

UNIT III SEMICONDUCTING MATERIALS

CLASSIFICATION OF SEMICONDUCTORS

Based on the purity, semiconductor is classified into two types.

1. Intrinsic semiconductors or Elemental semiconductors
2. Extrinsic semiconductors or Compound semiconductors

3.1 Intrinsic semiconductors

A pure semiconductor without any impurities is known as an intrinsic semiconductor.

Example: Ge, Si (In the form of pure)

These are made from single element. They also known as indirect band gap semiconductors. In which the recombination of free electron from the conduction band with the hole in the valence band takes place via traps. During recombination phonons [lattice vibrations] are produced and they heat the crystal lattice (position of the atom). These are the IV group element in the periodic table.

3.2 Compound Semiconductors

The Compound Semiconductor is a semiconductor compound composed of elements from two or more different groups of the periodic table. They also known as **direct band gap** semiconductors.

i.e., III – V group, II – VI group and IV – VI group.

Here the recombination electron and hole takes place directly, during recombination photo emitted.

Example : GaAs, GaP,

Based on the type of impurity they are classified into

- i) N-type semiconductor

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ii) P-type semiconductor

3.3 Difference between N-type and P-type semiconductor

S. No	N-type	P-type
1.	It is donor type	It is acceptor type
2.	Impurity atom is pentavalent	Impurity atom is trivalent
3.	Donor level lies close to the bottom of the conduction band	Acceptor level lies close to the top of the valence band.

N-type

1. It is donor type
2. Impurity atom is penta-valent
3. Donor level lies close to the bottom of the conduction band

P-type

1. It is acceptor type
2. Impurity atom is trivalent
3. Acceptor level lies close to the top of the valence band.

3.4 Difference between Elemental and Compound Semiconductors

Elemental semiconductors

These are made from single element. (mixed) element. These are made from IV group and VI group elements. These are called as indirect band gap semiconductor (electron-hole recombination takes place through traps) Heat is produced in the recombination. Life time of charge carriers is more due to indirect recombination. Current amplification is more

These are used for making diodes, transistor, etc. Example : Ge, S

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S.No	Elemental semiconductors	Compound semiconductors
1.	These are made from single element. (mixed) element.	These are made from compound
2.	These are made from IV group and VI group elements	These are made from III and V [or] II and VI elements.
3.	These are called as indirect band gap semiconductor (electron-hole recombination takes place through traps)	These are called as direct band gap semiconductor (electron-hole recombination takes place directly)
4.	Heat is produced in the recombination	Photons are emitted during recombination
5.	Life time of charge carriers is more due to indirect recombination	Life time of charge carriers is less due to direct recombination.
6.	Current amplification is more	Current amplification is less.
7.	These are used for making diodes, transistor, etc.	These are used for making LED, laser diodes, etc.
8.	Example : Ge, Si	Example : GaAs, GaP, CdS, MgO

Compound semiconductors

These are made from compound

These are made from III and V [or] II and VI elements.

These are called as direct band gap semiconductor (electron-hole recombination takes place directly) Photons are emitted during recombination. Life time of charge carriers is less due to direct recombination. Current amplification is less. These are used for making LED, laser diodes, etc.

Example: GaAs, GaP, CdS, MgO

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3.5 CLASSIFICATION OF CONDUCTORS, INSULATORS AND SEMICONDUCTORS BASED ON BAND THEORY

The electrical conduction properties of different elements and compounds can be explained in terms of the electrons having energies in the valence and conduction bands. The electrons lying in the lower energy bands, which are normally filled, play no part in the conduction process.

Conductors

Conductors are those materials in which plenty of free electrons are available for electric conduction. In terms of energy bands, it means that electrical conductors are those which have overlapping valence and conduction bands as shown in Figure. In fact, there is no physical distinction between the two bands, hence, the availability of a large number of conduction electrons. Hence the free electrons can easily move from the valence band to conduction band, and are available for electrical conduction under the action of an electric field. Another point worth noting is that in the absence of forbidden energy band in good conductors, there is no structure to establish holes. The total current in such conductors is simply a flow of electrons. It is exactly for this reason that the existence of holes was not discovered until semiconductors were studied thoroughly.

