Free Study Material from

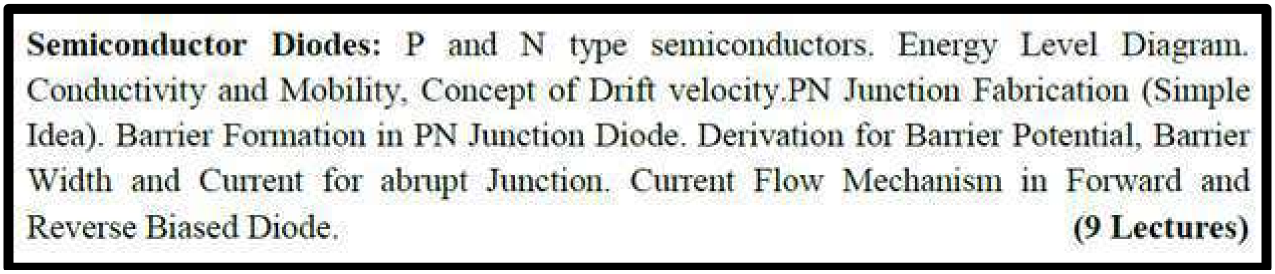
All Lab Experiments

Analog Systems & Applications

Chapter - 1, 2

1. Semiconductor Diodes
2. Two Terminal Devices & Their Applications

Chapter-1
Semiconductors diodes



Semiconductor Diodes: P and N type semiconductors. Energy Level Diagram. Conductivity and Mobility, Concept of Drift velocity.PN Junction Fabrication (Simple Idea). Barrier Formation in PN Junction Diode. Derivation for Barrier Potential, Barrier Width and Current for abrupt Junction. Current Flow Mechanism in Forward and Reverse Biased Diode. **(9 Lectures)**

Q: what are p-type and n-type semiconductors?

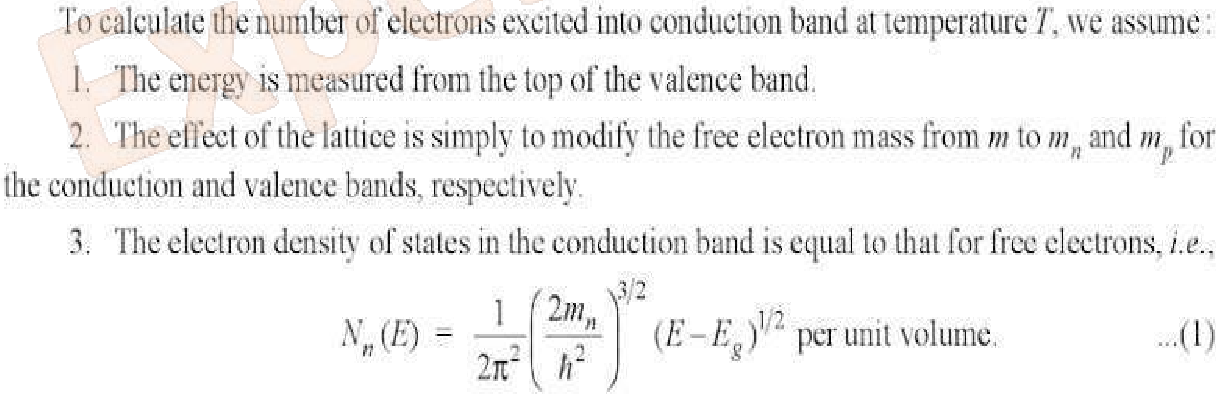
Ans: there are two types of semiconductors which are as follows:-

Intrinsic semiconductor:-When we have a semiconductor in pure form that is without doping then it is called as intrinsic semiconductor.
Extrinsic Semiconductor:- When a semiconductor is doped with some impurities then it is known as Extrinsic Semiconductor.
Now this Extrinsic Semiconductor has more two types

N- Type: - When we use a pentavalent impurity for doping then we get a n-type semiconductor. Examples of pentavalent impurities are phosphorus or arsenic.
P-type: - When we use trivalent impurities for doping then we get a p-type semiconductor. Examples of trivalent impurities are aluminum or boron.

Q: calculate the number of electrons into conduction band.

Ans:



To calculate the number of electrons excited into conduction band at temperature T, we assume :

1. The energy is measured from the top of the valence band.
2. The effect of the lattice is simply to modify the free electron mass from m to m_n and m_p for the conduction and valence bands, respectively.
3. The electron density of states in the conduction band is equal to that for free electrons, *i.e.*,

$$N_n(E) = \frac{1}{2\pi^2}\left(\frac{2m_n}{h^2}\right)^{3/2}(E-E_g)^{1/2} \text{ per unit volume.} \quad ...(1)$$

The Fermi function is

$$f(E) = \frac{1}{1+e^{(E-E_F)/kT}} \qquad \ldots(2)$$

The total number of electrons with energy between E and $E + dE$ is given by the product of $N(E)\,dE$ and the Fermi function. So the total number of electrons in the conduction band n is given by

$$n = \int_{E_g}^{\infty} \frac{1}{2\pi^2}\left(\frac{2m_n}{\hbar^2}\right)^{3/2} (E-E_g)^{1/2}\, f(E)\,dE \qquad \ldots(3)$$

$E_g - E_F >> kT$. So the Fermi function may, to a good aproximation, be written as,

$$f(E) = \left[1+e^{(E-E_F)/kT}\right]^{-1} = e^{-(E-E_F)/kT}$$

$$n = \frac{1}{2\pi^2}\left(\frac{2m_n}{\hbar^2}\right)^{3/2} \int_{E_g}^{\infty} (E-E_g)^{1/2}\, e^{-(E-E_F)/kT} \qquad \ldots(4)$$

$$\therefore \qquad n = 2\left(\frac{m_n kT}{2\pi\hbar^2}\right)^{3/2} e^{(E_F-E_g)/kT} \qquad \ldots(5)$$

This relation gives the density or concentration of electrons in the conduction band of an intrinsic semiconductor.

Q: calculate the number of holes into valence band.

The density of hole states in the valence band is given by

$$N_p(E) = \frac{1}{2\pi^2}\left(\frac{2m_p}{\hbar^2}\right)^{3/2} (E)^{1/2} \text{ per unit volume} \qquad \ldots(6)$$

The probability of finding a hole with energy E is just $1 - f(E)$.

$$\begin{aligned} f_p(E) &= 1 - f(E) \\ &= 1 - \frac{1}{1+e^{(E-E_F)/kT}} \\ &= 1 - \left[1+e^{(E-E_F)/kT}\right]^{-1} = 1 - \left[1 - e^{(E-E_F)/kT}\right] \\ &= e^{(E-E_F)/kT} \end{aligned}$$

Hence the density of holes in the valence band

$$p = \int_{-\infty}^{0} \frac{1}{2\pi^2}\left(\frac{2m_p}{\hbar^2}\right)^{3/2} (E)^{1/2}\, e^{(E-E_F)/kT}\, dE \qquad \ldots(7)$$

$$\therefore \qquad p = 2\left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-E_F/kT} \qquad \ldots(8)$$

This is the hole concentration in the valence band.

Q:derive an experssion for law of mass action.

Multiplying Eqs. (5) and (8), we get

$$np = 4\left(\frac{kT}{2\pi\hbar^2}\right)^3 (m_n m_p)^{3/2} e^{-E_g/kT} = AT^3 e^{-E_g/kT} \quad ...(9)$$

Here, E_g is the *width of forbidden energy gap* between conduction and valence bands and

$$A = 4\left(\frac{k}{2\pi\hbar^2}\right)^3 (m_n m_p)^{3/2} \rightarrow \text{a constant.}$$

Eq. (9) shows that the *product of hole and electron densities depends on temperature T and forbidden energy gap E_g but is independent of the Fermi level E_F.*

Thus the product of electron and hole concentrations, for a given material, is constant at a given temperature. If an impurity is added to increase n, there will be a corresponding decrease in p such that product np remains constant.

