Semiconductor Electronics

Semiconductor, Diode and Its Applications

1.1 Classification of Metals, Semiconductors and Insulators

On the basis of the relative value of electrical conductivity (σ) or resistivity (ρ = 1/σ), the solids are broadly classified as

(*i*) **Metals** They possess very low resistivity or high conductivity.

$\rho \sim 10^{-2}\text{-}10^{-8}\,\Omega\text{m},\ \sigma \sim 10^{2}\text{-}10^{8}\,\text{Sm}^{-1}$

(*ii*) **Semiconductors** They have resistivity or conductivity intermediate to metals and insulators.

$\rho \sim 10^{-5}\text{-}10^{-6}\,\Omega\text{m},\ \sigma \sim 10^{-5}$ to $10^{0}\,\text{Sm}^{-1}$

(*iii*) **Insulators** They have high resistivity or low conductivity.

$\rho \sim 10^{11}\text{-}10^{19}\,\Omega\text{m},\ \sigma \sim 10^{-11}\text{-}10^{-19}\,\text{Sm}^{-1}$

Types of semiconductors on the basis of their chemical composition are given below

(*i*) **Elemental Semiconductors** These semiconductors are available in natural form, e.g. silicon and germanium.

(*ii*) **Compound Semiconductors** These semiconductors are made by compounding the metals, e.g. CdS, GaAs, CdSe, InP, anthracene, polyaniline, etc.

1.2 Energy Band

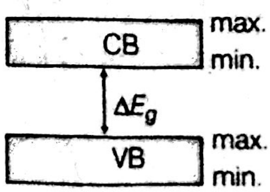
In a crystal due to interatomic interaction, valence electrons of one atom are shared by more than one atom. Now, splitting of energy level takes place.

The collection of these closely spaced energy levels are called energy bands.

(*i*) **Valence Band** It is the highest energy band which includes the energy levels of the valence electrons.

(*ii*) **Conduction Band** The lowest unfilled energy band next to valence band is called conduction band. It is the energy band above the valence band.

(*iii*) **Energy Band Gap** The minimum energy required for shifting electrons from valence band to conduction band is called energy band gap (E_g).



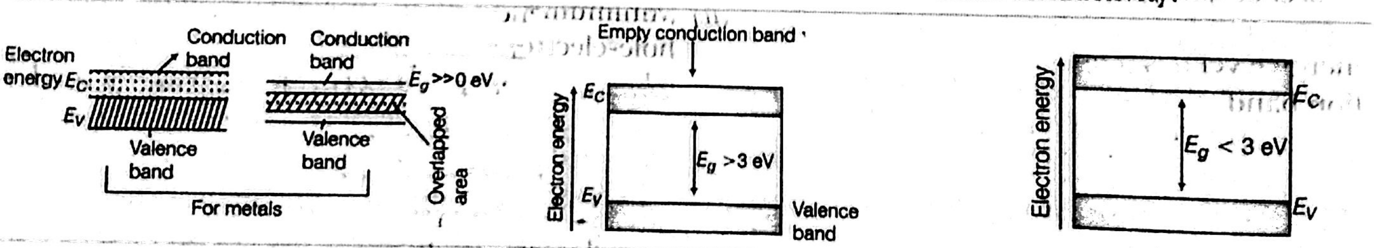
(*iv*) **Forbidden Energy Gap** (ΔE_g) Energy gap, i.e. difference between conduction band and valence band is called the forbidden energy gap, $\Delta E_g = (CB)_{min} - (VB)_{max}$

(*v*) **Fermi Energy** The highest energy level in the conduction band filled up with electrons at absolute zero is called **fermi level** and the energy corresponding to the fermi level is called **fermi energy**.

It is the maximum possible energy possessed by free electrons of a material at absolute zero temperature (i.e. 0 K).