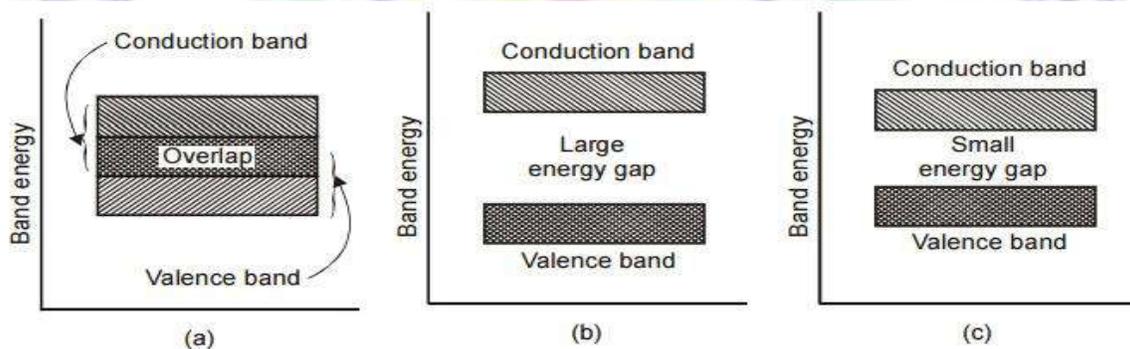


Fig.3.1 Energy band gap (a) conductor (b) insulator (c) semiconductor

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Insulators

Stated simply, insulators are those materials in which valence electrons are tightly bonded to their parent atoms, thus requiring very large electric field to remove them from the attraction of the nuclei

Have a filled valence band.

Have an empty conduction band and

Have a large energy gap (the order of > 3 eV) between them.

This is shown in Fig. 2.1(b). For conduction process, electrons must be given sufficient energy to jump from the valence band to the conduction band. Increase in temperature enables some electrons to go to the conduction band which in fact accounts for the negative resistance – temperature coefficient of insulators. Only at very high temperature, the thermal energy will be sufficient to raise the electrons from valence band to conduction band. Therefore at high temperatures even insulators can conduct electric current.

Semiconductors

A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. (Example: Ge, Si).

In terms of energy band, semiconductors can be defined as those materials which have almost an empty conduction band and almost filled valence band with a very narrow energy gap (of the order of 1 eV) separating the two as shown in Figure.

In semiconductors, there is a small energy gap. Hence, the electrons require small energy to jump from valence band to conduction band. This energy may be in the form of heat or light. Even

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at room temperature, the thermal energy is sufficient to transfer electrons from valence band to conduction band. But when the semiconductor is at zero Kelvin, the thermal energy is not sufficient to transfer the electrons from the valence band to conduction band. Semiconductors at 0K behave like insulators. In semiconductors the resistance decreases with increase in temperature.

The resistivity of the above three classes of materials as follows

Conductors = 10^{-8} to 10^{-6} ohm m

Insulators = 10^{10} to 10^{16} ohm m

Semiconductors = 10^{-4} to 0.5 ohm m

3.6 CARRIER CONCENTRATION IN INTRINSIC SEMI-CONDUCTORS

In a semiconductor both electrons and holes are charge carriers (known as carrier concentration). A semiconductor in which holes and electrons are created by thermal excitation across the energy gap is called an intrinsic semiconductor.

In an intrinsic semiconductor the number of holes is equal to the number of free electrons.

At $T = 0K$, valence band is completely filled and conduction band is completely empty. Thus the intrinsic semiconductor behaves as a perfect insulator.

At $T > 0K$, the electron from the valence band shifted to conduction band across the band gap.

Thus there are number of free electrons and holes in intrinsic semiconductor. Fermi level lies in midway between conduction band and valence band in intrinsic semiconductors

