Yukawa's Meson Theory of Nuclear Forces : A Japanese scientist Yukawa in 1935 suggested that the nuclear forces are 'exchange forces'. Which are produced by the exchange of new particles called π-mesons between nucleons. These particles were later on actually discovered in cosmic radiation. There are three types of π-mesons, π^+, π^- and π^0. There is a continuous exchange of π-mesons between protons and neutrons due to which they continue to be converted into one another. When a π^+ meson jumps from a proton to a neutron, the proton is converted into a neutron and the neutron is converted into a proton.

$$P - \pi^+ \longrightarrow n$$

and

$$n + \pi^+ \longrightarrow P$$

Conversely, when a π^- meson jumps from a neutron to a proton, the neutron is converted into a proton and the proton is converted into a neutron. Thus,

$$n - \pi^- \longrightarrow P$$

and

$$P + \pi^- \longrightarrow n$$

The exchange of π^+ and π^- mesons between protons and neutrons is responsible for the origin of nuclear forces between them. Similarly nuclear forces between two protons and between two neutrons are generated by a continuous exchange of π^0-mesons between them. Thus, the basis of nuclear forces is the exchange of mesons and hence these are called 'exchange forces'.

Note *According to modern concept, electrical and gravitational forces are also exchange forces. Electrical forces between two charged particles are generated by exchange of photons. A new particle 'graviton' is assumed to be responsible for the origin of gravitational forces between two bodies.*

Compton Effect : When a monochromatic beam of X-rays is scattered by an electron, the scattered X-rays contain radiation not only of the same wavelength but also the radiation of longer wavelength. This is called compton effect. According to compton effect the change in wavelength is given by,

$$\Delta\lambda = \frac{h}{m_0 c}(1 - \cos\phi)$$

Here h is the Planck's constant, m_0 the rest mass of electron ϕ the angle of scattering and c the speed of light.

For $\phi = 90°$, $\cos\phi = 0$

$$\therefore \quad \Delta\lambda = \frac{h}{m_0 c}$$

Substituting the values of h, m_0 and c we get,

$$\Delta\lambda = 0.024 \text{ Å}$$

This is called compton wavelength of the electron.

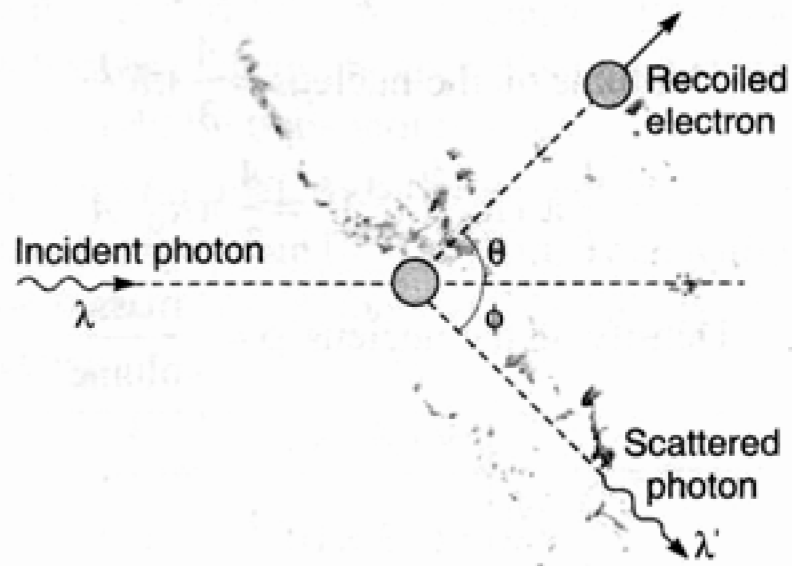


Fig. 31.19

$$\lambda' > \lambda$$

$$\Delta\lambda = \lambda' - \lambda$$

Further we can see that $(\Delta\lambda)_{max} = 0.048$ Å at $\phi = 180°$.

Sample Example 31.9 *X-rays of wavelength $\lambda_0 = 0.200$ nm are scattered from a block of material. The scattered X-rays are observed at an angle of 45° to the incident beam. Calculate their wavelength.*

Solution The shift in wavelength of the scattered X-rays is given by,

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\phi)$$

Substituting the values, we have

$$\lambda' - \lambda = \frac{6.626 \times 10^{-34}}{(9.11 \times 10^{-31})(3.00 \times 10^{8})}(1 - \cos 45°)$$

$$= 7.10 \times 10^{-13} \text{ m}$$

$$= 0.000710 \text{ nm}$$

$$\therefore \quad \lambda' = (0.200) + (0.000710)$$

$$= 0.200710 \text{ nm}$$

Ans.

Size and shape of the Nucleus : The Rutherford scattering experiment established that mass of an atom is concentrated within a small positively charged region at the centre which is called the nucleus of the atom. The nuclear radius is given by,

$$R = R_0 A^{1/3}$$

Here, A is the mass number of the particular nucleus and $R_0 = 1.3$ fm (fermi) $= 1.3 \times 10^{-15}$ m. This means that the nucleus radius is of the order of 10^{-15} m.

Here, $R_0 = 1.3$ fm is the distance of closest approach to the nucleus and is also known as nuclear unit radius.

Nuclear Density : Let us consider the nucleus of an atom having the mass number A.

$$\text{Mass of nucleus} \approx A \times 1.67 \times 10^{-27} \text{ kg}$$

$$\text{Volume of the nucleus} = \frac{4}{3} \pi R^3$$

$$= \frac{4}{3} \pi (R_0 A^{1/3})^3 = \frac{4}{3} \pi R_0^3 A$$

$\therefore$
$$\text{Density of the nucleus, } \rho = \frac{\text{mass}}{\text{volume}}$$

or
$$\rho = \frac{A \times 1.67 \times 10^{-27}}{\frac{4}{3} \times \pi \times (1.3 \times 10^{-15})^3 \times A}$$

$$= 1.8 \times 10^{17} \text{ kg/m}^3$$

Thus density of a nucleus is of the order of 10^{17} kg/m^3.

Magic Numbers

We know that the electrons in an atom are grouped in 'shells' and 'sub-shells'. Atoms with 2, 10, 18, 36, 54 and 86 electrons have all of their shells completely filled. Such atoms are unusually stable and chemically inert. A similar situation exists with nuclei also. Nuclei having 2, 8, 20, 28, 50, 82 and 126 nucleons of the same kind (either protons or neutrons) are more stable than nuclei of neighbouring mass numbers. These numbers are called as 'magic numbers'.

Fluorescence and Phosphorescence

Fluorescence : There are certain substances which on being illuminated by high frequency light (blue or ultraviolet) emit light of relatively low frequency. The emission occurs so long as the substance is being illuminated. This phenomenon is called fluorescence. Fluorescence has many applications in daily life. For example, the presence of invisible ultraviolet rays can be detected by their fluorescent effect.

Explanation : Every atom has discrete energy levels associated with it. Normally the electrons occupy the lowest energy states. When light of some appropriate energy falls on them, they absorb energy and jump to some higher energy state. They stay there only for 10^{-8} second. But they do not return directly to their ground state but are transferred step by step, emitting light of some lower frequency.

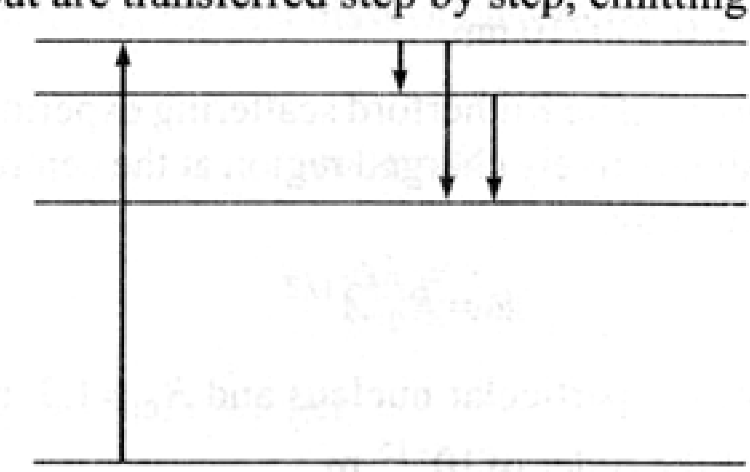


Fig. 31.20

Phosphorescence : Fluorescent materials emit light only so long as light is incident on them. There are certain substances which continue emitting light for some time after the light incident on them is stopped. This phenomenon is called 'phosphorescence'. Phosphorescent substances are painted on watch hands, electric switch boards and sign boards. These substances absorb sunlight during day-time and illuminate during the dark night by phosphorescence.

Explanation : Phosphorescent materials have metastable energy states. In these states the electron can remain for a period longer than 10^{-8} second. Thus while returning back to the lower energy levels the electron stays for some time in meta stable energy states. These delayed transitions are responsible for phosphorescence.