Since for an intrinsic semiconductor, $n = p = n_i$, we arrive at an important relationship, called the *law of mass action.*

$$np = n_i^2 = AT^3 e^{-E_g/kT} \quad ...(10)$$

Here n_i is called the intrinsic density of either carrier.

Eq. (10) is true for a semiconductor regardless of the donor or acceptor concentrations.

Q: Explain diffusion and drift current. Also derive the relation between mobility and diffusion constant.

Ans:

Diffusion is the process by which particles move from a region of higher concentration to a region of lower concentration. If the process is left undisturbed, it would result in uniform density of particles in the medium.

If the particles of the medium are charged carriers, like electrons and holes in a semiconductor, the diffusion along the concentration gradient results in a current, known as **diffusion current.** Unlike the **drift current**, the diffusion current depends on gradient of concentration rather than on the concentration itself. If the carriers are electrons, the diffusion current is proportional to ∇n, where n is the electron density.

Likewise, the hole diffusion current is proportional to ∇p.

Consider the diffusive motion of holes in one dimension. If $p(x)$ is the concentration at x, and $dp/dx > 0$, i.e., if the concentration is increasing where E_F^i is the intrinsic Fermi level and E_F is the Fermi level in the presence of acceptor impurities (we have dropped the redundant superscript p). Thus

$$\begin{aligned}\nabla p &= \frac{p_i}{kT} e^{(E_F^i - E_F)/kT} (\nabla E_F^i - \nabla E_F) \\ &= \frac{p}{kT} (\nabla E_F^i - \nabla E_F)\end{aligned}$$

Thus diffusion takes place when there exists an intrinsic Fermi level gradient. In order to evaluate the gradient of E_F^i, consider the valence band. The kinetic energy of the holes is the difference between the energy of the top of the valence band and the total energy of the holes. Thus the energy at the top of the valence band is the potential energy of the holes. Similarly, the energy at the bottom of the conduction band is the potential energy of the electrons. As the intrinsic Fermi energy depends on these two energy levels, temperature and other constants, the change in the electron or hole energy is also given by the difference between the intrinsic Fermi energy E_F^i and the (uniform) Fermi energy E_F,

$$q\phi = (E_F - E_F^i)$$

The electric field, $E(x)$ is then given by

$$E_x = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_F^i}{dx} (C)$$

Assume *quasi-charge neutrality* for which the concentration of holes is equal to the concentration of acceptors, $p \simeq N_a$. Using one dimensional form of (B),

$$\frac{dE_F^i}{dx} = \frac{kT}{p}\frac{dp}{dx} \simeq \frac{kT}{N_a}\frac{dN_a}{dx}$$

which gives

$$E(x) = \frac{kT}{q}\frac{1}{N_a}\frac{dN_a}{dx}$$

Substituting the above in (A) and cancelling common terms, we get

$$\frac{D_p}{\mu_h} = \frac{kT}{q}$$

A similar relation can be established for electrons. The relations

$$\boxed{\frac{D_p}{\mu_h} = \frac{D_n}{\mu_e} = \frac{kT}{q}}$$

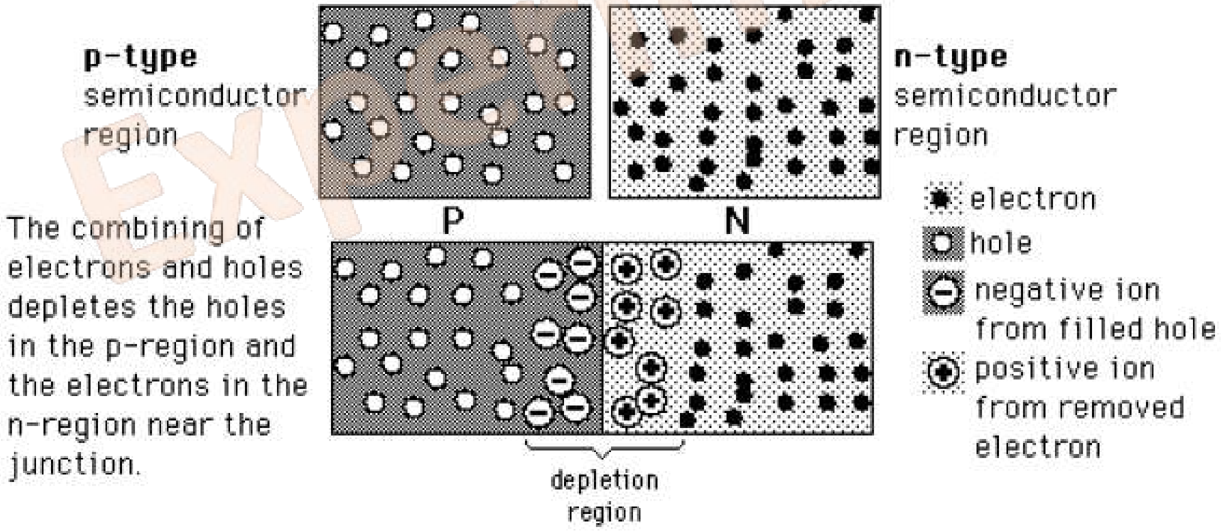
Are known as bf Einstein relations between mobility and diffusion constant.

Q: What is P-N junction? Explain the formation of potential barrier and depletion layer? With no external voltage.

Ans: A p–n junction is a junction formed by joining p-type and n-type semiconductors together in very close contact. The term junction refers to the boundary interface where the two regions of the semiconductor meet. If they were constructed of two separate pieces this would introduce a grain boundary, so p–n junctions are more often created in a single crystal of semiconductor by doping, for example by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant).

Formation of the Depletion Region.

At the instant of the PN junction formation free electrons near the junction diffuse across the junction into the P region and combine with holes.



Filling a hole makes a negative ion and leaves behind a positive ion on the N side.

These two layers of positive and negative charges form the depletion region, as the region near the junction is depleted of charge carriers.

As electrons diffuse across the junction a point is reached where the negative charge repels any further diffusion of electrons.

The depletion region now acts as a barrier.

Barrier Potential:

The electric field formed in the depletion region acts as a barrier. External energy must be applied to get the electrons to move across the barrier of the electric field. The potential difference required to move the electrons through the electric field is called the barrier potential. Barrier potential of a PN junction depends on the type of semiconductor material, amount of doping and temperature. This is approximately 0.7V for silicon and 0.3V for germanium.

Chapter-2
Semiconductors diodes

Two-terminal Devices and their Applications: (1) Rectifier Diode: Half-wave Rectifiers. Centre-tapped and Bridge Full-wave Rectifiers, Calculation of Ripple Factor and Rectification Efficiency, C-filter, (2) Zener Diode and Voltage Regulation. Principle, structure and characteristics of (1) LED, (2) Photodiode and (3) Solar Cell, Qualitative idea of Schottky diode and Tunnel diode. **(7 Lectures)**

Q: Draw a labeled diagram for half wave rectifier explains its working and derive its mathematical expression.

Sol:

58.8 Diode as a Half-Wave Rectifier

Construction. Fig. 58.13 shows the circuit for a half-wave rectifier. T is a transformer. The primary of the transformer is connected to the ac mains. The diode D is connected across the secondary in series with a load resistance R_L.

