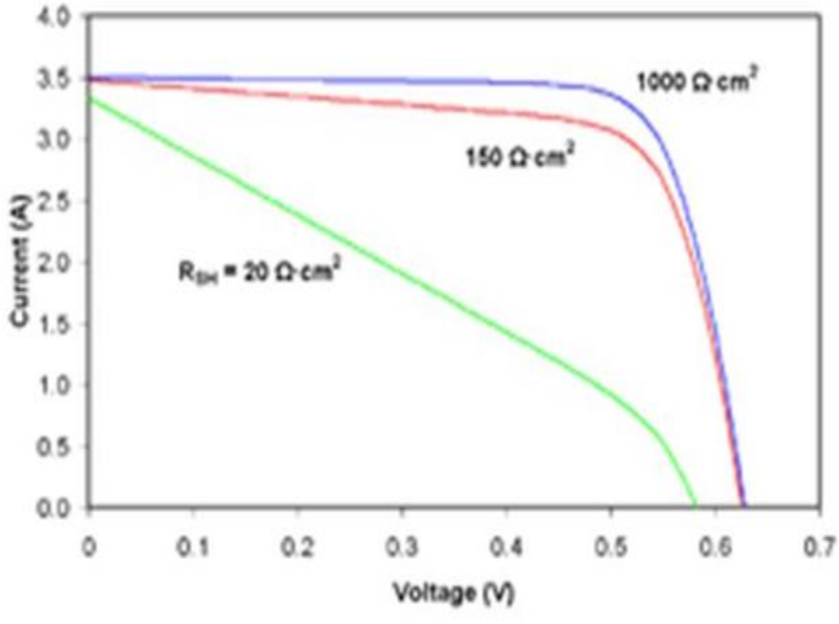
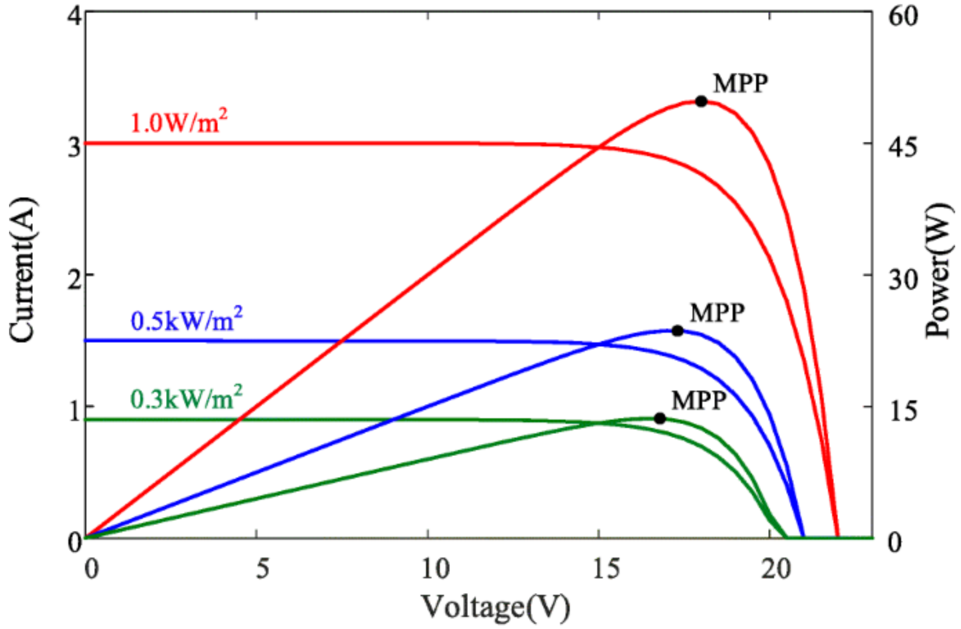
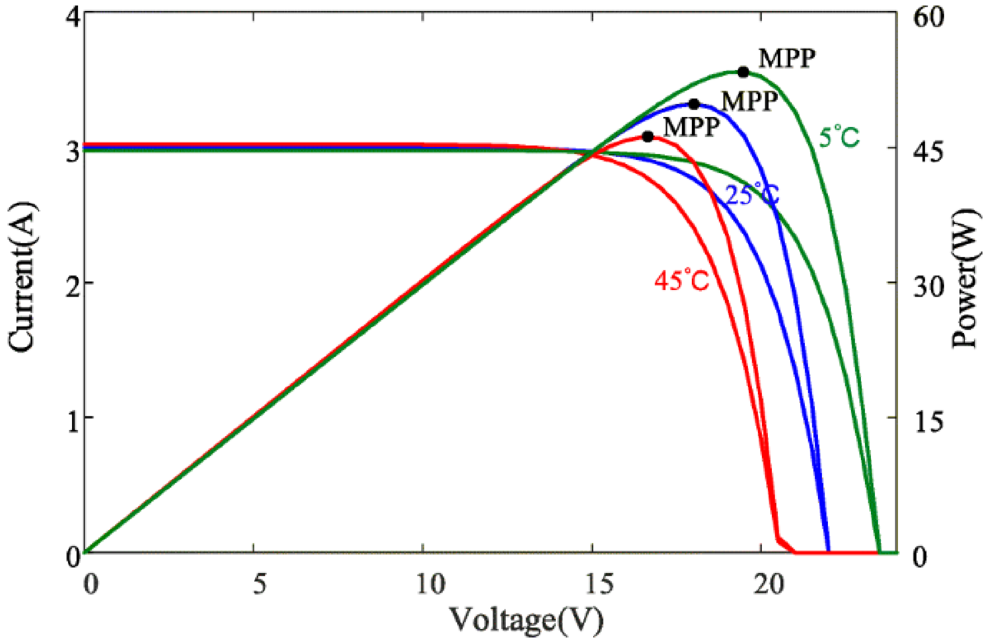