Differences between conductor, insulator and semiconductor on the basis of energy bands

Conductor (Metal)	**Insulator**	**Semiconductor**
In conductor, either there is no energy gap between the conduction band which is partially filled with electrons and valence band or the conduction band and valence band overlap each other.	In insulator, the valence band is completely filled, the conduction band is completely empty and energy gap between conduction band and valence band is quite large that small energy from any other source cannot overcome it.	In semiconductor also, like insulators the valence band is completely filled and the conduction band is empty but the energy gap between conduction band and valence band, unlike insulators is very small.
Thus, many electrons from below the fermi level can shift to higher energy levels above the fermi level in the conduction band and behave as free electrons by acquiring a little more energy from any other sources.	Thus, electrons are bound to valence band and are not free to move and hence, electric conduction is not possible in this type of material.	Thus, at room temperature, some electrons in the valence band acquire thermal energy greater than energy band gap and jump over to the conduction band where they are free to move under the influence of even a small electric field and acquire small conductivity.



1.3 Semiconductors

Semiconductors are the materials whose conductivity lies between metals and insulators. They are characterised by narrow energy gap (~1eV) between the valence band and conduction band.

On the basis of purity semiconductor can be classified as

Intrinsic Semiconductors

It is a pure semiconductor without any significant dopant species present.

$$n_e = n_h = n_i$$

where, n_e and n_h are number densities of electrons and holes respectively and n_i is called intrinsic carrier concentration. An intrinsic semiconductor is also called an **undoped semiconductor** or ***i*-type semiconductor.**

The total current I is the sum of the electron current I_e and hole current I_h.

$$I = I_e + I_h$$

where, I_e = electron current,

I_h = hole current

Extrinsic Semiconductors

A pure semiconductor when doped with the impurity, it is known as extrinsic semiconductor.

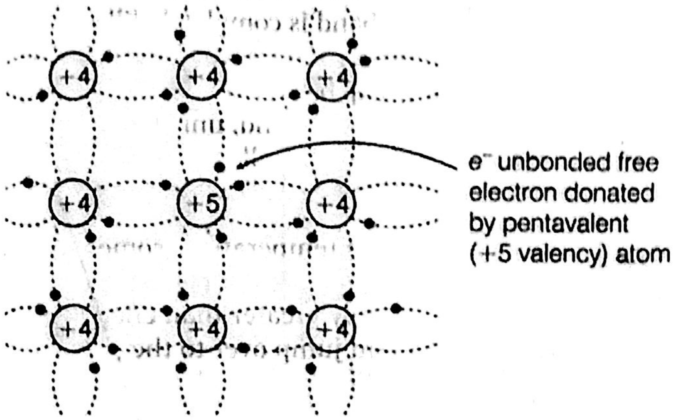
Extrinsic semiconductors are basically of two types:

(i) n-type Semiconductor

In this type of extrinsic semiconductor, majority charge carriers are electrons and minority charge carriers are holes, i.e. $n_e > n_h$.

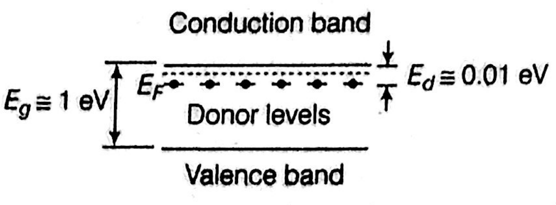
Here, we dope a tetravalent element like Si or Ge with a pentavalent element, such as As, P or Sb of group V, then four of its electrons bond with the four silicon neighbours, while fifth remains very weakly bound to its parent atom.

Formation of n-type semiconductor is shown below:



Pentavalent donor atom (As, Sb, P, etc.) doped in tetravalent Si or Ge giving n-type semiconductor

Donor energy level lies just below the conduction band



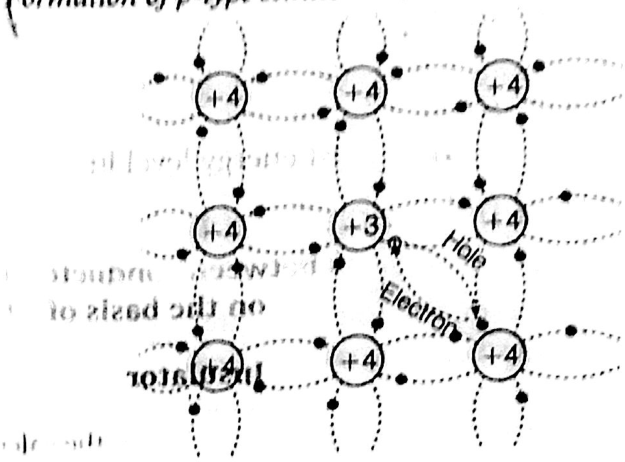
n-type

(ii) p-type Semiconductor

In this semiconductor, majority charge carriers are holes and minority charge carriers are electrons i.e. $n_h > n_e$.