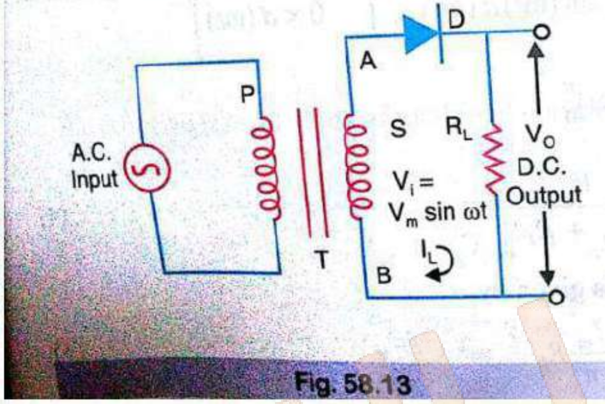


Fig. 58.13

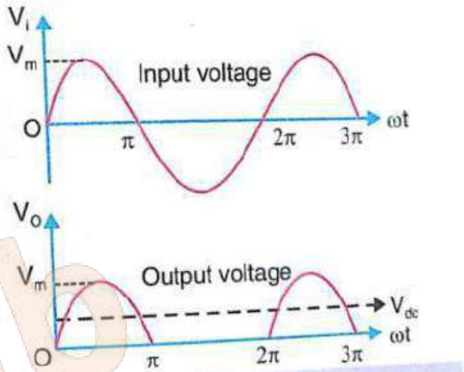


Fig. 58.14

Working. The primary of the transformer is connected to the ac mains. An ac voltage will be induced across the secondary. This voltage can be represented by

$$V_i = V_m \sin \omega t.$$

Fig. 58.14 shows the variation of this input voltage with time. V_m is the peak value.

During the first half cycle of a.c., one end of the secondary, say A, becomes positive. Then the diode is forward biased. Hence current flows through the load R_L in the direction of arrows (Fig. 58.13). The diode offers very little resistance when forward biased. Hence the p.d. across it is very small. The voltage across the load

R_L is therefore practically the same as that across the secondary of the transformer,

i.e., V_i. During the next half cycle, the end A becomes negative. The diode is now reverse biased. Therefore, no current flows through the load R_L. The voltage across the load is zero. The shape of the output voltage is shown in Fig. 58.14. This voltage in not a perfect dc. But it is unidirectional.

Mathematical Analysis

The input voltage applied to the diode is given by

$$V_i = V_m \sin \omega t \qquad \text{...(1)}$$

Then, the instantaneous output current through the load resistance R_L is given by

$$I_L = I_m \sin \omega t \qquad \text{when } 0 \le \omega t \le \pi \qquad \text{...(2)}$$

and $$I_L = 0 \qquad \text{when } \pi \le \omega t \le 2\pi \qquad \text{...(3)}$$

$$I_m = \frac{V_m}{R_L + R_f}$$

Here, I_m = peak value of the current

R_f = dynamic forward resistance of the diode.

(*i*) D.C. (average) value of output current

The average d.c. current over one complete cycle is given by

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} I_L \, d(\omega t)$$

$$= \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin(\omega t)\, d(\omega t) + \int_0^{2\pi} 0 \times d(\omega t)\right]$$

$$= \frac{I_m}{2\pi}[-\cos \omega t]_0^{\pi}$$

$$I_{dc} = \frac{I_m}{\pi} = \frac{1}{\pi}\left[\frac{V_m}{R_f + R_L}\right] \qquad \text{...(4)}$$

The dc voltage developed across the load R_L is given by

$$V_{dc} = I_{dc} \times R_L = \frac{I_m}{\pi} R_L \qquad \text{...(5)}$$

(*ii*) D.C. power output. The dc power output across the load R_L is

$$\text{D.C. power output} = P_{dc} = I_{dc}^2 \cdot R_L = \frac{I_m^2}{\pi^2} \cdot R_L \qquad \text{...(6)}$$

(*iii*) R.M.S. (effective) value of output current

The root mean square value of the current, by definition, is given by

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} i_L^2\, d(\omega t)\right]^{1/2}$$

$$= \left[\frac{1}{2\pi}\left\{\int_0^{\pi} i_m^2 \sin^2 \omega t\, d(\omega t) + \int_{\pi}^{2\pi} 0.d(\omega t)\right\}\right]^{1/2}$$

$$= \left[\frac{1}{2\pi}\int_0^{\pi} i_m^2 \sin^2 \omega t\, d(\omega t)\right]^{1/2}$$

$$\therefore \qquad I_{rms} = \frac{I_m}{2} \qquad \ldots(7)$$

(*iv*) A.C. power input : The power supplied to the circuit from the ac source is given by

$$P_{AC} = I_{rms}^2(R_f + R_L) = \frac{I_m^2}{4}(R_f + R_L) \qquad \ldots(8)$$

(*v*) Rectifier efficiency : It is defined as the ratio of dc output power to the total ac power supplied to the rectifier.

$$\eta = \frac{\text{D.C. power output}}{\text{A.C. power input}}$$

$$= \frac{I_m^2 R_L/\pi^2}{I_m^2(R_f + R_L)/4} = \frac{4}{\pi^2}\left[\frac{R_L}{R_L + R_f}\right]$$

$$\eta = \frac{0.406}{1 + R_f/R_L}$$

Efficiency is maximum when $R_f << R_L$.

Theoretical maximum efficiency $\eta = 0.406 = 40.6\%$.

(*vi*) Ripple factor : The ripple factor is the ratio of r.m.s. value of A.C. component to the D.C. component in the rectifier output, *i.e.*,

$$\gamma = \frac{\text{r.m.s. value of A.C. component of output voltage}}{\text{D.C. component of output voltage}}$$

$$\gamma = \frac{V_{ac}}{V_{dc}} = \frac{I_{ac}}{I_{dc}}$$

The effective (r.m.s.) value of total load current is given by,

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2}$$

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

For a half-wave rectifier,

$$\frac{I_{rms}}{I_{dc}} = \frac{I_m/2}{I_m/\pi} = \frac{\pi}{2}.$$

$$\gamma = \sqrt{\frac{\pi^2}{4} - 1} = 1.21.$$

This indicates that the amount of A.C. component present in the output of a half-wave rectifier is 121% of D.C. output voltage. The half-wave rectifier is therefore a poor converter of ac into dc.

(vii) Peak inverse voltage. Peak inverse voltage (PIV) is defined as the *maximum reverse voltage which the rectifier has to withstand during the non-conducting period.* Thus for a half-wave rectifier,

$$PIV = V_m$$

(viii) Voltage regulation. Voltage regulation is the ability of a rectifier to *maintain a specific output voltage irrespective of the variation in the load resistance.* In a half-wave rectifier,

$$I_{dc} = \frac{I_m}{\pi} = \frac{V_m}{\pi(R_L + R_f)}$$

or

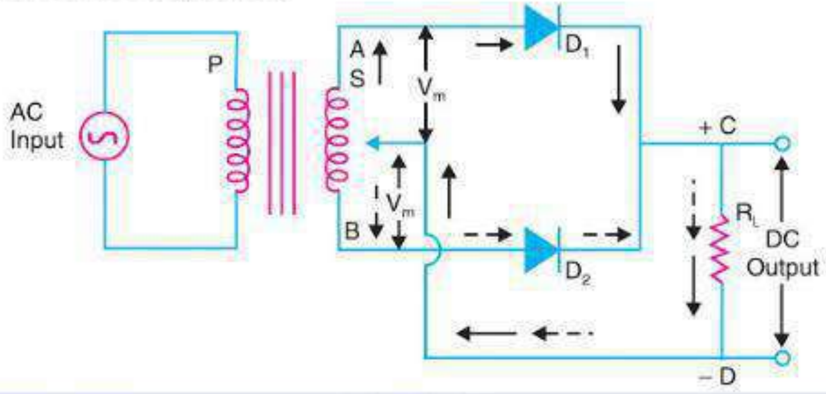
$$I_{dc} R_L = \frac{V_m}{\pi} - I_{dc} R_f$$

$$\therefore \quad V_{dc} = \frac{V_m}{\pi} - I_{dc} R_f.$$

When $I_{dc} = 0$, V_{dc} has its maximum value (V_m / π). As I_{dc} increases, V_{dc} decreases linearly. Therefore, *voltage regulation of a half-wave rectifier is poor.*

Q: Draw a labeled diagram for centre tapped full wave rectifier explain its working and derive its mathematical expression.