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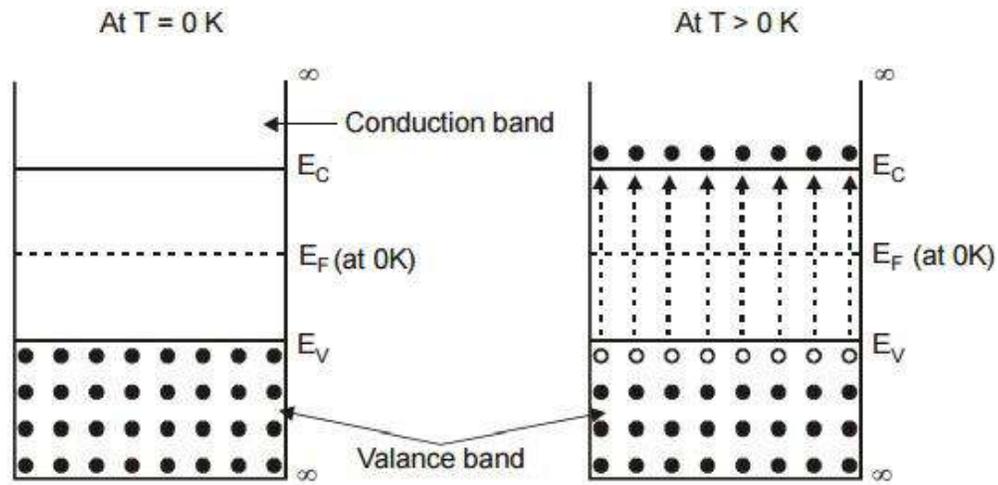


Fig. 3.2 Energy Band Diagram in an Intrinsic Semiconductor

3.7 Density of electrons in conduction band

Let dN be the number of electrons in the energy interval E and $E + dE$ in the conduction band.

$$dN = N(E) dE F(E) \quad \dots (1)$$

Where $N(E) dE$ is the density of states in the energy interval E and $E + dE$ and $F(E)$ is the probability that a state of energy E is occupied.

The number of electrons in conduction band can be calculated by integrating the equation(1) from energy E_c (ie., energy from the bottom of the conduction E_c to the top of conduction band infinity)

$$N_e = \int_{E_c}^{\infty} N(E) dE F(E) \quad \dots (2)$$

We know that,

$$N(E) dE = \frac{\pi}{2h^3} (8m)^{3/2} E^{1/2} dE$$

Since, the semiconductor is a crystal, the electron motion is considered in the periodic potential.

So, the mass 'm' is replaced as effective mass m^* and the kinetic energy of the electron, $E = E - E_c$

$$N(E) dE = \frac{\pi}{2h^3} (8m_e^*)^{3/2} [E - E_c]^{1/2} dE \quad \dots (3)$$

$$F(E) = \frac{1}{1 + \exp\left[\frac{[E - E_F]}{K_B T}\right]}$$

In the above expression $E \gg E_F$, So we can neglect one (1) in the denominator.

$$F(E) = \frac{1}{\exp\left[\frac{[E - E_F]}{K_B T}\right]} \quad \dots (4)$$

Substituting equation (3) & (4) in equation (2)

$$N_c = \int_{E_c}^{\infty} \frac{\pi}{2h^3} (8m_e^*)^{3/2} [E - E_c]^{1/2} \exp\left[\frac{[E_F - E]}{K_B T}\right] dE \quad \dots (5)$$

To solve this integral

$$\text{Put } E - E_c = x K_B T$$

$$E = E_c + x K_B T$$

Differentiating above equation, we get

Put $E - E_c = x K_B T$

$$E = E_c + x K_B T$$

Differentiating above equation, we get

$$dE = K_B T dx$$

Lower limits

When $E - E_c = x K_B T$

$$E = E_c$$

$$E_c - E_c = x K_B T$$

$$0 = x$$

Upper limits

When $E - E_c = x K_B T$

$$\infty - E_c = x K_B T$$

$$\infty = x$$

∴ The limits are 0 to ∞

$$N_c = \frac{\pi}{2h^3} (8m_e^*)^{3/2} \int_0^{\infty} (xK_B T)^{1/2} \exp\left[\frac{E_F - xK_B T - E_c}{K_B T}\right] K_B T dx$$

$$N_c = \frac{\pi}{2h^3} (8m_e^*)^{3/2} \int_0^{\infty} (x)^{1/2} (K_B T)^{3/2} \exp\left[\frac{E_F - E_c}{K_B T}\right] \exp\left[\frac{-xK_B T}{K_B T}\right] dx$$