Figure 18: Load effect in solar power system

Example for Tutorial 1:

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 (top) and their temperature conditions (bottom).





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)

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

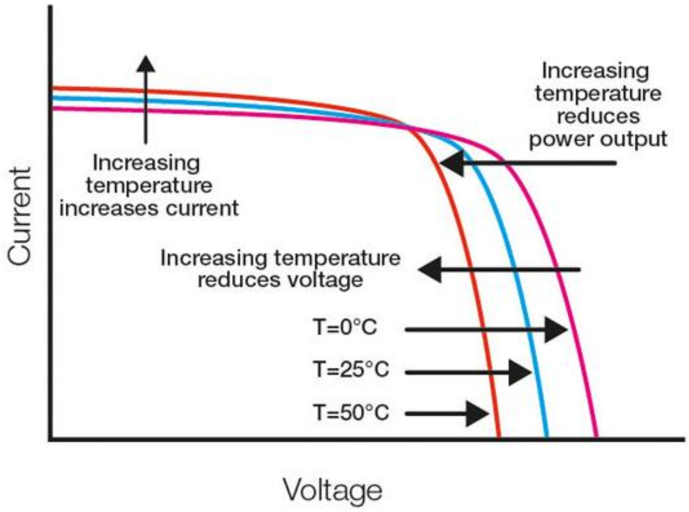
And

I_{OC} = 1.6 A

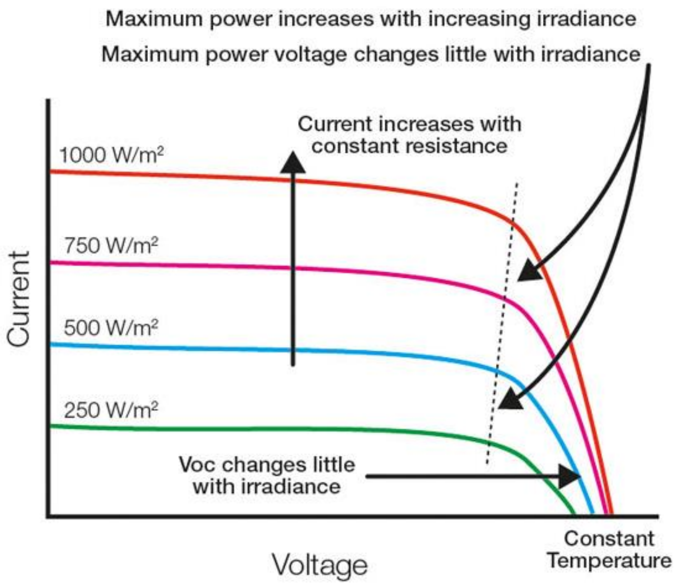
The maximum power of the given solar cells system is: (2.5)

$P_{Max} = V_{OC}I_{OC}$ = 17 V x 1.6 A = 27.2 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 solar cell figure driving a load of 3 Ω. The cell has an area of 3 x 3 cm and is illuminated with light of intensity 700 $W.m^{-2}$.