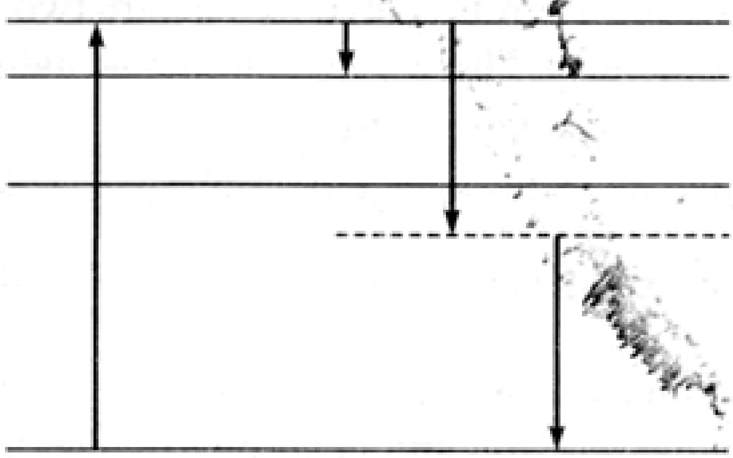


Fig. 31.21

Fundamental Particles

The particles which are not constituted by any other particles are called fundamental particles. A brief discussion of important fundamental particles is as follows.

(i) Electron : It was discovered in 1897 by Thomson. Its charge is $-e$ and mass is 9.1×10^{-31} kg. Its symbol is e^- (or $_{-1}\beta^0$).

(ii) Proton : It was discovered in 1919 by Rutherford in artificial nuclear disintegration. It has a positive charge $+e$ and its mass is 1836 times (1.673×10^{-27} kg) the mass of electron. In free state, the proton is a stable particle. Its symbol is P^+. It is also written as $_1H^1$.

(iii) Neutron : It was discovered in 1932 by Chadwick. Electrically it is a neutral particle. Its mass is 1839 times (1.675×10^{-27} kg) the mass of electron. In free state the neutron is unstable (mean life $\approx$ 17 minutes) but it constitutes a stable nucleus with the proton. Its symbol is n or $_0n^1$.

(iv) Positron : It was discovered by Anderson in 1932. It is the antiparticle of electron, *i.e.*, its charge is $+e$ and its mass is equal to that of the mass of electron. Its symbol is e^+ (or $_{+1}\beta^0$).

(v) Antiproton : It is the antiparticle of proton. It was discovered in 1955. Its charge is $-e$ and its mass is equal to that of the mass of proton. Its symbol is P^-.

(vi) Antineutron : It was discovered in 1956. It has no charge and its mass is equal to the mass of neutron. The only difference between neutron and antineutron is that if they spin in the same direction, their magnetic momenta will be in opposite directions. The symbol for antineutron is $\bar{n}$.

(vii) Neutrino and antineutrino : The existence of these particles was predicted in 1930 by Pauli while explaining the emission of β-particles from radioactive nuclei, but these particles were actually observed experimentally in 1956. Their rest mass and charge are both zero but they have energy and momentum. These are mutually antiparticles of each other. They have the symbol ν and $\bar{\nu}$.

(viii) Pi-Mesons : The existence of pi-mesons was predicted by Yukawa in 1935, but they were actually discovered in 1947 in cosmic rays. Nuclear forces are explained by the exchange of pi-mesons between the nucleons. pi-mesons are of three types, positive π-mesons (π^+), negative pi-mesons (π^-) and neutral π-mesons (π^0). Charge on $\pi^\pm$ is $\pm e$. Whereas mass of $\pi^\pm$ is 274 times the mass of electron. π^0 has mass nearly 264 times the electronic mass.

(ix) Mu-Mesons : These were discovered in 1936 by Anderson and Neddermeyer. These are found in abundance in the cosmic rays at the ground level. There are two types of mu-mesons. Positive mu-meson (μ^+) and negative mu-meson (μ^-). There is no neutral mu-meson. Both the mu-mesons have the same rest mass 207 times the rest mass of the electron.

(x) Photon : These are bundles of electromagnetic energy and travel with the speed of light. Energy and momentum of a photon of frequency ν are $h\nu$ and $\frac{h\nu}{c}$ respectively.

Antiparticles : For every fundamental particle there exists an identical fundamental particle just opposite in some property. For example electron and positron are identical in all respects, except that charges on them are opposite.

The following table shows various particles and their antiparticles. Some particles are their own antiparticles. For example π^0 and γ.

Name of Particle	Symbol	Antiparticle	Mass in comparison to mass of electron	Average life (in seconds) for the unstable particles
Electron	e^-	e^{+1}	1	stable
Proton	P^+	P^-	1836	stable
Neutron	n	$\bar{n}$	1839	1010
Neutrino	ν	$\bar{\nu}$	0	stable
Pi-Mesons	π^+	π^-	274	$2.6 \times 10^{-8}0$
	π^0	π^0	264	0.9×10^{-16}
Mu-Mesons	μ^-	μ^+	207	2.2×10^{-6}
Photon	γ	γ	0	stable

Solved Examples

Example 1 *In the fusion reaction* $^2_1H + ^2_1H \longrightarrow ^3_2He + ^1_0n$, *the masses of deuteron, helium and neutron expressed in amu are* 2.015, 3.017 *and* 1.009 *respectively. If* 1 *kg of deuterium undergoes complete fusion, find the amount of total energy released.* 1 *amu* $\equiv 931.5\ MeV/c^2$.

Solution $\Delta m = 2\,(2.015) - (3.017 + 1.009) = 0.004$ amu

$$\therefore \quad \text{Energy released} = (0.004 \times 931.5)\ \text{MeV} = 3.726\ \text{MeV}$$

$$\text{Energy released per deuteron} = \frac{3.726}{2} = 1.863\ \text{MeV}$$

$$\text{Number of deuterons in 1 kg} = \frac{6.02 \times 10^{26}}{2} = 3.01 \times 10^{26}$$

$$\therefore \quad \text{Energy released per kg of deuterium fusion} = (3.01 \times 10^{26} \times 1.863) = 5.6 \times 10^{26}\ \text{MeV}$$

$$\approx 9.0 \times 10^{13}\ \text{J}$$

Ans.

Example 2 *In the chemical analysis of a rock the mass ratio of two radioactive isotopes is found to be* 100 : 1. *The mean lives of the two isotopes are* 4×10^9 *years and* 2×10^9 *years respectively. If it is assumed that at the time of formation the atoms of both the isotopes were in equal proportional, calculate the age of the rock. Ratio of the atomic weights of the two isotopes is* 1.02 : 1.

Solution At the time of observation ($t = t$),

$$\frac{m_1}{m_2} = \frac{100}{1} \quad \text{(given)}$$

Further it is given that

$$\frac{A_1}{A_2} = \frac{1.02}{1}$$

Number of atoms

$$N = \frac{m}{A}$$

$$\therefore \quad \frac{N_1}{N_2} = \frac{m_1}{m_2} \times \frac{A_2}{A_1} = \frac{100}{1.02} \qquad \ldots\text{(i)}$$

Let N_0 be the number of atoms of both the isotopes at the time of formation, then

$$\frac{N_1}{N_2} = \frac{N_0\, e^{-\lambda_1 t}}{N_0\, e^{-\lambda_2 t}} = e^{(\lambda_2 - \lambda_1)\,t} \qquad \ldots\text{(ii)}$$

Equating (i) and (ii), we have

$$e^{(\lambda_2 - \lambda_1)\,t} = \frac{100}{1.02} \quad \text{or} \quad (\lambda_2 - \lambda_1)t = \ln(100) - \ln(1.02)$$

$$\therefore \qquad t = \frac{\ln(100) - \ln(1.02)}{\left(\frac{1}{2\times10^9} - \frac{1}{4\times10^9}\right)}$$

Substituting the values, we have

$$t = 1.834\times10^{10}\ \text{yr}$$ **Ans.**

Example 3 *A proton is bombarded on a stationary lithium nucleus. As a result of the collision two α-particles are produced. If the direction of motion of the α-particles with the initial direction of motion makes an angle* $\cos^{-1}(1/4)$, *find the kinetic energy of the striking proton. Given binding energies per nucleon of* Li^7 *and* He^4 *are 5.60 and 7.06 MeV respectively.*
(Assume mass of proton ≈ mass of neutron).