3.8 FERMİ LEVEL AND VARIATION OF FERMİ LEVEL WITH TEMPERATURE IN AN INTRINSIC SEMICONDUCTOR

Derivation of Fermi Level

In an intrinsic semiconductor,

i.e., Density of electrons (N_e) = Density of holes (N_h)

$$2 \left[\frac{2\pi m_e^* K_B T}{h^2} \right]^{3/2} \exp \left[\frac{E_F - E_C}{K_B T} \right] = 2 \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/2} \exp \left[\frac{E_V - E_F}{K_B T} \right]$$

$$\left[m_e^* \right]^{3/2} \exp \left[\frac{E_F - E_C}{K_B T} \right] = \left[m_h^* \right]^{3/2} \exp \left[\frac{E_V - E_F}{K_B T} \right]$$

$$\left[\frac{m_h^*}{m_e^*} \right]^{3/2} = \exp \left[\frac{E_F - E_C - E_V + E_F}{K_B T} \right]$$

$$\left[\frac{m_h^*}{m_e^*} \right]^{3/2} = \exp \left[\frac{2E_F - E_C - E_V}{K_B T} \right]$$

Taking log on both sides, we get,

$$\log \left[\frac{m_h^*}{m_e^*} \right]^{3/2} = \frac{[2E_F - E_C - E_V]}{K_B T}$$

$$\frac{3}{2} \log \left[\frac{m_h^*}{m_e^*} \right] = \frac{[2E_F - E_C - E_V]}{K_B T}$$

$$\frac{3}{2} K_B T \log \left[\frac{m_h^*}{m_e^*} \right] = [2E_F - (E_C + E_V)]$$

$$2E_F = (E_C + E_V) + \frac{3}{2} K_B T \log \left[\frac{m_h^*}{m_e^*} \right]$$

$$E_F = \frac{E_C + E_V}{2} + \frac{3}{4} K_B T \log \left[\frac{m_h^*}{m_e^*} \right] \quad (13)$$

$$\text{If } m_h^* = m_e^*, \text{ then at } T = 0 \text{ K, } \frac{3}{2} K_B T \log \left[\frac{m_h^*}{m_e^*} \right]$$

$$E_F = \left[\frac{E_C + E_V}{2} \right] \quad \dots (12)$$

Therefore, the Fermi level lies in the midway between Conduction level E_c and Valence level E_v at $T = 0K$.

But in general $m_h = m_e$ so the Fermi level is a function of temperature and is raised slightly with temperature.

3.9 Light emitting diode (LED)

The symbol of LED is similar to the normal p-n junction diode except that it contains arrows pointing away from the diode indicating that light is being emitted by the diode.

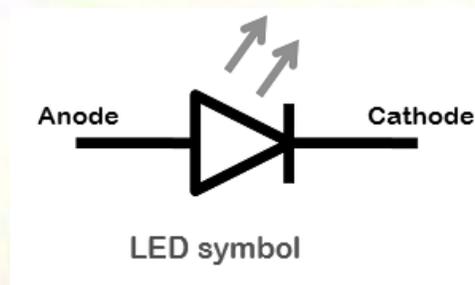


Fig 3.3 LED symbol

LEDs are available in different colors. The most common colors of LEDs are orange, yellow, green and red. The schematic symbol of LED does not represent the color of light. The schematic symbol is same for all colors of LEDs. Hence, it is not possible to identify the color of LED by seeing its symbol.

LED construction

One of the methods used to construct LED is to deposit three semiconductor layers on the substrate. The three semiconductor layers deposited on the substrate are n-type semiconductor, p-type semiconductor and active region. Active region is present in between the n-type and p-type semiconductor layers.

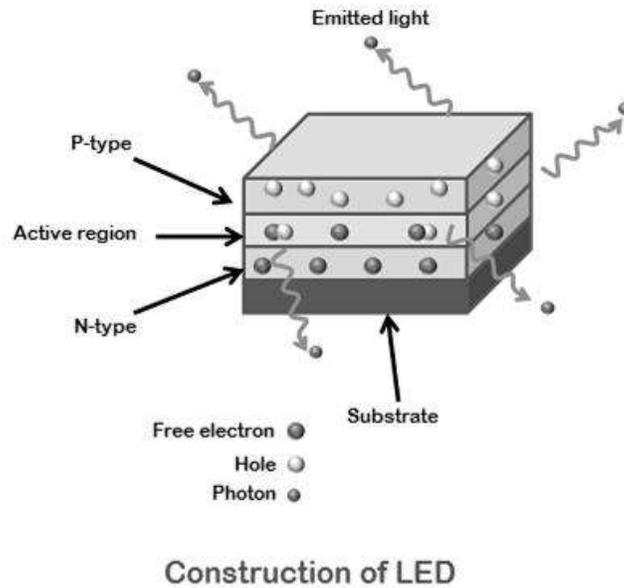


Fig 3.4 Construction of LED

When LED is forward biased, free electrons from n-type semiconductor and holes from p-type semiconductor are pushed towards the active region. When free electrons from n-side and holes from p-side recombine with the opposite charge carriers (free electrons with holes or holes with free electrons) in active region, an invisible or visible light is emitted. In LED, most of the charge carriers recombine at active region. Therefore, most of the light is emitted by the active region. The active region is also called as depletion region.