Centre tapped full-wave rectifier. A full wave rectifier circuit consists of two diodes D_1 and D_2 connected to the secondary of the step-down transformer. The input A.C. signal is fed to the primary of the transformer (Fig. 58.15).



Working. During the positive half-cycle of the secondary voltage, one end of the secondary, say A, becomes positive and end B becomes negative. So the diode D_1 is forward biased, and diode D_2 is reverse biased. As a result of this, the diode D_1 conducts current whereas the diode D_2 does not conduct. Current through the load resistance flows from C to D producing output voltage V_0. The current is shown by solid arrows.

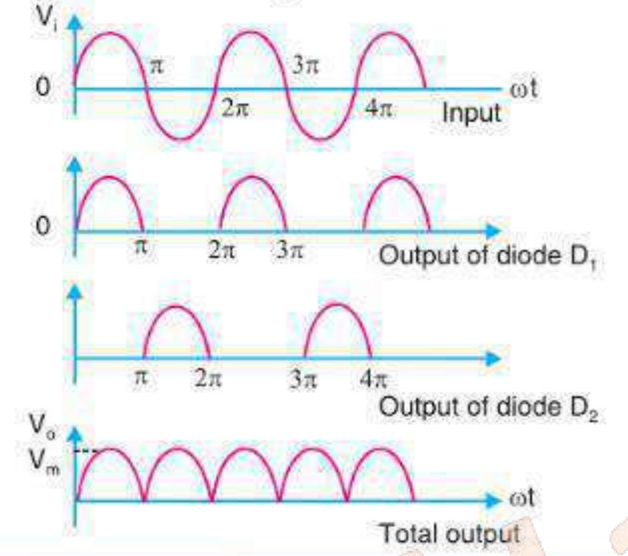


Fig. 58.16

During the negative half cycle of AC input, end A becomes negative and end B positive. So the diode D_1 is reverse biased and the diode D_2 is forward biased. As a result, the diode D_1 does not conduct and D_2 conducts current. Again current flows from C to D through the load resistance R_L producing output voltage V_0. The current is shown by the dotted arrows.

Thus, during both the half cycles, current flows through the load in the same direction. The output voltage is developed across the load R_L during the entire cycle. It is a pulsating D.C. voltage containing both A.C. and D.C. components. The input and the rectified output wave-forms are shown in Fig. 58.16.

Mathematical Analysis

Let the diodes D_1 and D_2 be identical and have the same dynamic resistance R_f. At any instant, let the magnitudes of AC voltages applied to the diodes be each equal to $V_i = V_m \sin \omega t$. V_m is the peak input voltage.

Let R_f = dynamic forward resistance of the diode.

The current pulses in the two diodes are given by

$$i = \begin{Bmatrix} I_m \sin \omega t & \text{for } 0 < \omega t < \pi \\ -I_m \sin \omega t & \text{for } \pi < \omega t < 2\pi \end{Bmatrix} \qquad \ldots(1)$$

Here, $$I_m = \frac{V_m}{R_f + R_L}.$$

(*i*) D.C. (average) value of output current. The output dc current I_{dc} is given by

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i\,d(\omega t)$$

$$= \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin\omega t\,d(\omega t) + \int_{\pi}^{2\pi} -I_m \sin\omega t\,d(\omega t)\right]$$

$$= \frac{I_m}{2\pi}\left[[-\cos\omega t]_0^{\pi} + [\cos\omega t]_{\pi}^{2\pi}\right] = \frac{I_m}{2\pi}[2+2]$$

$$\therefore \qquad I_{dc} = \frac{2I_m}{\pi}. \qquad \text{...(2)}$$

(*ii*) R.M.S. (effective) value of load current. The r.m.s. value of total output current is given by

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2 d(\omega t)}$$

$$= \left[\frac{1}{2\pi}\left\{\int_0^{\pi} I_m^2 \sin^2 \omega t.d(\omega t) + \int_{\pi}^{2\pi} I_m^2 \sin^2 \omega t.d(\omega t)\right\}\right]^{1/2}$$

$$\therefore \qquad I_{rms} = \frac{I_m}{\sqrt{2}}. \qquad \text{...(3)}$$

(*iii*) Power supplied to the circuit. The a.c. power input to the rectifier from the supply is given by

$$P\propto = I_{rms}^2\,(R_f + R_L) = \frac{(R_f + R_L)I_m^2}{2}. \qquad \text{...(4)}$$

(*iv*) Average power supplied to the load R_L. The d.c. power output across the load R_L is given by

$$P_{dc} = I_{dc}^2 R_L = \frac{4I_m^2 R_L}{\pi^2}. \qquad \text{...(5)}$$

(*v*) Rectifier efficiency. In a rectifier, the useful power output is the d.c. power which is developed across the load R_L. Therefore, efficiency

$$\eta = \frac{\text{d.c. power supplied to the load}}{\text{Total input A.C. power}} \times 100\%$$

$$= \frac{P_{dc}}{P_{ac}} \times 100\% = \frac{4I_m^2 R_L/\pi^2}{(R_f + R_L)I_m^2/2} \times 100\%$$

[Using Eqs. (4) and (5)]

$$\therefore \qquad \eta = \frac{81.2}{1+\dfrac{R_f}{R_L}}\% \qquad \text{...(6)}$$

Thus, the rectification efficiency of a full-wave rectifier is double that of a half-wave rectifier under identical conditions.

The maximum possible efficiency of a full-wave rectifier is 81.2 % when $R_f << R_L$.

(*vi*) Ripple factor. The ripple factor γ is given by

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2I_m/\pi}\right)^2 - 1}$$

$$\therefore \qquad \gamma = \mathbf{0.482}$$

The ripple factor of a full-wave rectifier is 0.482 and is much smaller than that of half-wave rectifier. Hence, in actual practice, a full-wave rectifier is preferred to a half-wave rectifier.

(*vii*) Peak inverse voltage. *PIV is the maximum reverse voltage which the rectifier has to withstand during the non-conduction period.* Suppose the diode D_1 is conducting and D_2 non-conducting.

The reverse voltage across diode D_2

$$\text{PIV} = \text{PD across } R_L - (-V_m) = V_m + V_m = 2V_m$$

Thus in a full-wave rectifier, PIV across each diode is two times the maximum transformer voltage measured from the centre-tap to either end.

Q: explain the working of bridge rectifier.

The circuit is shown in Fig. 58.17. The diodes D_1, D_2, D_3 and D_4 are arranged in the form of Wheatstone Bridge network. The two opposite ends A and C of the network are connected to the ends S_1 and S_2 of the secondary of transformer T. The ends B and D are connected to the load resistance R_L. The primary P of the transformer is connected to the ac mains.

When an AC voltage is applied to the primary, at some instant the positive half of the input cycle passes through the secondary, keeping the point A positive and C negative. Diodes D_1 and D_3 conduct and a current flows in the direction $ABR_L\ DC\ S_2\ S_1\ A$.

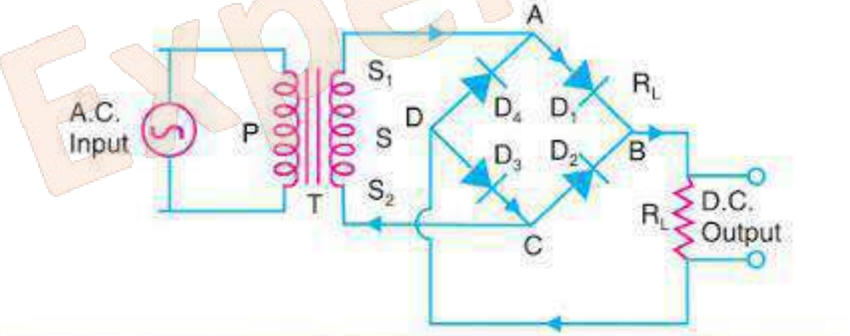


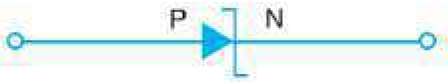
Fig. 58.17

At the same time D_2 and D_4 will not be conducting, since they are reverse biased. During the next half cycle, the point A is negative and C is positive. Therefore in this case diodes D_2 and D_4 conduct and current flows in the direction $CBR_L\ DAS_1\ S_2\ C$. But now D_1 and D_3 will not be conducting. Therefore during both the halves of the input cycle, current flows through the load R_L in the same direction. Thus a DC output is developed across R_L and we have full wave rectification.