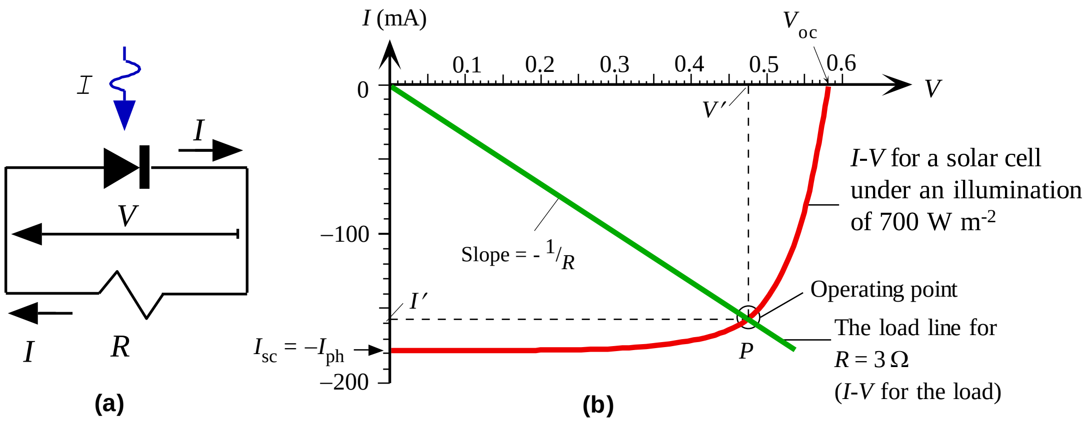
The diagrams given below are equivalent circuit and an MPP curve of a given solar power unit. Find:

a. The current (I) and voltage (V) in the circuit.

b. The power (P) delivered to the load.

c. The efficiency (η) of the solar cell.

d. The fill factor (FF) of the solar cell.



(a) (b)

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:

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

$$= 157 \text{ mA x } 0.475 \text{ V} = 74.6 \text{ mW}$$

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

$$P_{in} = \text{(light intensity)(area)}$$

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

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%

4. Solar Cell Industries

After studying its characteristics and properties, it is very important to learn on how to manufacture the solar cells in the factories and industries.

4.1. Solar Cell Materials and Manufacturing

There are various types of solar Cell Materials: Single crystal silicon, polycrystalline silicon, amorphous silicon, CdTe, $CuInSe_2$, GaAs, etc…, or nowadays, organic (plastic) solar cells. As shown in the diagram given below, these materials are different from one to another in terms of their efficiencies and band gaps. Typically, binary compound materials such as GaAs, InP, CdTe are more efficient than their intrinsic counterparts i.e. Si or Ge.

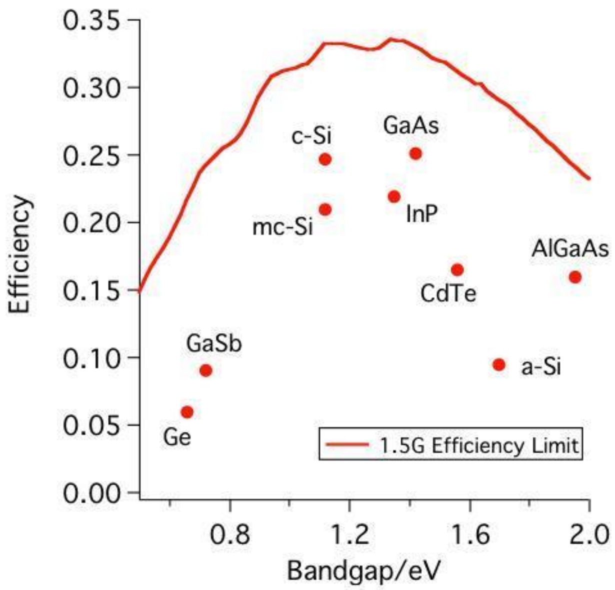


Figure 21: Materials used for solar cells

We have said previously that silicon a poor light-to-electrical converter due to the indirect band gap i.e. typical efficiency ~ 15% in commercial cells. So, why do we use it for solar cells? Are there not many more efficient materials?

Manufacturing of Solar Cells in the industries involved several processes: substrate preparation, deposition of layers and interconnection and assembly of the parts.