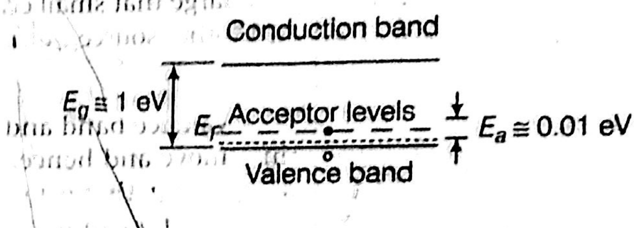
In a p-type semiconductor, doping of tetravalent atoms is done with trivalent impurity atoms such as Al, B, i.e. those atoms which have three valence electrons in their valence shell.

Formation of p-type semiconductor is shown below:



Trivalent acceptor atom (In, Al, B, etc) doped in tetravalent Si or Ge lattice giving p-type semiconductor

Acceptor energy level lies just above the valence band



p-type

(*i*) At equilibrium condition, $n_e n_h = n_i^2$

(*ii*) Minimum energy required to create a hole-electron pair, $h\nu \geq E_g$
where, E_g is energy band gap.
i.e. $E_g = h\nu_{min} = hc/\lambda_{max}$

(*iii*) Electric current, $I = eA\,(n_e v_e + n_h v_h)$
where, A is area of cross-section and v_e and v_h are speed of electron and hole respectively.

(*iv*) Mobility of charge carriers, $\mu = v/E$, where E is applied electric field.
Hence, $v_e = \mu_e E$ and $v_h = \mu_h E$

(*v*) Electrical conductivity, $\sigma = 1/\rho = e(\mu_e n_e + n_h \mu_h)$
where, n_e and n_h are concentration of electron and hole respectively and μ_e and μ_h are mobilities of electron and hole, respectively, applying the formula.

$$I = \frac{V}{R} = \frac{E \times l}{\rho l / A} = \frac{EA}{\rho} = l(n_e v_e + n_h v_h)$$

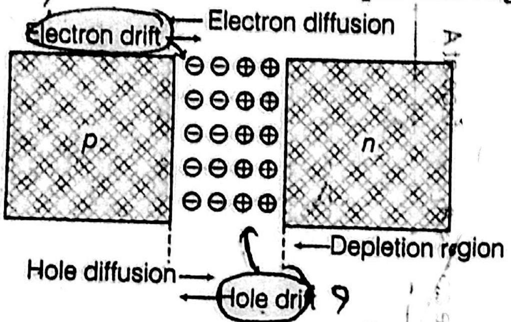
1.4 *p-n* Junction

A *p-n* junction is an arrangement made by a close contact of *n*-type semiconductor with *p*-type semiconductor.

Formation of Depletion Region in *p-n* Junction

During formation of *p-n* junction, due to the concentration gradient across *p* and *n*-sides, holes diffuse from *p*-side to *n*-side ($p \rightarrow n$) and electrons diffuse from *n*-side to *p*-side ($n \rightarrow p$).

This space charge region on either side of the junction together is known as **depletion region.**

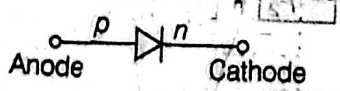


Depletion region is the small region in the vicinity of the junction which is depleted of free charge carriers. Width of depletion region is of the order of 10^{-6}m. The potential difference developed across the depletion region is called the **potential barrier.**

Semiconductor Diode/ *p-n* Junction Diode

(*i*) A semiconductor diode is basically a *p-n* junction with metallic contacts provided at the ends for the application of an external voltage.