Q: what is zener diode? Draw its symbol and explain zener and avalanche effect.

Ans:

The diode which operates in the reverse breakdown region with a sharp breakdown voltage is called a *Zener diode*



It is an ordinary *P-N* junction diode except that it is properly doped to have a very sharp and almost vertical breakdown. It is exclusively operated under reverse bias conditions. It is designed to operate in breakdown region without damage. By adjusting the doping level it is possible to produce zener diodes with a breakdown voltage ranging from 2V to 800 V.

Zener diode primarily depends for its working on *Zener Effect*. In a heavily doped diode, the depletion region is very narrow. When the reverse bias voltage across the diode is increased, the electric field across the depletion region becomes very strong. When this field is ≈ 3×10^7 V/m, electrons are pulled out of the covalent bonds. A large number of electron-hole pairs are thereby produced. The reverse current rises steeply. This is *Zener effect*.

The external applied voltage accelerates the minority carriers in the depletion region. These carriers gain sufficient energy to ionise atoms by collision. The electrons produced thereby accelerate to sufficiently large velocities to be able to ionise other atoms. This creates a sort of chain reaction. The cumulative effect of this chain reaction is the *avalanche ef*

Q: explain zener diode as voltage regulator.

Ans:

In a voltage regulated power supply unit, the output voltage is constant and it is independent of the variations of input supply voltage and load resistance. The circuit diagram of a Zener diode voltage regulator is shown in Fig. 58.11. The unregulated dc is applied across the diode through a series resistor *R*, which limits the input current. The value of the series resitor *R* is so chosen that initially the diode operates in the breakdown region. The *P*-junction of the Zener diode is connected to the negative of the input voltage and *N*-junction to the positive. Thus the Zener diode is reverse biased. The output voltage V_0 remains essentially constant (equal to V_z) even though the input voltage V_i and the load resistance R_l may vary over a wide range.

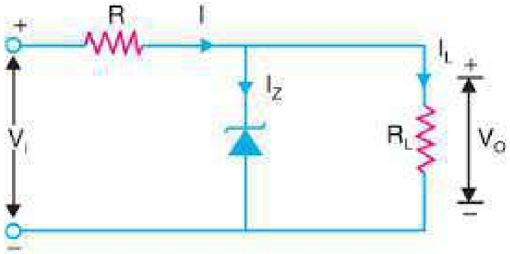


Fig. 58.11

Working. Let I be the current drawn from the supply source, I_z the current through the Zener diode and I_L that across the load resistance R_L.

Applying Kirchhoff 's laws, we get

$$I = I_z + I_L \quad ...(1)$$

$$V_0 = V_i - IR \quad ...(2)$$

and

$$V_0 = I_L R_L \quad ...(3)$$

The variation in the output voltage may be due to two causes. First, the load current may vary. Second, the input voltage may vary.

Variation of load current : Suppose the load resistance R_L varies and the input voltage V_i remains constant. Since the output voltage V_0 tends to remain constant, Eq. (2) gives

$$\delta I = 0 \quad (\because V_i \text{ and } R \text{ are constant})$$

Then Eq. (1) gives $\delta I = \delta I_z + \delta I_L = 0$

or $\delta I_z = -\delta I_L$.

Thus, *if the load resistance increases*, when the supply voltage is fixed, *the load current I_L decreases* and the Zener diode current I_z increases by an equal amount. Thus the *voltage V_0 across the load will tend to remain constant.*

Variation in input voltage : Now suppose that the load resistance R_L remains constant and supply voltage V_i varies. Since V_0 tends to remain constant, we get from Eq. (2),

$$\delta V_i = R\,\delta I$$

Also Eq. (3) gives, $\delta I_L = 0 \quad (\because R_L \text{ is constant})$

$\therefore$ Eq. (1) gives, $\delta I = \delta I_z$

Thus when the supply voltage varies but the load resistance remains constant, the *total current I and the Zener current I_z change equally to keep the load current I_L constant.* Thus if total current I decreases by δI, the diode current I_z also decreases by the same amount, so that load current I_L remains constant and the *voltage V_0 across the load will tend to remain constant.*

Q:distinguish between zener diode and ordinary diode.

Solution. 1. Ordinary junction diodes are operated within the breakdown voltage in reverse biased condition. Operation beyond breakdown voltage may damage them.

But a Zener diode is specially designed for operation beyond breakdown voltage. This breakdown voltage is called the *Zener breakdown potential.*

2. Ordinary diode is usually used for rectification while Zener diode is used for voltage regulation.

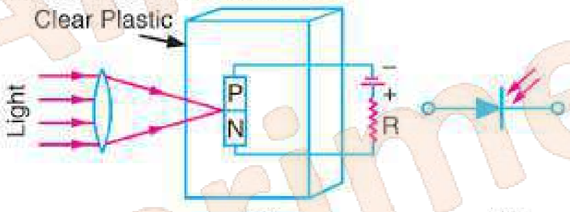
Q: write principle, structure and construction of photodiode.

Principle. A reverse-biased *P-N* junction diode has a reverse saturation current which is mainly due to the flow of the minority carriers. When light is incident on the depletion region of the reverse-biased *p-n* junction, the concentration of minority carriers (electrons in *p* type and holes in *n* type) increases to a great extent. But the change in majority carriers is too low. Consequently reverse current increases. The reverse current through the diode varies almost linearly with the intensity of light.

A photo diode is essentially a reverse-biased P-N junction diode which is designed to respond to photon absorption.

Construction. A photo diode consists of a *P-N* junction embedded in a clear plastic capsule [Fig. 56.1(*a*)]. The symbol of a photo diode is shown in Fig. 56.1(*b*). Light is allowed to fall upon one surface across the junction. All the sides of the plastic capsule, excepting the illuminated one, are either painted black or enclosed in a metallic case.

Working and Characteristics. When photo diode is kept under dark condition and a sufficient reverse voltage is applied, then an almost constant current, independent of magnitude of reverse bias, is obtained. This current corresponds to the reverse saturation current due to thermally generated minority carriers. It is called *dark current*. It is proportional to the concentrations of minority carriers and is denoted by I_d. Majority charge carriers are not allowed to cross the junction by the potential hill under this reverse bias condition.



(*a*) (*b*)

When light falls on the diode surface, additional electron-hole pairs are formed. But since the concentration of majority carriers is much greater as compared to that of minority carriers, the percentage increase of majority carriers is much smaller than the percentage increase of minority carriers. Hence, we can neglect the increase in majority carrier density and can consider the radiation entirely as a *minority carrier injector*. These injected minority carriers diffuse to the junction, cross it and contribute to the additional current.

Thus under large reverse bias conditions, the total reverse current is given by

$$I = I_s + I_d$$

where I_s is the short circuit current and is proportional to light intensity.