Working

Light Emitting Diode (LED) works only in forward bias condition. When Light Emitting Diode (LED) is forward biased, the free electrons from n-side and the holes from p-side are pushed towards the junction. When free electrons reach the junction or depletion region, some of the free electrons recombine with the holes in the positive ions. We know that positive ions have less number of electrons than protons. Therefore, they are ready to accept electrons. Thus, free

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electrons recombine with holes in the depletion region. In the similar way, holes from p-side recombine with electrons in the depletion region.

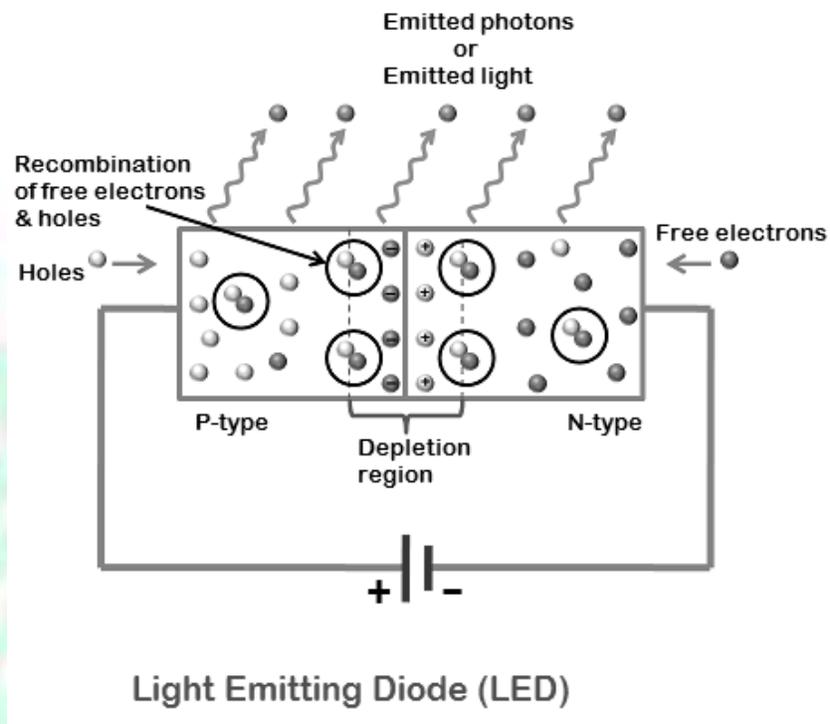


Fig 3.5 Light Emitting Diode

Because of the recombination of free electrons and holes in the depletion region, the width of depletion region decreases. As a result, more charge carriers will cross the p-n junction. Some of the charge carriers from p-side and n-side will cross the p-n junction before they recombine in the depletion region. For example, some free electrons from n-type semiconductor cross the p-n junction and recombines with holes in p-type semiconductor. In the similar way, holes from p-type semiconductor cross the p-n junction and recombines with free electrons in the n-type semiconductor. Thus, recombination takes place in depletion region as well as in p-type and n-type semiconductor. The free electrons in the conduction band releases energy in the form of light before they recombine with holes in the valence band. In silicon and germanium diodes, most of the energy is released in the form of heat and emitted light is too small .However, in materials like

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gallium arsenide and gallium phosphide the emitted photons have sufficient energy to produce intense visible light.

Advantages of LED

1. The brightness of light emitted by LED is depends on the current flowing through the LED. Hence, the brightness of LED can be easily controlled by varying the current. This makes possible to operate LED displays under different ambient lighting conditions.
2. Light emitting diodes consume low energy.
3. LEDs are very cheap and readily available.
4. LEDs are light in weight.
5. Smaller size.
6. LEDs have longer lifetime.
7. LEDs operates very fast. They can be turned on and off in very less time.
8. LEDs do not contain toxic material like mercury which is used in fluorescent lamps.
9. LEDs can emit different colors of light.