Solution Q value of the reaction is,

$$Q = (2\times4\times7.06 - 7\times5.6)\ \text{MeV} = 17.28\ \text{MeV}$$

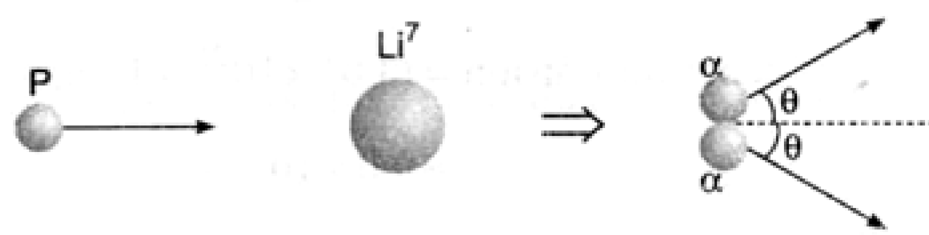


Fig. 31.22

Applying conservation of energy for collision,

$$K_p + Q = 2K_\alpha \qquad \text{...(i)}$$

(Here, K_p and K_α are the kinetic energies of proton and α-particle respectively)
From conservation of linear momentum,

$$\sqrt{2m_pK_p} = 2\sqrt{2m_\alpha K_\alpha}\cos\theta \qquad \text{...(ii)}$$

$$\therefore \qquad K_p = 16K_\alpha\cos^2\theta = (16K_\alpha)\left(\frac{1}{4}\right)^2 \qquad (\text{as } m_\alpha = 4m_p)$$

$$\therefore \qquad K_\alpha = K_p \qquad \text{...(iii)}$$

Solving Eqs. (i) and (iii) with $Q = 17.28$ MeV

we get $$K_p = 17.28\ \text{MeV}$$ **Ans.**

Example 4 *A radionuclide with half-life 1620 s is produced in a reactor at a constant rate 1000 nuclei per second. During each decay energy 200 MeV is released. If production of radio nuclides started at* $t = 0$, *calculate*
(a) rate of release of energy at $t = 3240$ s.
(b) total energy released upto $t = 405$ s.

Solution (a) Let N be the number of nuclei at time t, then net rate of increase of nuclei at instant t is,

$$\frac{dN}{dt} = \alpha - \lambda N \qquad (\text{where } \alpha = \text{rate of production of nuclei})$$

$$\therefore \quad \int_0^N \frac{dN}{\alpha - \lambda N} = \int_0^t dt$$

$$\therefore \quad N = \frac{\alpha}{\lambda}(1 - e^{-\lambda t}) \quad \ldots(i)$$

Rate of decay at this instant $\quad R = \lambda N = \alpha\,(1 - e^{-\lambda t})$

Hence, rate of release of energy at this time = R (energy released in each decay)

$$= \alpha\,(1 - e^{-\lambda t})\,(200)\ \text{MeV/s}$$

Substituting the values, we have

$$\text{rate of release of energy} = 1000\,(1 - e^{-\frac{0.693}{1620}\times 3240})\,(200)$$

$$= 1.5 \times 10^5\ \text{MeV/s}$$ **Ans.**

(b) Total number of nuclei decayed upto time $t = \alpha t - N$

$$= \alpha t - \frac{\alpha}{\lambda}\,(1 - e^{-\lambda t})$$

Hence, total energy released upto this instant

$$E = [\alpha t - \frac{\alpha}{\lambda}\,(1 - e^{-\lambda t})]\,(200)\ \text{MeV}$$

Substituting the values, we have

$$E = \left[1000 \times 405 - \frac{1000}{0.693/1620}\,(1 - e^{-\frac{0.693}{1620}\times 405})\right] \times 200\ \text{MeV}$$

$$= 6.63 \times 10^6\ \text{MeV}$$ **Ans.**

Example 5 *The mean lives of a radioactive substances are 1620 yr and 405 yr for α-emission and β-emission respectively. Find out the time during which three-fourth of a sample will decay if it is decaying both by α-emission and β-emission simultaneously.*

Solution Let at some instant of time t, number of atoms of the radioactive substance are N. It may decay either by α-emission or by β-emission. So, we can write,

$$\left(\frac{-dN}{dt}\right)_{\text{net}} = \left(\frac{-dN}{dt}\right)_{\alpha} + \left(\frac{-dN}{dt}\right)_{\beta}$$

If the effective decay constant is λ, then

$$\lambda N = \lambda_\alpha N + \lambda_\beta N$$

or

$$\lambda = \lambda_\alpha + \lambda_\beta = \frac{1}{1620} + \frac{1}{405}$$

$$= \frac{1}{324}\ \text{year}^{-1}$$

Now,

$$\frac{N_0}{4} = N_0\, e^{-\lambda t}$$

$$\therefore \quad -\lambda t = \ln\left(\frac{1}{4}\right) = -1.386$$

or
$$\left(\frac{1}{324}\right) t = 1.386$$

$$\therefore \quad t = 449 \text{ yr}$$ **Ans.**

Example 6 *A* ^{7}Li *target is bombarded with a proton beam current of* 10^{-4} *A for* 1 *hour to produce* ^{7}Be *of activity* 1.8×10^8 *disintegrations per second. Assuming that one* ^{7}Be *radioactive nucleus is produced by bombarding* 1000 *protons, determine its half-life.*

Solution At time t, let say there are N atoms of ^{7}Be (radioactive). Then net rate of formation of ^{7}Be nuclei at this instant is,

$$\frac{dN}{dt} = \frac{10^{-4}}{1.6 \times 10^{-19} \times 1000} - \lambda N$$

or
$$\frac{dN}{dt} = 6.25 \times 10^{11} - \lambda N$$

or
$$\int_o^{N_0} \frac{dN}{6.25 \times 10^{11} - \lambda N} = \int_0^{3600} dt$$

where N_0 are the number of nuclei at $t = 1$ h or 3600 s.

$$\therefore \quad -\frac{1}{\lambda} \ln\left(\frac{6.25 \times 10^{11} - \lambda N_0}{6.25 \times 10^{11}}\right) = 3600$$

λN_0 = activity of ^{7}Be at $t = 1\text{ h} = 1.8 \times 10^8$ disintegrations/s

$$\therefore \quad -\frac{1}{\lambda} \ln\left(\frac{6.25 \times 10^{11} - 1.8 \times 10^8}{6.25 \times 10^{11}}\right) = 3600$$

$$\therefore \quad \lambda = 8.0 \times 10^{-8} \text{ sec}^{-1}$$

Therefore, half-life
$$t_{1/2} = \frac{0.693}{8.0 \times 10^{-8}} = 8.66 \times 10^6 \text{ s}$$

$$= 100.26 \text{ days}$$ **Ans.**

Example 7 *A* ^{118}Cd *radionuclide goes through the transformation chain.*

$$^{118}\text{Cd} \xrightarrow[30\ min]{} {}^{118}\text{In} \xrightarrow[45\ min]{} {}^{118}\text{Sn} \ (stable)$$

The half lives are written below the respective arrows. A time $t = 0$ *only Cd was present. Find the fraction of nuclei transformed into stable over* 60 *minutes.*

Solution At time $t = t$ $\quad N_1 = N_0 e^{-\lambda_1 t}$ and $N_2 = \frac{N_0 \lambda_1}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})$ (see Article 31.3)

$$\therefore \quad N_3 = N_0 - N_1 - N_2$$

$$= N_0\left[1 - e^{-\lambda_1 t} - \frac{\lambda_1}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})\right]$$

$\therefore$ $$\frac{N_3}{N_0} = 1 - e^{-\lambda_1 t} - \frac{\lambda_1}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

$$\lambda_1 = \frac{0.693}{30} = 0.0231 \text{ min}^{-1}$$

$$\lambda_2 = \frac{0.693}{45} = 0.0154 \text{ min}^{-1}$$

and $$t = 60 \text{ minutes}$$

$\therefore$ $$\frac{N_3}{N_0} = 1 - e^{-0.0231 \times 60} - \frac{0.0231}{0.0154 - 0.0231}(e^{-0.0231 \times 60} - e^{-0.0154 \times 60})$$

$$= 1 - 0.25 + 3\,(0.25 - 0.4)$$

$$= 0.31$$ **Ans.**

Example 8 *A nucleus X-initially at rest, undergoes alpha-decay, according to the equation*

$$^{A}_{92}X \longrightarrow {}^{228}_{z}Y + \alpha$$

(a) Find the value of A and z in the above process.

(b) The α*-particle in the above process is found to move in a circular track of radius* 1.1×10^2 *m in a uniform magnetic field of* 3.0×10^3 *T. Find the energy (in MeV) released during the process and binding energy of the parent nucleus X.*

Given : $m_y = 228.03$ *amu* $m_\alpha = 4.003$ *amu* $m\,({}^1_0 n) = 1.009$ *amu* $m({}^1_1\text{H}) = 1.008$ *amu*

$1\,amu = 1.66 \times 10^{-27}\,kg \equiv 931.5\,MeV/c^2$.