With any bias V, the reverse current due to thermal electron-hole pairs, *i.e.*, dark current is, given by

$$I_d = I_0(1 - e^{Ve/\eta kT}).$$

Hence, the volt-ampere characteristic of photo diode is given by

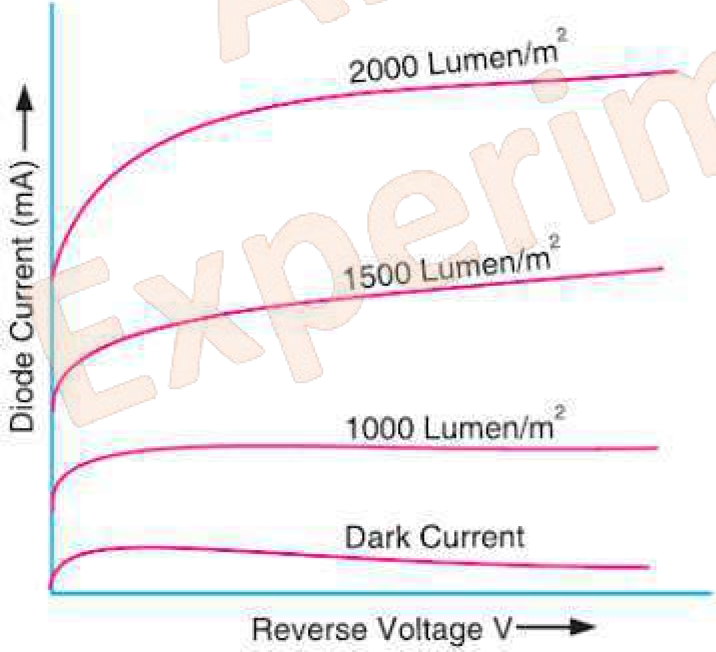
$$I = I_s + I_0\,(1 - e^{Ve/\eta kT})$$

where η is equal to 1 for Ge and equals 2 for Si.

The volt-ampere characteristic curve of a photo diode is as shown in Fig. 56.2. From the curve it is seen that

(*i*) the current increases with increase in the level of illumination for a given reverse voltage.

(*ii*) only for the dark current at zero voltage the current is zero.



The photo diode finds extensive application in light detection systems, reading of film sound track, light operated switches, high-speed reading of computer punched cards and tapes.

Q: write principle, structure and construction of light emitting diode.

Ans:

A light emitting diode (LED) is a specially made forward-biased P-N junction diode which emits visible light when energized.

Theory

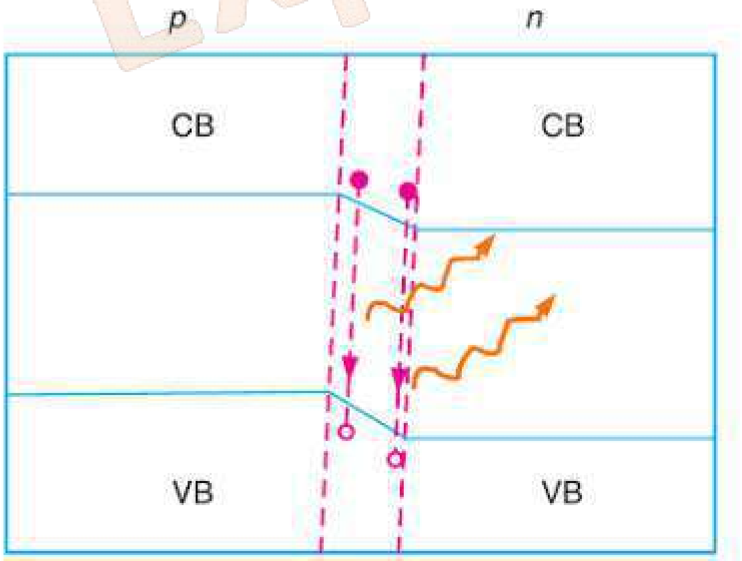
When a junction diode is forward-biased, electrons from n–side and holes from p–side move towards the depletion region and they recombine. During this process, energy is released because electrons make transition from conduction band (higher energy level) to valence band (lower energy level) [Fig. 56.7].

If E_g is the semiconductor band gap, then the energy $E_g = h\nu = \frac{hc}{\lambda}$ is emitted in the form of radiation. The corresponding emission wavelength is given by

$$\lambda = \frac{hc}{E_g}.$$

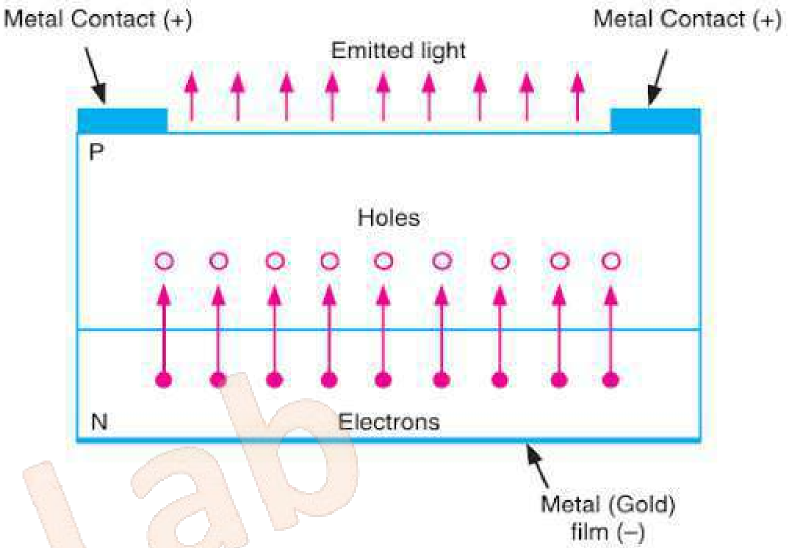
In case of Gallium Arsenide Phosphide (Ga As P), band gap $E_g = 1.9$ eV, and we get

$$\lambda = \frac{hc}{E_g} = \frac{6{\cdot}62 \times 10^{-34} \times 3 \times 10^{8}}{1{\cdot}9 \times 1{\cdot}6 \times 10^{-19}}\ \text{m} = 653{\cdot}3\,\text{nm (red)}.$$

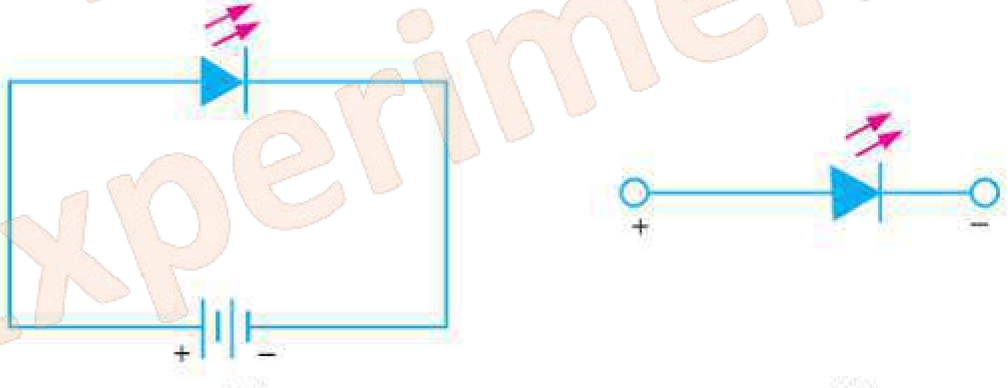


Construction

At first an *N*-type layer is grown on a substrate and then a *P*-type layer is deposited on it by the process of diffusion [Fig 56.8]. Metal contacts (Anode) are made at the outer edge of the *P*-layer so that more upper surface is left free for light to escape. For making Cathode connections, a metal film (preferably gold) is coated at the bottom of the substrate. This film also reflects as much light as possible to the surface of the device.



Ga As *P* LED emits red light when forward-biased [Fig. 56.9 (*a*)]. Fig. 56.9 (*b*) shows the schematic symbol of LED.