Disadvantages of LED

1. LEDs need more power to operate than normal p-n junction diodes.
2. Luminous efficiency of LEDs is low.

Applications of LED

The various applications of LEDs are as follows

1. Burglar alarms systems
2. Calculators
3. Picture phones

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4. Traffic signals
5. Digital computers
6. Multimeters
7. Microprocessors
8. Digital watches
9. Automotive heat lamps
10. Camera flashes
11. Aviation lighting

3.10 SOLAR CELL

Since a solar cell is the only generator in a solar PV system, it is one of the most important parts in a solar PV system. In the following paragraphs, a simple introduction of a solar cell and how it operates is discussed, with reference links for better understanding.

A solar cell: A solar cell is a solid-state electrical device (p-n junction) that converts the energy of light directly into electricity (DC) using the photovoltaic effect. The process of conversion first requires a material which absorbs the solar energy (photon), and then raises an electron to a higher energy state, and then the flow of this high-energy electron to an external circuit. Silicon is one such material that uses such process. A solar cell structure is shown in figure 3.6 and a solar panel configuration in figure 3.7.

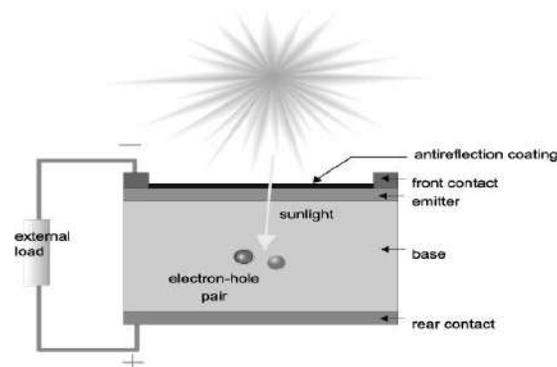


Fig 3.6 Solar Cell Structure

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon. [1] It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels.

- ✓ The operation of a photovoltaic (PV) cell requires 3 basic attributes:
- ✓ The absorption of light, generating either electron-hole pairs or excitons.
- ✓ The separation of charge carriers of opposite types.
- ✓ The separate extraction of those carriers to an external circuit.

Construction-

It essentially consists of a silicon PN junction diode with a glass window on top surface layer of P material is made extremely thin so, that incident light photon's may easily reach the PN junction.

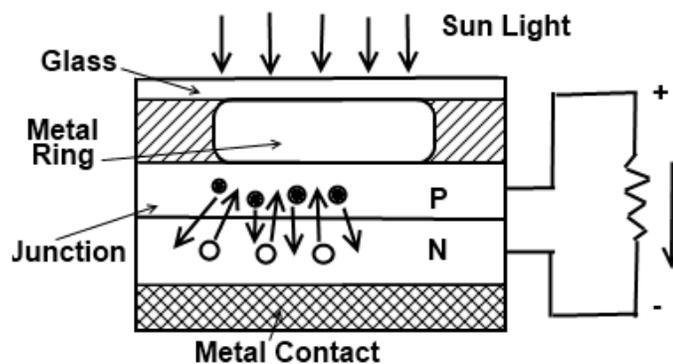


Fig 3.7 PN junction

Working of solar cell

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- ❖ Solar cell works under the principle of photovoltaic effect-when light is incident on 'P-N' junction a potential gets developed across the junction, this potential is capable of driving a current through the circuit.
- ❖ Hence light energy is getting converted to electrical energy.
- ❖ Here electrons absorb photons having energy greater than the band gap energy hence they can make transition from the valence band to the conduction band & hence contributes current.
- ❖ The wavelength of light is given by the relation, $E_g = hc/\lambda = 1.24$

Advantages of Solar Cell

- A solar plant is basically a re-newable power source. Hence it is not harmful to the environment.
- It is very easy to operate compare to other power sources of re-newable type.
- It does not produce any noise as it does not have any moving parts.
- It does not generate emissions or radiations.
It does not require fuels or water to produce electricity.

Disadvantages of Solar Cell

- It cannot be used in absence of the light from any source.
It incurs very high initial cost for installation.
- During cloudy weather, less power is being generated.
- Very large geographical area is needed in order to deploy solar panels or cells.

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