Solution (a) The given equation is,

$$^{A}_{92}X \longrightarrow {}^{228}_{z}Y + {}^4_2\text{He}$$

$$A = 228 + 4 = 232$$ **Ans.**

and $$92 = z + 2 \quad \therefore \quad z = 90$$ **Ans.**

(b) $$\frac{m_\alpha v_\alpha^2}{r} = q v_\alpha B$$

$\therefore$ $$v_\alpha = \sqrt{\frac{rqB}{m_\alpha}}$$

$$= \sqrt{\frac{1.1 \times 10^2 \times 2 \times 1.6 \times 10^{-19} \times 3 \times 10^3}{4.003 \times 1.66 \times 10^{-27}}}$$

$$= 4.0 \times 10^6 \text{ m/s}$$

From conservation of linear momentum,

$$m_\alpha v_\alpha = m_y v_y$$

$$\therefore \qquad v_y = \frac{m_\alpha v_\alpha}{m_y} = \frac{(4.003)(4.0\times10^6)}{(228.03)}$$

$$= 7.0\times10^4 \text{ m/s}$$

Therefore, energy released during the process

$$= \frac{1}{2}[m_\alpha v_\alpha^2 + m_y v_y^2]$$

$$= \frac{(1.66\times10^{-27})}{(2\times1.6\times10^{-13})}[(4.003)(4.0\times10^6)^2 + (228.03)(7.0\times10^4)^2] \text{ MeV}$$

$$= 0.34 \text{ MeV} = \frac{0.34}{931.5} \text{ amu} = 0.000365 \text{ amu}$$ **Ans.**

Therefore, mass of $\quad {}^{232}_{92}X = m_y + m_\alpha + 0.000365 = 232.033365 \text{ u}$

Mass defect $\quad \Delta m = 92(1.008) + (232-92)(1.009) - 232.033365$

$$= 1.962635 \text{ amu}$$

$\therefore \quad$ Binding energy $= 1.962635 \times 931.5$ MeV

$$= 1828.2 \text{ MeV}$$ **Ans.**

Example 9 *Natural uranium is a mixture of three isotopes* ${}^{234}_{92}\text{U}$, ${}^{235}_{92}\text{U}$ *and* ${}^{238}_{92}\text{U}$ *with mass percentage* 0.01% 0.71% *and* 99.28% *respectively. The half-life of three isotopes are* 2.5×10^5 *yr,* 7.1×10^8 *yr and* 4.5×10^9 *yr respectively. Determine the share of radioactivity of each isotope into the total activity of the natural uranium.*

Solution Let R_1, R_2 and R_3 be the activities of U^{234}, U^{235} and U^{238} respectively.

Total activity $\quad R = R_1 + R_2 + R_3$

Share of U^{234}, $\quad \dfrac{R_1}{R} = \dfrac{\lambda_1 N_1}{\lambda_1 N_1 + \lambda_2 N_2 + \lambda_3 N_3}$

Let m be the total mass of natural uranium.

Then $m_1 = \dfrac{0.01}{100} m$, $\quad m_2 = \dfrac{0.71}{100} m \quad$ and $\quad m_3 = \dfrac{99.28}{100} m$

Now, $N_1 = \dfrac{m_1}{M_1}$, $\quad N_2 = \dfrac{m_2}{M_2} \quad$ and $\quad N_3 = \dfrac{m_3}{M_3}$

where M_1, M_2 and M_3 are atomic weights.

$$\therefore \quad \frac{R_1}{R} = \frac{\left(\frac{m_1}{M_1}\right)\frac{1}{T_1}}{\frac{m_1}{M_1}\cdot\frac{1}{T_1} + \frac{m_2}{M_2}\cdot\frac{1}{T_2} + \frac{m_3}{M_3}\cdot\frac{1}{T_3}}$$

$$= \frac{\frac{(0.01/100)}{234} \times \frac{1}{2.5 \times 10^5 \text{ years}}}{\left(\frac{0.01/100}{234}\right)\left(\frac{1}{2.5\times10^5}\right) + \left(\frac{0.71/100}{235}\right)\left(\frac{1}{7.1\times10^8}\right) + \left(\frac{99.28/100}{238}\right)\left(\frac{1}{4.5\times10^9}\right)}$$

$$= 0.648 \approx 64.8\%$$

Similarly, share of $U^{235} = 0.016\%$

and of $U^{238} = 35.184\%$ **Ans.**

EXERCISES

For JEE Main

Subjective Questions

Note *You can take approximations in the answers.*

Radioactivity

1. The disintegration rate of a certain radioactive sample at any instant is 4750 disintegrations per minute. Five minutes later the rate becomes 2700 per minute. Calculate
   (a) decay constant and (b) half-life of the sample
2. A radioactive sample contains 1.00×10^{15} atoms and has an activity of 6.00×10^{11} Bq. What is its half-life?
3. Obtain the amount of ^{60}Co necessary to provide a radioactive source of 8.0 Ci strength. The half-life of ^{60}Co is 5.3 years?
4. The half-life of $^{238}_{92}U$ against alpha decay is 4.5×10^{9} year. How much disintegration per second occurs in 1 g of $^{238}_{92}U$?
5. What is the probability that a radioactive atom having a mean life of 10 days decays during the fifth day?
6. In an ore containing Uranium, the ratio of ^{238}U to ^{206}Pb nuclei is 3. Calculate the age of the ore, assuming that all the lead present in the ore is the final stable product of ^{238}U. Take the half-life of ^{238}U to be 4.5×10^{9} years.
7. The half-lives of radioisotopes P^{32} and P^{33} are 14 days and 25 days respectively. These radioisotopes are mixed in the ratio of 4 : 1 of their atoms. If the initial activity of the mixed sample is 3.0 m Ci, find the activity of the mixed isotopes after 60 year.

Nuclear Reactions

8. Complete the following reactions.
   (a) $^{226}_{88}Ra \rightarrow \alpha +$ (b) $^{19}_{8}O \rightarrow {}^{19}_{9}F +$ (c) $^{25}_{13}Al \rightarrow {}^{25}_{12}Mg +$
9. Consider two decay reactions.
   (a) $^{238}_{92}U \rightarrow {}^{206}_{82}Pb + 10$ protons $+ 22$ neutrons (b) $^{238}_{92}U \rightarrow {}^{206}_{82}Pb + 8\,{}^{4}_{2}He + 6$electrons
   Are both the reactions possible?
10. Obtain the binding energy of a nitrogen nucleus from the following data :
   $$m_H = 1.00783 \text{ u}, \; m_N = 1.00867 \text{ u}, \; m({}^{14}_{7}N) = 14.00307 \text{ u}$$
   Give your answer in units of MeV. [Remember $1 \text{ u} = 931.5 \text{ MeV/c}^2$]
11. 8 protons and 8 neutrons are separately at rest. How much energy will be released if we form $^{16}_{8}O$ nucleus?

Given : Mass of ${}^{16}_{8}O$ atom = 15.994915 u

Mass of neutron = 1.008665 u

Mass of hydrogen atom = 1.007825 u

12. Assuming the splittng of U^{235} nucleus liberates 200 MeV energy, find

(a) the energy liberated in the fission of 1 kg of U^{235} and

(b) the mass of the coal with calorific value of 30 kJ/g which is equivalent to 1 kg of U^{235}.

13. ${}^{212}_{83}Bi$ decays as per following equation.

$$ {}^{212}_{83}Bi \rightarrow {}^{208}_{82}Tl + {}^{4}_{2}He $$

The kinetic energy of α-particle emitted is 6.802 MeV. Calculate the kinetic energy of Tl recoil atoms.

14. In a neutron induced fission of ${}_{92}U^{235}$ nucleus, usable energy of 185 MeV is released. If ${}_{92}U^{235}$ reactor is continuously operating it at a power level of 100 MW how long will it take for 1 kg of uranium to be consumed in this reactor?

15. Calculate the Q-values of the following fusion reactions :

(a) ${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H$ (b) ${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + n$ (c) ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + n$

Atomic masses are $m({}^{2}_{1}H) = 2.014102$ u, $m({}^{3}_{1}H) = 3.016049$ u,

$m({}^{3}_{2}He) = 3.016029$ u, $m({}^{4}_{2}He) = 4.002603$ u

16. Calculate the Q-value of the fusion reaction

$$ {}^{4}He + {}^{4}He \rightarrow {}^{8}Be $$

Is such a fusion energetically favourable? Atomic mass of ${}^{8}Be$ is 8.0053 u and that of ${}^{4}He$ is 4.0026 u.

17. Calculate the energy that can be obtained from 1 kg of water through the fusion reaction.

$$ {}^{2}H + {}^{2}H \rightarrow {}^{3}H + p $$

Assume that 1.5×10^{-2}% of natural water is heavy water D_2O and all the deuterium is used for fusion.