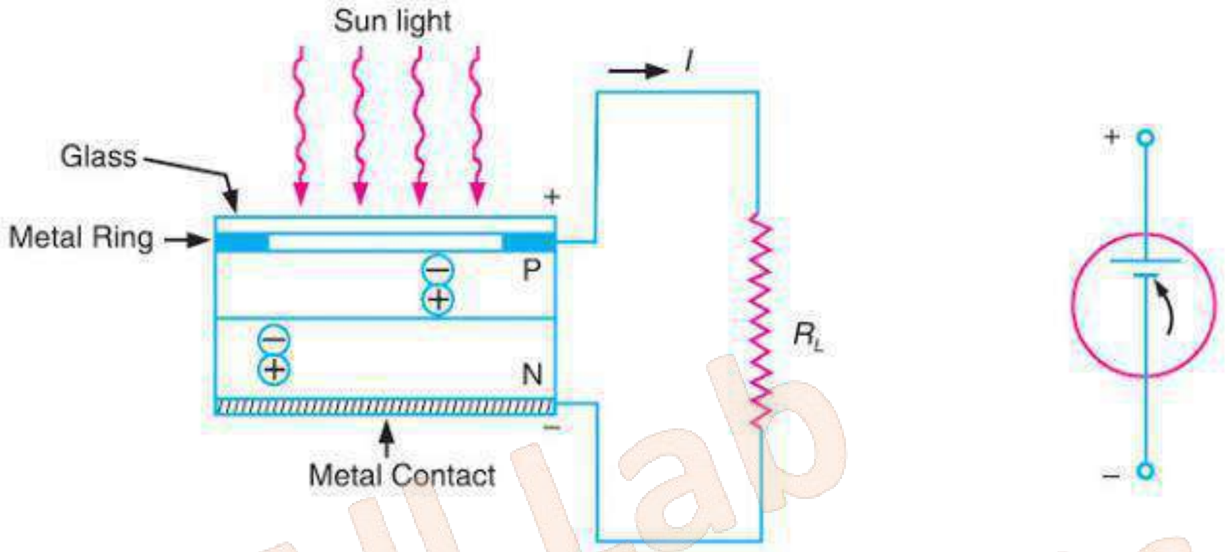


(*a*) (*b*)

Q: write principle, structure and construction of light emitting diode.

A *solar cell* is basically a *P-N* junction diode which converts solar energy (light energy) into electrical energy. In principle, a solar cell is nothing but a light emitting diode (LED) operating in reverse.

Common materials for solar cells include silicon, gallium Arsenide (Ga As), indium Arsenide (In As) and cadmium Arsenide (Cd As). The most common is silicon. For silicon, the band gap (the energy necessary to transfer an electron from the upper valence level to the conduction band) is 1.12 eV. The maximum theoretical efficiency of a solar cell depends on this band gap. For silicon, the maximum efficiency is 22%.



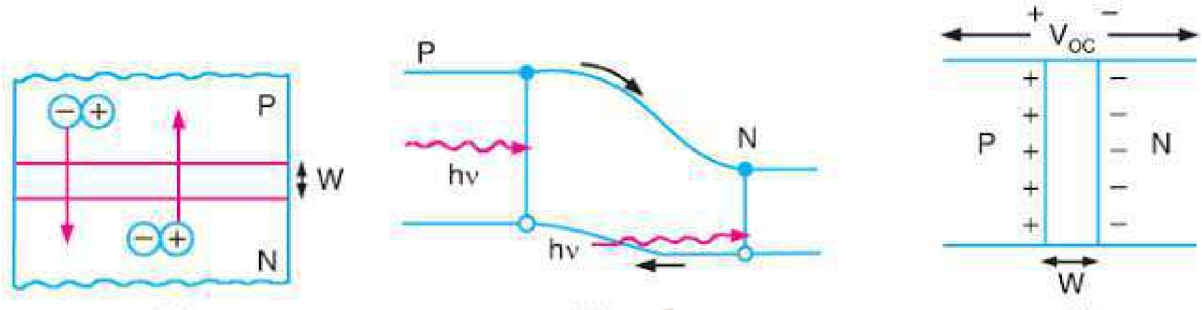
(a) (b)

Construction

A solar cell consists of *P-N* junction diode made of Si [Fig. 56.13 (*a*)]. Fig. 56.13 (*b*) gives the schematic symbol of a solar cell. The inward arrow indicates the incoming light. The *P-N* diode is packed in a can with glass window on top so that light may fall upon *P* and *N* type materials. The thickness of the *P*-region is kept very small so that electrons generated in this region can diffuse to the junction before recombination takes place. Thickness of *N*-region is also kept small to allow holes generated near the surface to diffuse to the junction before they recombine. A heavy doping of *P* and *N* regions is recommended to obtain a large photo voltage. A nickel plated ring is provided around the *P*-layer which acts as the positive output terminal. A metal contact at the bottom serves as the negative output terminal.

Working

The working of a solar cell may be understood from Fig. 56.14. When light radiation falls on a *P-N* junction diode, photons collide with valence electrons and impart them sufficient energy enabling them to leave their parent atoms. Thus electron-hole pairs are generated in both the *P* and *N* sides of the junction. These electrons and holes reach the depletion region *W* by diffusion [Fig. 56.14 (*a*)] and are then separated by the strong barrier field existing there. However, the minority carrier electrons in the *P*-side slide down the barrier potential to reach the *N*-side and the holes in the *N*-side move to the *P*-side [Fig. 56.14 (*b*)]. Their flow constitutes the minority current which is directly proportional to the illumination and also depends on the surface area being exposed to light.

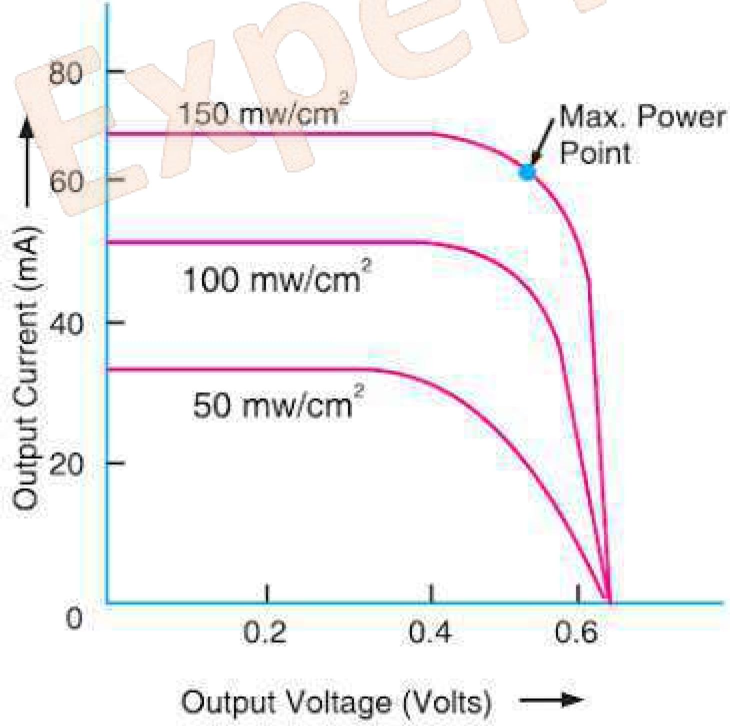


(a) (b) (c)

The accumulation of electrons and holes on the two sides of the junction [Fig. 56.14 (c)] gives rise to an *open circuit voltage* V_{oc} which is a function of illumination. The open-circuit voltage produced for a silicon solar cell is typically 0.6 volt and the short-circuit current is about 40 mA / cm^2 in bright noon day sun light.