(*ii*) A *p-n* junction diode is represented as



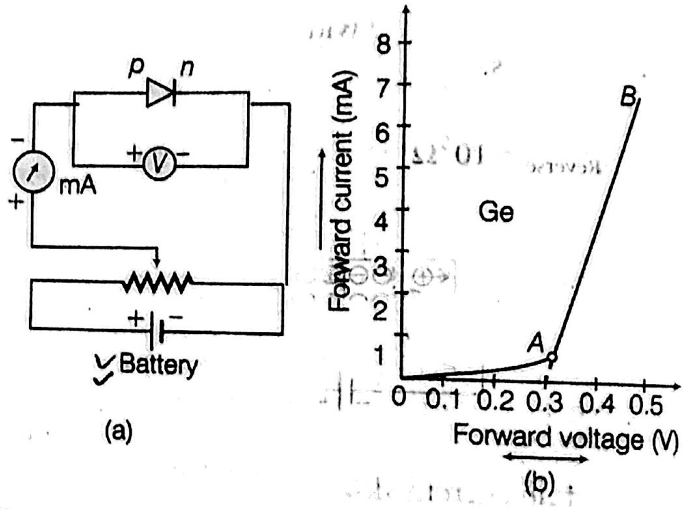
(*iii*) The direction of arrow indicates the conventional direction of current (when the diode is under forward bias).

(*iv*) The graphical relations between voltage applied across *p-n* junction and current flowing through the junction are called *I-V* characteristic.

I-V (Current-Voltage) Characteristic of *p-n* Junction Diode

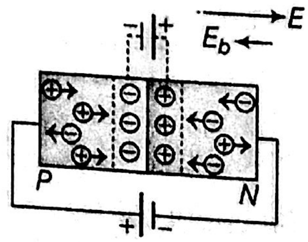
Forward Biased Characteristic

Junction diode is said to be forward biased when the positive terminal of the external battery is connected to the *p*-side and negative terminal to the *n*-side of the diode.
Similarly, if the positive terminal of a battery is connected to *n*-side and negative terminal to the *p*-side, then the *p-n* junction is said to be reverse biased. The circuit diagram and *I-V* characteristics of a forward biased diode is shown below:



Consequences of forward biasing

(*i*) In forward biasing width of depletion layer decreases.

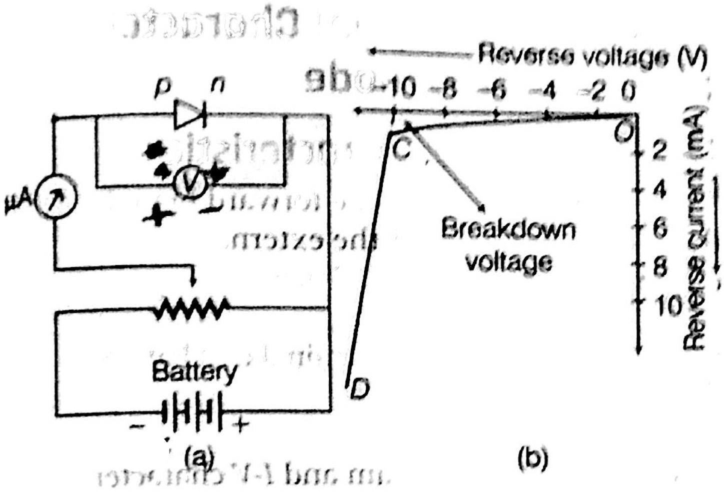


(*ii*) In forward biasing resistance offered $R_{Forward} \approx 10\Omega - 25\Omega$

Reverse Biased Characteristic

In reverse biased, the applied voltage supports the flow of minority charge carriers across the junction. So, very small current flows across the junction due to minority charge carriers.

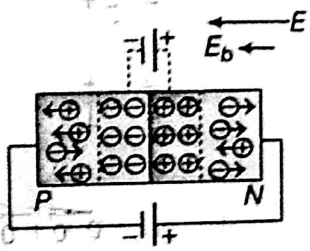
The circuit diagram and *I-V* characteristics of a reverse biased diode is shown below.



Consequences of reverse biasing

(*i*) In reverse biasing width of depletion layer increases.

(*ii*) In reverse biasing resistance offered $R_{Reverse} \approx 10^5 \Omega$



(*iii*) Reverse bias supports the potential barrier and no current flows across the junction due to the diffusion of the majority carriers.