Objective Questions

Single Correct Option

1. During a beta decay

(a) an atomic electron is ejected

(b) an electron present inside the nucleus is ejected

(c) a neutron in the nucleus decays emitting an electron

(d) a part of the binding energy is converted into electron

2. In the nucleus of helium if F_1 is the net force between two protons, F_2 is the net force between two neutrons and F_3 is the net force between a proton and a neutron. Then

(a) $F_1 = F_2 = F_3$ (b) $F_1 > F_2 > F_3$ (c) $F_2 > F_3 > F_1$ (d) $F_2 = F_3 > F_1$

3. What are the respective number of α and β-particles emitted in the following radioactive decay?

$$^{200}_{90}X \rightarrow {}^{168}_{80}Y$$

(a) 6 and 8 (b) 6 and 6 (c) 8 and 8 (d) 8 and 6

4. If an atom of $^{235}_{92}U$, after absorbing a slow neutron, undergoes fission to form an atom of $^{138}_{54}Xe$ and an atom of $^{94}_{38}Sr$, the other particles produced are

(a) one proton and two neutrons (b) three neutrons
(c) two neutrons (d) one proton and one neutron

5. Nucleus A is converted into C through the following reactions

$$A \rightarrow B + \alpha$$
$$B \rightarrow C + 2\beta$$

then

(a) A and B are isotopes (b) A and C are isobars
(c) A and B are isobars (d) A and C are isotopes

6. The binding energy of α-particle is

(if $m_p = 1.00785$ u, $m_n = 1.00866$ u and $m_\alpha = 4.00274$ u)

(a) 56.42 MeV (b) 2.821 MeV (c) 28.21 MeV (d) 32.4 MeV

7. $\frac{7}{8}$ th of the active nuclei present in a radioactive sample has decayed in 8 s. The half life of the sample is

(a) 2 s (b) 1 s (c) 7 s (d) $\frac{8}{3}$ s

8. A radioactive element disintegrates for a time interval equal to its mean life. The fraction that has disintegrated is

(a) $\frac{1}{e}$ (b) $1-\frac{1}{e}$ (c) $\frac{0.693}{e}$ (d) $0.693\left(1-\frac{1}{e}\right)$

9. Starting with a sample of pure ^{66}Cu, (7/8) of it decays into Zn in 15 minutes. The corresponding half-life is

(a) 5 minutes (b) $7\frac{1}{2}$ minutes (c) 10 minutes (d) 14 minutes

10. A sample of radioactive substance loses half of its activity in 4 days. The time in which its activity is reduced to 5% is

(a) 12 days (b) 8.3 days (c) 17.3 days (d) None of these

11. On bombardment of U^{235} by slow neutrons, 200 MeV energy is released. If the power output of atomic reactor is 1.6 MW, then the rate of fission will be

(a) 5×10^{16} per second (b) 10×10^{16} per second
(c) 15×10^{16} per second (d) 20×10^{16} per second

12. Atomic masses of two heavy atoms are A_1 and A_2. Ratio of their respective nuclear densitities will be approximately

(a) $\frac{A_1}{A_2}$ (b) $\left(\frac{A_1}{A_2}\right)^{1/3}$ (c) $\left(\frac{A_2}{A_1}\right)^{1/3}$ (d) 1

13. A radioactive element is disintegrating having half-life 6.93 s. The fractional change in number of nuclei of the radioactive element during 10 s is

(a) 0.37 (b) 0.63 (c) 0.25 (d) 0.50

14. The activity of a radioactive sample goes down to about 6% in a time of 2 hour. The half-life of the sample in minute is about

(a) 30 (b) 15 (c) 60 (d) 120

15. What is the probability of a radioactive nucleus to survive one mean life?

(a) $\frac{1}{e}$ (b) $\frac{1}{e+1}$ (c) $1-\frac{1}{e}$ (d) $\frac{1}{e}-1$

For **JEE Advanced**

Assertion and Reason

Directions : *Choose the correct option.*

(a) *If both **Assertion** and **Reason** are true and the **Reason** is correct explanation of the **Assertion.***
(b) *If both **Assertion** and **Reason** are true but **Reason** is not the correct explanation of **Assertion.***
(c) *If **Assertion** is true, but the **Reason** is false.*
(d) *If **Assertion** is false but the **Reason** is true.*

1. Assertion : Rate of radioactivity can not be increased or decreased by increasing or decreasing pressure or temperature.

Reason : Rate depends on number of nuclei present in the radioactive sample.

2. Assertion : Only those nuclei which are heavier than lead are radioactive.

Reason : Nuclei of elements heavier than lead are unstable.

3. Assertion : After emission of one α-particle and two β-particles, atomic number remains unchanged.

Reason : Mass number changes by four.

4. Assertion : γ-rays are produced by the transition of a nucleus from some higher energy state to some lower energy state.

Reason : Electromagnetic waves are always produced by the transition process.

5. Assertion : During β-decay a proton converts into a neutron and an electron. No other particle is emitted.

Reason : During β-dacay linear momentum of system should remains constant.

6. Assertion : If we compare the stability of two nuclei, then that nucleus is more stable whose total binding energy is more.

Reason : More the mass defect during formation of a nculeus more will be the binding energy.

7. **Assertion :** In a nuclear process energy is released if total binding energy of daughter nuclei is more than the total binding energy of parent nuclei.

   Reason : Total mass of daughter nuclei is less than the total mass of parent nuclei.

8. **Assertion :** Binding energy per nucleon is of the order of MeV.

   Reason : $1 \text{ MeV} = 1.6 \times 10^{-13}$ J.

9. **Assertion :** 1 amu is equal to 931.48 MeV.

   Reason : 1 amu is equal to $\frac{1}{12}$th the mass of C^{12} atom.

10. **Assertion :** Between α, β and γ radiations, penetrating power of γ-rays is maximum.

    Reason : Ionising power of γ-rays is least.

11. **Assertion :** The nuclear energy can be obtained by the nuclear fission of heavier nuclei as well as by fusion of lighter nuclei.

    Reason : The binding energy per nucleon with increase in mass number, first increases and then decreases.

Objective Questions

Single Correct Option

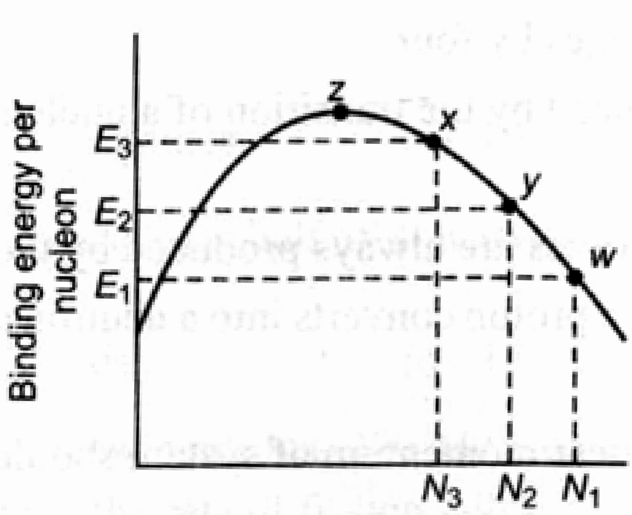
1. The count rate observed from a radioactive source at t second was N_0 and at $4t$ second it was $\frac{N_0}{16}$. The count rate observed, at $\left(\frac{11}{2}\right) t$ second will be

   (a) $\frac{N_0}{128}$ (b) $\frac{N_0}{64}$ (c) $\frac{N_0}{32}$ (d) None of these

2. The half lives of a radioactive sample are 30 years and 60 years for two decay processes. If the sample decays by both the processes simultaneously. The time after which, only one-fourth of the sample will remain is

   (a) 10 years (b) 20 years (c) 40 years (d) 60 years

3. Consider the nuclear fission reaction $W \rightarrow X + Y$. What is the Q value (energy released) of the reaction?



   (a) $E_1N_1 - (E_2N_2 + E_3N_3)$ (b) $(E_2N_2 + E_3N_3 - E_1N_1)$

   (c) $E_2N_2 + E_1N_1 - E_3N_3$ (d) $E_1N_1 + E_3N_3 - E_2N_2$

4. Consider the following nuclear reaction

$$X^{200} \rightarrow A^{110} + B^{90} + \text{Energy}$$

If the binding energy per nucleon for X, A and B are 7.4 MeV, 8.2 MeV and 8.2 MeV respectively, the energy released will be

(a) 90 MeV (b) 110 MeV (c) 200 MeV (d) 160 MeV

5. The binding energy per nucleon for deuteron ($_1^2H$) and helium ($_2^4He$) are 1.1 MeV and 7.0 MeV, respectively. The energy released when two deutrons fuse to form a helium nucleus is

(a) 47.12 MeV (b) 23.6 MeV (c) 11.8 MeV (d) 34.4 MeV

6. The energy released by the fission of a single uranium nucleus is 200 MeV. The number of fissions of uranium nucleus per second required to produce 16 MW of power is

(Assume efficiency of the reactor is 50%)

(a) 2×10^6 (b) 2.5×10^6 (c) 5×10^6 (d) None of these

7. A radioactive isotope is being produced at a constant rate A. The isotope has a half-life T. Initially there are no nuclei, after a time $t >> T$, the number of nuclei becomes constant. The value of this constant is

(a) AT (b) $\frac{A}{T} \ln(2)$ (c) $AT \ln(2)$ (d) $\frac{AT}{\ln(2)}$

8. A moving hydrogen atom makes a head on collision with a stationary hydrogen atom. Before collision both atoms are in the ground state and after collision they move together. What is the velocity of the moving atom if after the collision one of the atom gets minimum excitation energy?