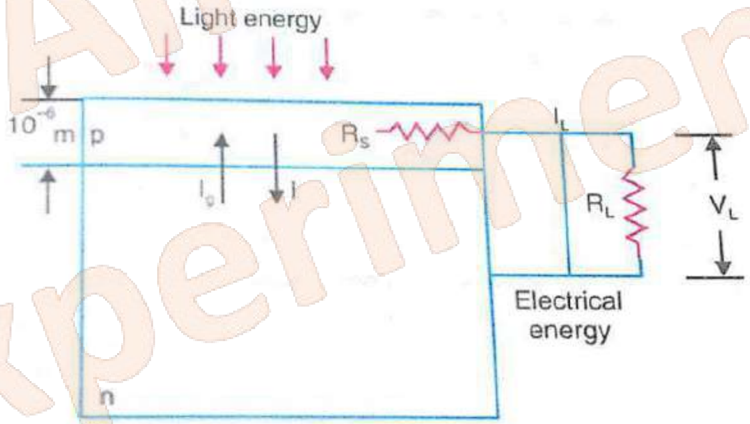
Characteristics

Typical V-I characteristics of a solar cell, corresponding to different levels of illumination are shown in Fig. 56.15. Maximum power output is obtained when the cell is operated at the knee of the curve.



Relation between Load Current and Load Voltage

Holes and electrons produced in the junction region are swept to the *p*-type and *n*-type sides, respectively, as shown in Fig. 56.14. This produces a current I_s across the junction and also acts to charge the *p*-region positively and the *n*-type region negatively. Hence if there are no external connections to the junction, this forward bias causes a forward current I to flow. Under this condition, the forward current just balances the current I_g. When the *p*-and *n*-type sides are connected externally through an electrical load (Fig. 56.16), a portion of I_g flows in the external circuit.

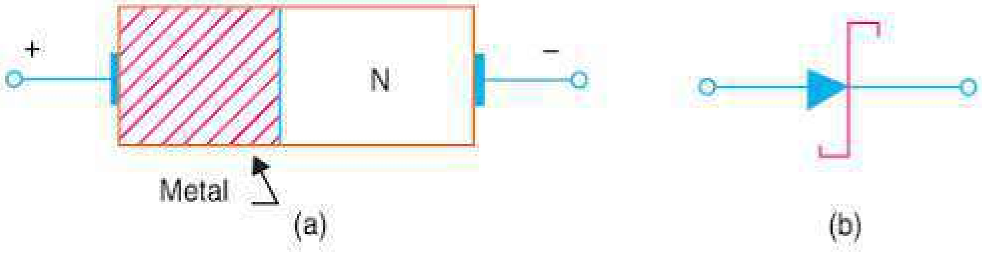


Q:Explain the contruction ,operation and characterstics of schottky diode.

A metal-semiconductor junction diode is known as **Schottky Diode**.

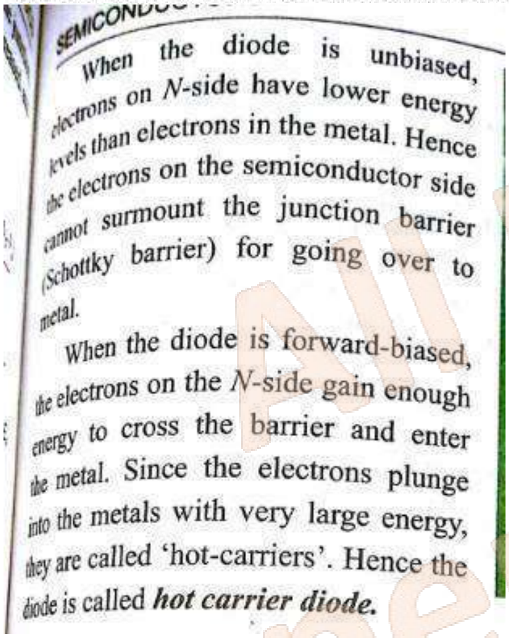
Construction

It consists of a junction between a metal (like platinum, gold, silver, tungsten etc.) and *N*-type doped semi conductor. The most common semiconductor material used is silicon. GaAs can also be used which has lower noise and higher operating frequency. Schottky diode has no depletion layer. Fig. 55.27 shows the diode and its schematic symbol.



Operation

Metals have a work function which is defined as the minimum energy required for an electron to escape into vacuum. It is the energy difference between the Fermi and vacuum levels. For semiconductors, the energy differences between vacuum level and the bottom of conduction band is known as electron affinity. When a junction is formed between a metal and a semiconductor, the Fermi levels on both sides get aligned and a barrier (to electron flow) is formed due to energy difference between work function of the metal and electron affinity of the semiconductor.



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When the diode is unbiased, electrons on *N*-side have lower energy levels than electrons in the metal. Hence the electrons on the semiconductor side cannot surmount the junction barrier (Schottky barrier) for going over to metal.

When the diode is forward-biased, the electrons on the *N*-side gain enough energy to cross the barrier and enter the metal. Since the electrons plunge into the metals with very large energy, they are called 'hot-carriers'. Hence the diode is called ***hot carrier diode.***

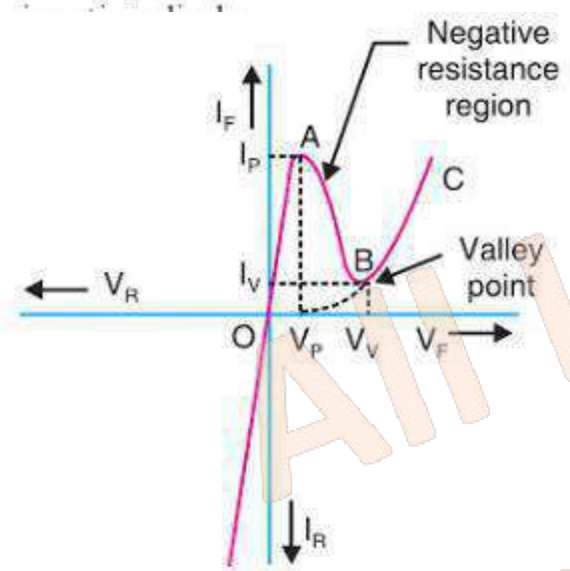
Q:explain tunnel diode.

It is a *p-n* junction semiconductor diode in which the concentration of impurity atoms is very large in *p* and *n* regions ($\approx 10^{24}/\text{m}^3$). The width of the depletion region is very small ($\approx 10^{-8}$ m). Since the depletion region is very narrow, electrons are capable of tunneling through from one side of the junction to the other at relatively low forward bias voltage. This phenomenon is called *tunneling*. This type of diode is called Tunnel Diode (Fig. 58.36)

Fig. 58.36

The Volt-Ampere (V–I) Characteristics

The V–I characteristics of a tunnel diode are shown in Fig. 58.37. When forward voltage increases from zero, the forward current quickly reaches the peak value I_p (point *A*) at a particular low forward voltage V_p. When the forward voltage exceeds the value V_p, the forward current decreases and reaches a minimum value called valley current I_v at valley voltage V_v (point *B*). The region between the peak current I_p and the valley current I_v is called *negative resistance region*. When the forward voltage is further increased beyond the valley point, the current increases again as in ordinary *p-n*



Explanation. Forward current in a tunnel diode is the sum of two components due to two different mechanisms:

(*i*) Normal injection current : It arises from an external voltage which reduces the potential barrier across the depletion region and allows current to flow due to majority carriers in the conduction band. It is shown by *dashed curve*.

(*ii*) Tunnel current : In a tunnel diode due to heavy doping, the depletion region is very narrow. It results in a very high electric field across the junction and allows carriers in the valence energy band on one side of the junction to 'tunnel' through to the conduction energy band on the other side of the junction without overcoming the potential barrier. The increase in current from 0 to its peak value I_P (at *A*) at a forward voltage V_P is due to tunneling phenomenon. The normal injection current is negligible at this value of forward bias.

The application of the *forward bias beyond* V_P reduces the electric field strength because the depletion region becomes less well defined due to diffusion of carriers across the *p-n* junction. Consequently the *tunneling current decreases*. Thus *current decreases with increase in applied voltage* between the peak point *A* and valley point *B*. It causes a negative slope in the *V-I* curve and the tunnel diode *exhibits a negative resistance property*.

If forward voltage is increased beyond V_v, the tunneling effect ceases and current rises because of injection currents as in any ordinary junction diode.