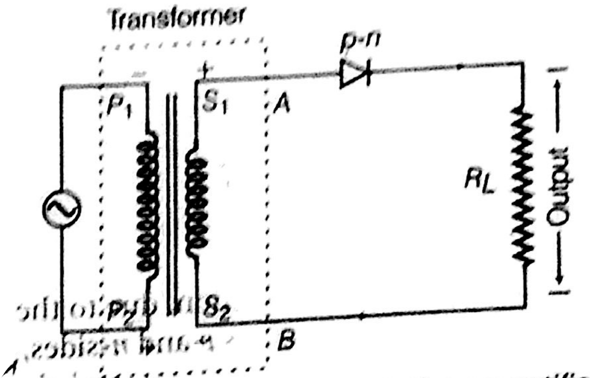
- The DC resistance of a junction diode, $r_{DC} = \frac{V}{I}$
- The dynamic resistance or AC-resistance of junction diode, $r_{AC} = \frac{\Delta V}{\Delta I}$

1.5 Diode as a Rectifier

The process of converting alternating voltage/current into direct voltage/current is called **rectification.** Diode is used as a rectifier for converting alternating current/voltage into direct current/voltage. There are two ways of using a diode as a rectifier.

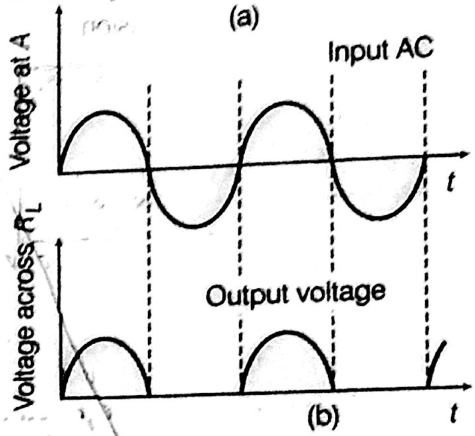
(i) Diode as a Half-Wave Rectifier

Diode conducts corresponding to positive half cycle and does not conduct during negative half cycle. Hence, AC is converted by diode into unidirectional pulsating DC. This action is known as **half-wave rectification.**



Circuit diagram for Diode as a half-wave rectifier

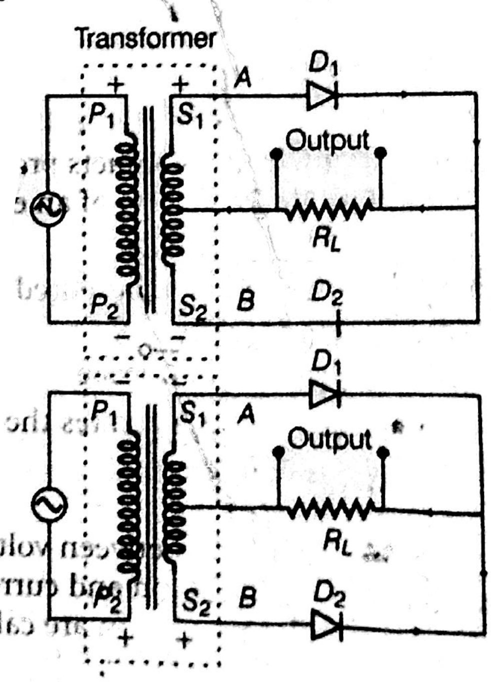
The input and output waveforms have been given below:



Input and output waveforms

(ii) Diode as a Full-Wave Rectifier

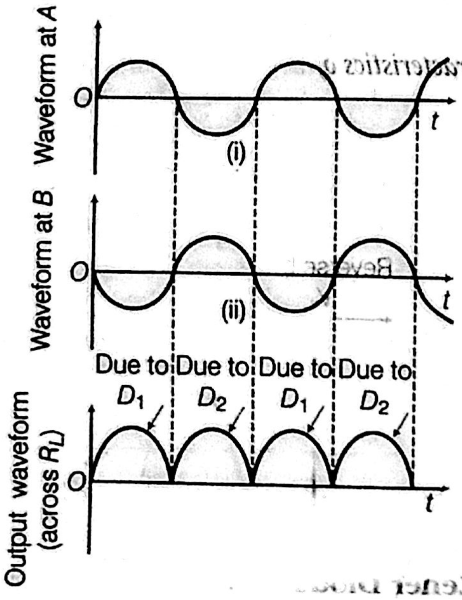
In the full-wave rectifier, two *p-n* junction diodes, D_1 and D_2 are used. Its working is based on the



Circuit diagram of full-wave rectifier

principle that junction diode offer very low resistance in forward bias and very high resistance in reverse bias.