(Mass of hydrogen atom is 1.673×10^{-27} kg)

(a) 5.25×10^4 m/s (b) 4.25×10^4 m/s (c) 6.25×10^4 m/s (d) 10.25×10^4 m/s

9. A bone containing 200 g carbon-14 has a β-decay rate of 375 decay/min. Calculate the time that has elapsed since the death of the living one. Given the rate of decay for the living organism is equal to 15 decay per min per gram of carbon and half-life of carbon-14 = 5730 years

(a) 27190 years (b) 1190 years (c) 17190 years (d) None of these

10. Two identical samples (same material and same amount) P and Q of a radioactive substance having mean life T are observed to have activities A_P and A_Q respectively at the time of observation. If P is older than Q, then the difference in their age is

(a) $T \ln\left(\frac{A_P}{A_Q}\right)$ (b) $T \ln\left(\frac{A_Q}{A_P}\right)$ (c) $T\left(\frac{A_P}{A_Q}\right)$ (d) $T\left(\frac{A_Q}{A_P}\right)$

11. A star initially has 10^{40} deuterons. It produces energy via the processes $_1^2H + _1^2H \rightarrow _1^3H + p$ and $_1^2H + _1^3H \rightarrow _2^4He + n$. Where the masses of the nuclei are :

$m(^2H) = 2.014$ amu, $m(p) = 1.007$ amu, $m(n) = 1.008$ amu and $m(^4He) = 4.001$ amu. If the average power radiated by the star is 10^{16} W, the deuteron supply of the star is exhausted in a time of the order of

(a) 10^6 s (b) 10^8 s (c) 10^{12} s (d) 10^{16} s

12. Two radioactive samples of different elements (half lives t_1 and t_2 respectively) have same number of nuclei at $t = 0$. The time after which their activities are same is

(a) $\frac{t_1 t_2}{0.693\,(t_2 - t_1)} \ln \frac{t_2}{t_1}$
(b) $\frac{t_1 t_2}{0.693} \ln \frac{t_2}{t_1}$
(c) $\frac{t_1 t_2}{0.693\,(t_1 + t_2)} \ln \frac{t_2}{t_1}$
(d) None of these

13. A nucleus X initially at rest, undergoes alpha decay according to the equation

$$^{232}_{Z}X \rightarrow {}^{A}_{90}Y + \alpha$$

What fraction of the total energy released in the decay will be the kinetic energy of the alpha particle?

(a) $\frac{90}{92}$
(b) $\frac{228}{232}$
(c) $\sqrt{\frac{228}{232}}$
(d) $\frac{1}{2}$

14. A stationary nucleus of mass 24 amu emits a gamma photon. The energy of the emitted photon is 7 MeV. The recoil energy of the nucleus is

(a) 2.2 keV
(b) 1.1 keV
(c) 3.1 keV
(d) 22 keV

15. A radioactive material of half-life T was kept in a nuclear reactor at two different instants. The quantity kept second time was twice of that kept first time. If now their present activities are A_1 and A_2 respectively then their age difference equals

(a) $\frac{T}{\ln 2} \ln \frac{2A_1}{A_2}$
(b) $T \ln \frac{A_1}{A_2}$
(c) $\frac{T}{\ln 2} \ln \frac{A_2}{2A_1}$
(d) $T \ln \frac{A_2}{2A_1}$

Passage : (Q. 16 to 18)

The atomic masses of the hydrogen isotopes are

$$\text{Hydrogen } m_1 \text{H}^1 = 1.007825 \text{ amu}$$

$$\text{Deuterium } m_1 \text{H}^2 = 2.014102 \text{ amu}$$

$$\text{Tritium } m_1 \text{H}^3 = 3.016049 \text{ amu}$$

16. The energy released in the reaction

$$_1\text{H}^2 + {}_1\text{H}^2 \rightarrow {}_1\text{H}^3 + {}_1\text{H}^1 \text{ is nearly}$$

(a) 1 MeV
(b) 2 MeV
(c) 4 MeV
(d) 8 MeV

17. The number of fusion reactions required to generate 1 kWh is nearly

(a) 10^8
(b) 10^{18}
(c) 10^{28}
(d) 10^{38}

18. The mass of deuterium, $_1\text{H}^2$ that would be needed to generate 1 kWh

(a) 3.7 kg
(b) 3.7 g
(c) 3.7×10^{-5} kg
(d) 3.7×10^{-8} kg

More than One Correct Options

1. At $t=0$, number of radioactive nuclei of a radioactive substance are x and its radioactivity is y. Half-life of radioactive substance is T. Then
   (a) $\frac{x}{y}$ is constant throughout
   (b) $\frac{x}{y} > T$
   (c) value of xy remains half after one half-life
   (d) value of xy remains one fourth after one half-life
2. Choose the correct options.
   (a) Isotopes have same number of atomic number
   (b) Isobars have same atomic weight
   (c) Isotones have same number of neutrons
   (d) In neutral isotope atoms number of electrons are same
3. Choose the correct options
   (a) By gamma radiations atomic number is not changed
   (b) By gamma radiations mass number is not changed
   (c) By the emission of one α and two β particles isotopes are produced
   (d) By the emission of one α and four β particles isobars are produced
4. Two radioactive substances have half lives T and $2T$. Initially they have equal number of nuclei. After time $t=4T$, the ratio of their number of nuclei is x and the ratio of their activity is y. Then
   (a) $x=1/8$ (b) $x=1/4$ (c) $y=1/2$ (d) $y=1/4$
5. Regarding the nuclear forces, choose the correct options.
   (a) They are short range forces (b) They are charge independent forces
   (c) They are not electromagnetic forces (d) They are exchange forces
6. Regarding a nucleus choose the correct options.
   (a) Density of a nucleus is directly proportional to mass number A
   (b) Density of all the nuclei is almost constant, of the order of 10^{17} kg/m^3
   (c) Nucleus radius is of the order of 10^{-15} m
   (d) Nucleus radius $\propto A$

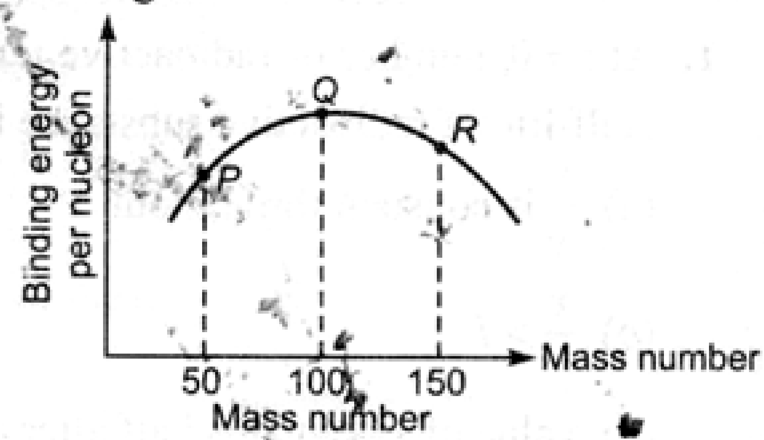
Match the Columns

1. At $t=0$, x nuclei of a radioactive substance emit y nuclei per second. Match the following two columns.

Column I	Column II
(a) Decay constant λ	(p) $(\ln 2)(x/y)$
(b) Half-life	(q) x/y
(c) Activity after time $t=\frac{1}{\lambda}$	(r) y/e
(d) Number of nuclei after time $t=\frac{1}{\lambda}$	(s) None of these

2. Corresponding to the graph shown in figure, match the following two columns.

Column I	Column II
(a) $P + P = Q$	(p) energy is released
(b) $P + P + P = R$	(q) energy is absorbed
(c) $P + R = 2Q$	(r) No energy transfer will take place
(d) $P + Q = R$	(s) data insufficient



3. In the following chain,

$$A \rightarrow B \rightarrow C$$

A and B are radioactive, while C is stable. Initially we have only A and B nuclei. There is no nucleus of C. As the time passes, match the two columns.