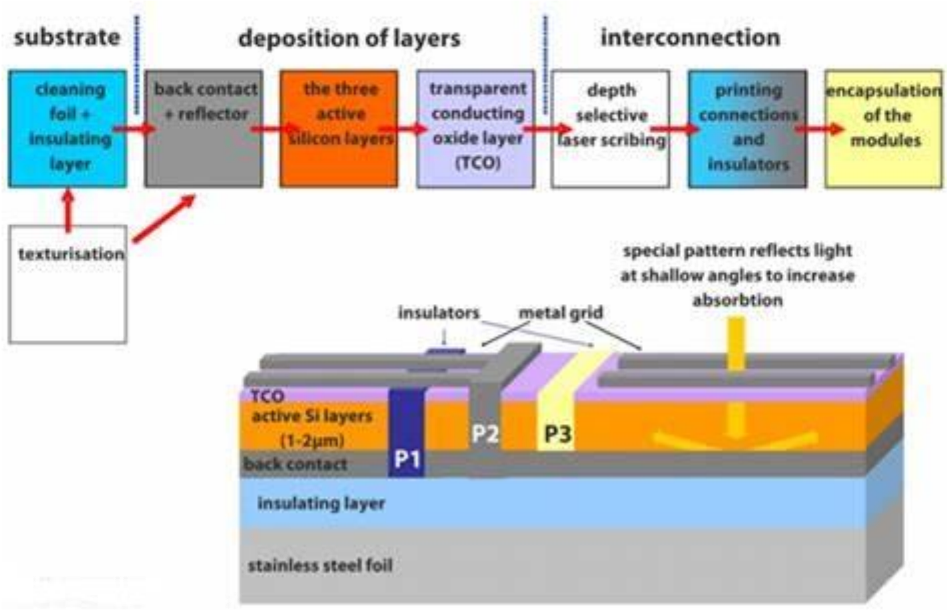


Figure 22: Processes in the manufacturing of solar cells

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

Notice from the graph given below that in 2015 we managed to invent solar cells that have 40-45% efficiency. This is a lot more than conventional or early model of the solar cell that have typical values of 10-15%.

The semiconductor materials developed for these solar cells are typically classified as multi-junction cells whereas emerging photovoltaic materials such as organic and inorganic variants are still struggling to achieve the high efficiency of the other semiconductor materials.

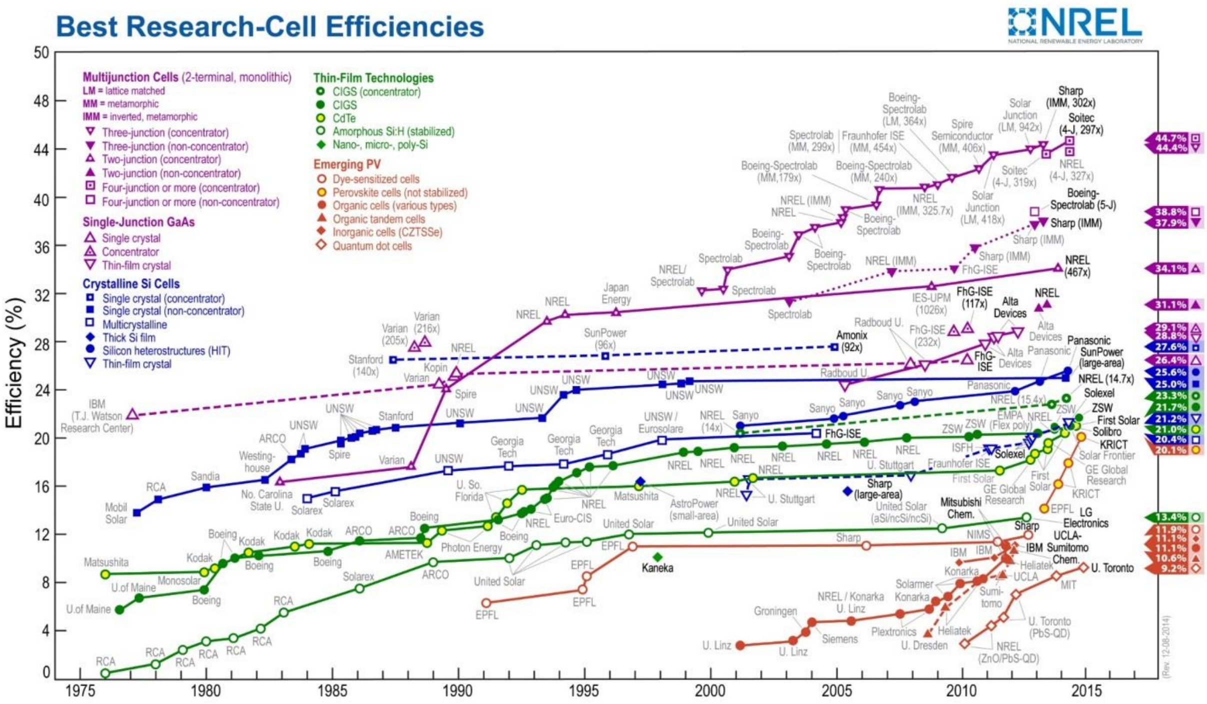


Figure 23: Research and development trends in solar cells