The input and output waveforms have been given below:



(*i*) The average value or DC value obtained from a half-wave rectifier,

$$I_{DC} = \frac{I_0}{\pi}$$

(*ii*) The average value or DC value obtained from a full-wave rectifier,

$$I_{DC} = \frac{2I_0}{\pi}$$

(*iii*) The pulse frequency of a half-wave rectifier is equal to frequency of AC.

(*iv*) The pulse frequency of a full-wave rectifier is double to that of AC.

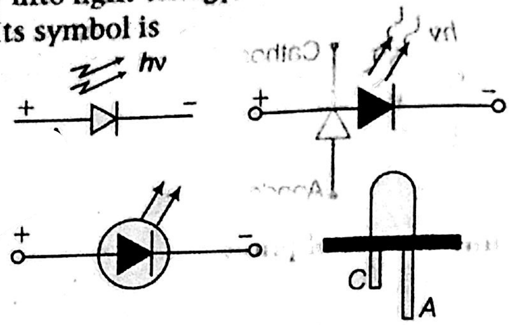
1.6 Optoelectronic Junction Devices

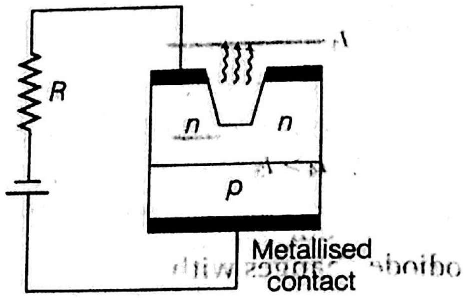
Semiconductor diodes in which carriers are generated by photons. i.e. photo-excitation, such devices are known as optoelectronic devices.

These are as follows:

Light Emitting Diode (LED)

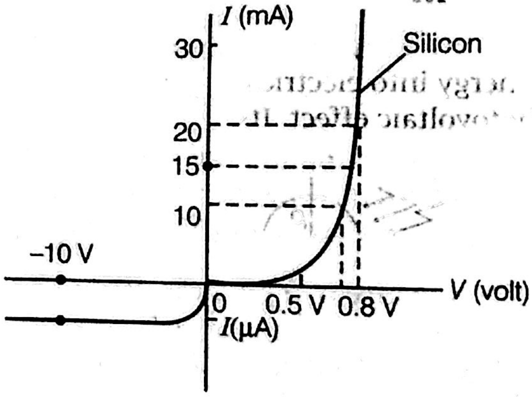
It is a heavily doped forward biased p-n junction diode which spontaneously converts electrical energy into light energy, like infrared and visible light. Its symbol is





A forward biased LED

V-I characteristics of LED are shown below:



LEDs has the following advantages over conventional incandescent low power lamps.

(a) Fast action and no warm up time required

(b) It is nearly monochromatic

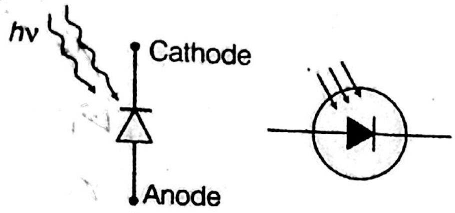
(c) Low operational voltage and less power consumed, long life, ruggedness

(d) Fast ON-OFF switching capability in nanoseconds.

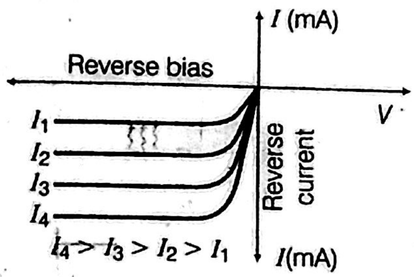
Photodiode

A photodiode is a special type of junction diode used for detecting optical signals. It is a reverse biased *p-n* junction made from a photosensitive material, such a way that light can fall on its junction.