Column I	Column II
(a) Nuclei of $(A + B)$	(p) will increase continuously
(b) Nuclei of B	(q) will decrease continuously
(c) Nuclei of $(C + B)$	(r) will first increase then decrease
(d) Nuclei of $(A + C)$	(s) data insufficient

4. Match the following two columns.

Column I	Column II
(a) After emission of one α and one β particles	(p) atomic number will decrease by 3.
(b) After emission of two α and one β particles	(q) atomic number will decrease by 2
(c) After emission of one α and two β particles	(r) mass number will decrease by 8
(d) After emission of two α and two β-particles.	(s) mass number will decrease by 4

5. Match the following two columns.

Column I	Column II
(a) The energy of air molecules at room temperature	(p) 0.02 eV
(b) Binding energy of heavy nuclei per nucleon	(q) 2 eV
(c) X-ray photon energy	(r) 10 keV
(d) Photon energy of visible light	(s) 7 MeV

Subjective Questions

1. A F^{32} radionuclide with half-life $T = 14.3$ days is produced in a reactor at a constant rate $q = 2 \times 10^9$ nuclei per second. How soon after the beginning of production of that radionuclide will its activity be equal to $R = 10^9$ disintegration per second?

2. Consider a radioactive disintegration according to the equation $A \rightarrow B \rightarrow C$. Decay constant of A and B is same and equal to λ. Number of nuclei of A, B and C are $N_0, 0, 0$ respectively at $t = 0$. Find
   (a) Number of nuclei of B as function of time t.
   (b) Time t at which the activity of B is maximum and the value of maximum activity of B.

3. Nuclei of a radioactive element A are being produced at a constant rate α. The element has a decay constant λ. At time $t = 0$, there are N_0 nuclei of the element.
   (a) Calculate the number N of nuclei of A at time t.
   (b) If $\alpha = 2N_0\lambda$, calculate the number of nuclei of A after one half-life of A, and also the limiting value of N as $t \rightarrow \infty$.

4. A small quantity of solution containing Na^{24} radio nuclide (half-life = 15 hour) of activity 1.0 microcurie is injected into the blood of a person. A sample of the blood of volume $1\,cm^3$ taken after 5 hours shows an activity of 296 disintegrations per minute. Determine the total volume of the blood in the body of the person. Assume that the radioactive solution mixes uniformly in the blood of the person.

   (1 curie $= 3.7 \times 10^{10}$ disintegration per second)

5. A solution contains a mixture of two isotopes A (half-life = 10 days) and B (half-life = 5 days). Total activity of the mixture is 10^{10} disintegration per second at time $t = 0$. The activity reduces to 20% in 20 days. Find :
   (a) the initial activities of A and B,
   (b) the ratio of initial number of their nuclei.

6. A radionuclide with disintegration constant λ is produced in a reactor at a constant rate α nuclei per second. During each decay energy E_0 is released. 20% of this energy is utilized in increasing the temperature of water. Find the increase in temperature of m mass of water in time t. Specific heat of water is s. Assume that there is no loss of energy through water surface.

7. A radioactive nucleus X decays to a nucleus Y with a decay constant $\lambda_x = 0.1\,sec^{-1}$. Y further decays to a stable nucleus Z with a decay constant $\lambda_y = 1/30\,sec^{-1}$. Initially, there are only X nuclei and their number is $N_0 = 10^{20}$. Set up the rate equations for the populations of X, Y and Z. The population of the Y nucleus as a function of time is given by $N_y(t) = \{N_0\lambda_X/(\lambda_X - \lambda_Y)\}.\{\exp(-\lambda_Y t) - \exp(-\lambda_X t)\}$. Find the time at which N_y is maximum and determine the population of X and Z at that instant.

8. A stable nuclei C is formed from two radioactive nuclei A and B with decay constant of λ_1 and λ_2 respectively. Initially the number of nuclei of A is N_0 and that of B is zero. Nuclei B are produced at a constant rate of P. Find the number of the nuclei of C after time t.

9. Polonium ($^{210}_{84}Po$) emits $^{4}_{2}He$ particles and is converted into lead ($^{206}_{82}Pb$). This reaction is used for producing electric power in a space mission. Po^{210} has half-life of 138.6 days. Assuming an efficiency of 10% for the thermoelectric machine, how much ^{210}Po is required to produce 1.2×10^7 J of electric energy per day at the end of 693 days. Also find the initial activity of the material.

Given : Masses of nuclei

$$^{210}Po = 209.98264 \text{ amu}, \; ^{206}Pb = 205.97440 \text{ amu}, \; ^{4}_{2}He = 4.00260 \text{ amu},$$

$$1 \text{ amu} = 931 \text{ MeV/c}^2 \text{ and Avogadro number} = 6 \times 10^{23} \text{/mol}$$

10. It is proposed to use the nuclear fusion reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4$ in a nuclear reactor of 200 MW rating. If the energy from the above reaction is used with a 25% efficiency in the reactor, how many grams of deuterium fuel will be needed per day. (the masses of ${}_1H^2$ and ${}_1He^4$ are 2.0141 atomic mass units and 4.0026 atomic mass units respectively).

11. The element Curium $^{248}_{96}Cm$ has mean life of 10^{13} seconds. Its primary decay modes are spontaneous fission and α-decay, the former with a probability of 8% and the latter with a probability of 92%. Each fission releases 200 MeV of energy. The masses involved in decay are as follows :

$$^{248}_{96}Cm = 248.072220 \text{ u}, \; ^{244}_{94}Pu = 244.064100 \text{ u and } ^{4}_{2}He = 4.002603 \text{ u}$$

Calculate the power output from a sample of 10^{20} Cm atoms ($1 \text{ u} = 931 \text{ MeV/c}^2$)

12. A radionuclide consists of two isotopes. One of the isotopes decays by α-emission and other by β-emission with half lives $T_1 = 405$ s and $T_2 = 1620$ s, respectively. At $t = 0$, probabilities of getting α and β-particles from the radionuclide are equal. Calculate their respective probabilities at $t = 1620$ s. If at $t = 0$, total number of nuclei in the radio nuclide are N_0. Calculate the time t when total number of nuclei remained undecayed becomes equal to $N_0/2$.

$\log_{10} 2 = 0.3010, \log_{10} 5.94 = 0.7742$ and $x^4 + 4x - 2.5 = 0, x = 0.594$

13. Find the amount of heat generated by 1 mg of Po^{210} preparation during the mean-life period of these nuclei if the emitted alpha particles are known to possess kinetic energy 5.3 MeV and practically all daughter nuclei are formed directly in the ground state.

14. In an agricultural experiment, a solution containing 1 mole of a radioactive material ($T_{1/2} = 14.3$ days) was injected into the roots of a plant. The plant was allowed 70 h to settle down and then activity was measured in its fruit. If the activity measured was 1 μCi, what percentage of activity is transmitted from the root to the fruit in steady state?

ANSWERS

Introductory Exercise 31.1

1. 3 days, 4.33 days 2. 9.47×10^9 nuclei
3. (a) 1.55×10^{-5} /s, 12.4 h (b) 2.39×10^{13} atoms (c) 1.87 mCi 4. 1.16×10^3 s 5. $\frac{1}{4}$

Introductory Exercise 31.2

1. N/P ratio required for stability decreases with decreasing A, hence there is an excess of neutrons when fission occurs. Some of the excess neutrons are released directly, and others change to protons by beta decay in the fission products.
2. (a) 9.6×10^{-4} kg (b) 3.125×10^{19} 3. 4.27 MeV 4. (a) ${}^2_1H$ (b) ${}^1_1H$ (c) ${}^1_0n$ (d) ${}^{79}_{36}Kr$

For JEE Main

Subjective Questions

1. (a) 0.113 min^{-1} (b) 6.132 min 2. 19.25 min 3. 7.11×10^{-3} g 4. 1.23×10^4 dps
5. 0.39 6. 1.88×10^9 yr 7. 0.205 mCi 8. (a) ${}_{86}Rn^{222}$ (b) $\bar{e}+\bar{\nu}$ (c) $e^+ + \nu$
9. Reaction (a) is not possible (b) is possible 10. 104.72 MeV 11. 127.6 MeV
12. (a) 8.09×10^{13} J (b) 2.7×10^6 kg 13. 0.1308 MeV 14. 8.78 day
15. (a) 4.05 MeV (b) 3.25 MeV (c) 17.57 MeV 16. – 93.1 keV, No

Objective Questions

1. (c) 2. (a) 3. (d) 4. (b) 5. (d) 6. (c) 7. (d) 8. (b) 9. (a) 10. (c)
11. (a) 12. (d) 13. (b) 14. (a) 15. (a)

For JEE Advanced

Assertion and Reason

1. (b) 2. (d) 3. (b) 4. (c) 5. (d) 6. (d) 7. (a or b) 8. (b) 9. (d) 10. (b)
11. (a or b)

Objective Questions

1.(b) 2.(c) 3.(b) 4.(d) 5.(b) 6.(d) 7.(d) 8.(c) 9.(c) 10.(b)
11.(c) 12.(a) 13.(b) 14.(b) 15.(c) 16.(c) 17.(b) 18.(d)