Its symbol is



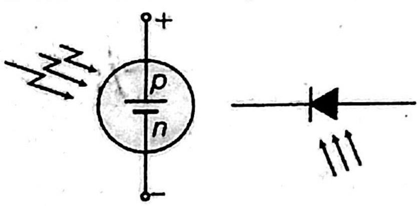
V-I characteristics of photodiode are shown below:



We observe from the figure that current in photodiode changes with the change in light intensity (I), when reverse bias is applied.

Solar Cell

Solar cell is a *p-n* junction diode which converts solar energy into electrical energy. It is based on the photovoltaic effect. Its symbol is



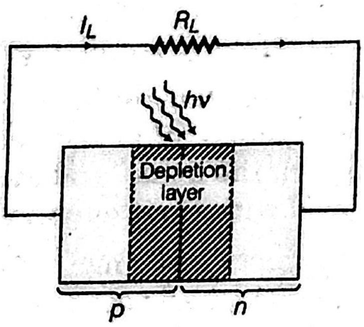
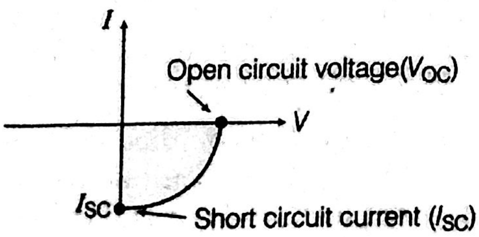


Photo current through an illuminated *p-n* junction

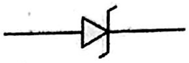
V-I characteristics of solar cell are shown below:



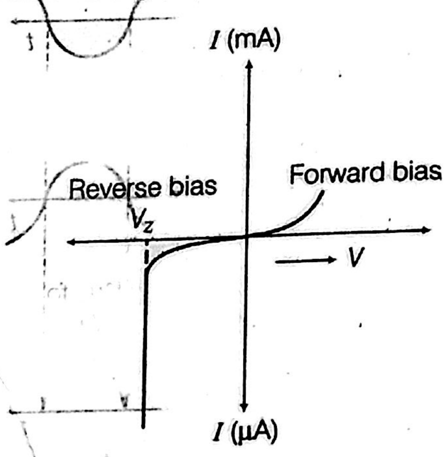
The materials used for solar cell are Si, Ga and As.

Zener Diode

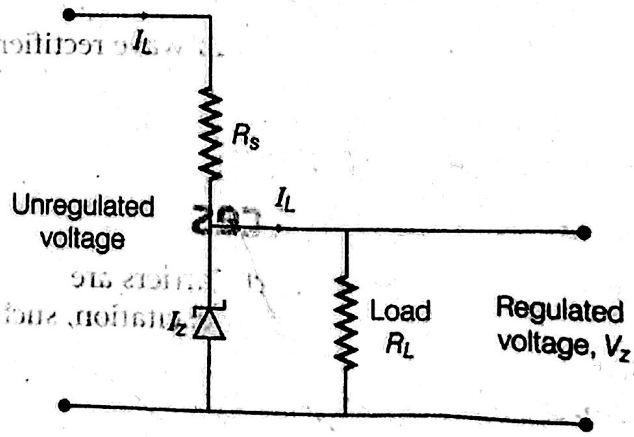
Zener diode is a reverse biased heavily doped *p-n* junction diode. It is operated in breakdown region.

Its symbol is 

V-I characteristics of Zener diode are shown below



(*i*) **Zener Diode as a Voltage Regulator**
When the applied reverse voltage (V) reaches the breakdown voltage (V_z) of the Zener diode there is a large change in the current. So, after the breakdown voltage V_z, a large change in the current can be produced by almost insignificant change in the reverse bias voltage i.e. Zener voltage remains constant even though the current through the Zener diode varies over a wide range. The circuital arrangement is shown here.



(*ii*) This breakdown in a diode due to the band to band tunneling is called **Zener breakdown.**