More than One Correct Options

1.(a,b,d) 2.(a,b,c,d) 3.(a,b,c) 4.(b,c) 5.(a,b,c,d) 6.(b,c)

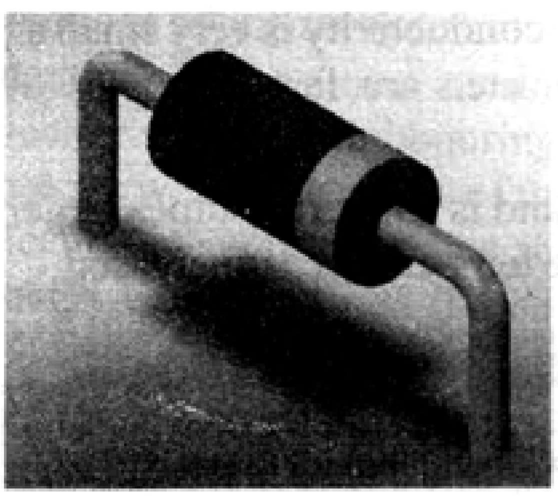
Match the Columns

1. (a) → s (b) → p (c) → r (d) → s
2. (a) → p (b) → p (c) → p (d) → s
3. (a) → q (b) → s (c) → p (d) → s
4. (a) → s (b) → p,r (c) → s (d) → q,r
5. (a) → p (b) → s (c) → r (d) → q

Subjective Questions

1. 14.3 h 2. (a) $N_B = \lambda N_0 (te^{-\lambda t})$ (b) $t = \frac{1}{\lambda}, R_{max} = \frac{\lambda N_0}{e}$
3. (a) $\frac{1}{\lambda}[\alpha - (\alpha - \lambda N_0)e^{-\lambda t}]$ (b) $\frac{3}{2}N_0, 2N_0$ 4. 5.95 litre
5. (a) 0.73×10^{10} dps, 0.27×10^{10} dps (b) 5.4 6. $\frac{0.2\, E_0\left[\alpha t - \frac{\alpha}{\lambda}(1 - e^{-\lambda t})\right]}{ms}$
7. (a) $\frac{dN_x}{dt} = -\lambda_x N_x, \frac{dN_y}{dt} = \lambda_x N_x - \lambda_y N_y, \frac{dN_z}{dt} = \lambda_y N_y$ (b) 16.48 s

   (c) $N_x = 1.92 \times 10^{19}, N_y = 5.76 \times 10^{19}\ N_z = 2.32 \times 10^{19}$
8. $N_c = N_0 (1 - e^{-\lambda_1 t}) + P\left(t + \frac{e^{-\lambda_2 t} - 1}{\lambda_2}\right)$ 9. 10 g, 4.57×10^{21} disintegrations/day
10. 120.35 g 11. 3.32×10^{-5} W 12. $\frac{1}{9}, \frac{8}{9}$, 1215 s 13. 1.55×10^{6} J
14. $1.26 \times 10^{-11}\%$



32 SEMICONDUCTORS

Chapter Contents

32.1 Introduction

Solids can be classified in three types as per their electrical conductivity. (i) conductors, (ii) insulators and (iii) semiconductors. In a conductor, large number of free electrons are present. They are always in *zig-zag* motion inside the conductor. In an insulator, all the electrons are tightly bound to the nucleus. If an electric field is applied inside a conductor, the free electrons experience force due to the field and acquire a drift speed. This results in an electric current. The conductivity of a conductor such as copper decreases as the temperature is increased. This is because as the temperature is increased, the random collisions of the free electrons with the particles in the conductor become more frequent. This results in a decrease in the drift speed and hence the conductivity decreases.

In insulators almost zero current is obtained unless a very high electric field is applied. Semiconductors conduct electricity when an electric field is applied, but the conductivity is very small as compared to the usual metallic conductors. Silicon, germanium, carbon etc., are few examples of semiconductors.

Conductivity of silicon is about 10^{11} times smaller than that of copper and is about 10^{13} times larger than that of fused quartz. Conductivity of a semiconductor increases as the temperature is increased.

• Important Points

1. Before the discovery of transistors (in 1948) mostly vacuum tubes (also called valves) were used in all electrical circuits.
2. The order of electrical econductivity (σ) and resistivity $\left(\rho = \frac{1}{\sigma}\right)$ of metals, semiconductors and insulators are given below in tabular form.

Table 32.1

S.No	Types of Solid	$\rho\ (\Omega - m)$	$\sigma\ (\Omega^{-1} - m^{-1})$
1.	Metals	$10^{-2} - 10^{-8}$	$10^{2} - 10^{8}$
2.	Semiconductors	$10^{-5} - 10^{6}$	$10^{5} - 10^{-6}$
3.	Insulators	$10^{11} - 10^{19}$	$10^{-11} - 10^{-19}$

32.2 Energy Bands In Solids

To understand the energy bands in solids, let us consider the electronic configuration of sodium atom which has 11 electrons. The configuration is $(1s)^2$, $(2s)^2$, $(2p)^6$ and $(3s)^1$. The levels $1s$, $2s$ and $2p$ are completely filled. The level $3s$ is half filled and the levels above $3s$ are empty. Consider a group of N sodium atoms all in ground state separated from each other by large distances such as in sodium vapour. There are total $11N$ electrons. Each atom has two energy states is $1s$ energy level. So, there are $2N$ identical energy states lebelled $1s$ and all them are filled from $2N$ electrons. Similarly, energy level $2p$ has $6N$ identical energy states which are also completely filled. In $3s$ energy levels N of the $2N$ states are filled by the electrons and the remaining N states are empty. These ideas are shown in the table given below.

Table 32.2

Energy level	Total available energy states	Total occupied states
1s	2N	2N
2s	2N	2N
2p	6N	6N
3s	2N	N
3p	6N	0

In the above discussion we have assumed that N sodium atoms are widely spread and hence the electrons of one atom do not interact with others. As a result energy states of different states (*e.g.*, 1*s*) are identical. When atoms are drawn closer to one another electron of one atom starts interacting with the electrons of the neighbouring atoms of the same energy states. For example 1*s* electrons of one atom interact with 1*s* electrons of the other. Due to interaction of electrons the energy states are not identical, but a sort of energy band is formed. These bands are shown in figure.

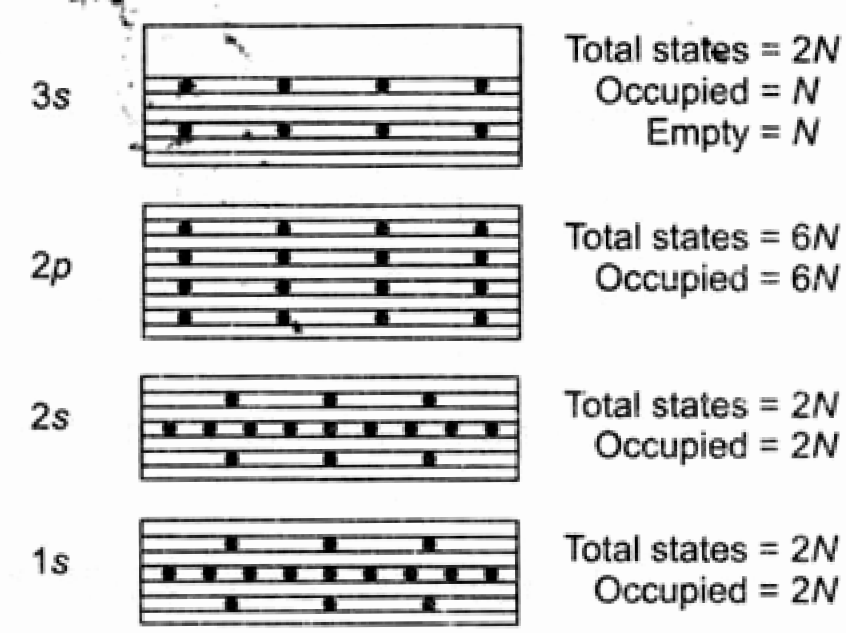


Fig. 32.1

The difference between the highest energy in a band and the lowest energy in the next higher band is called the **band gap** between the two energy bands.

Thus, we can conclude that energy levels of an electron in a solid consists of bands of allowed states. There are regions of energy, called gaps, where no states are possible. In each allowed band, the energy levels are very closely spaced. Electrons occupy states which minimize the total energy. Depending on the number of electrons and on the arrangement of the bands, a band may be fully occupied or partially occupied.

Now, electrical conductivity of conductors, insulators and semiconductors can be explained by these energy bands.

Conductors The energy band structure of a conductor is shown in figure (a). The last occupied band of energy level (called conduction band) is only partially filled. In conductors this band overlaps with completely filled valence band.

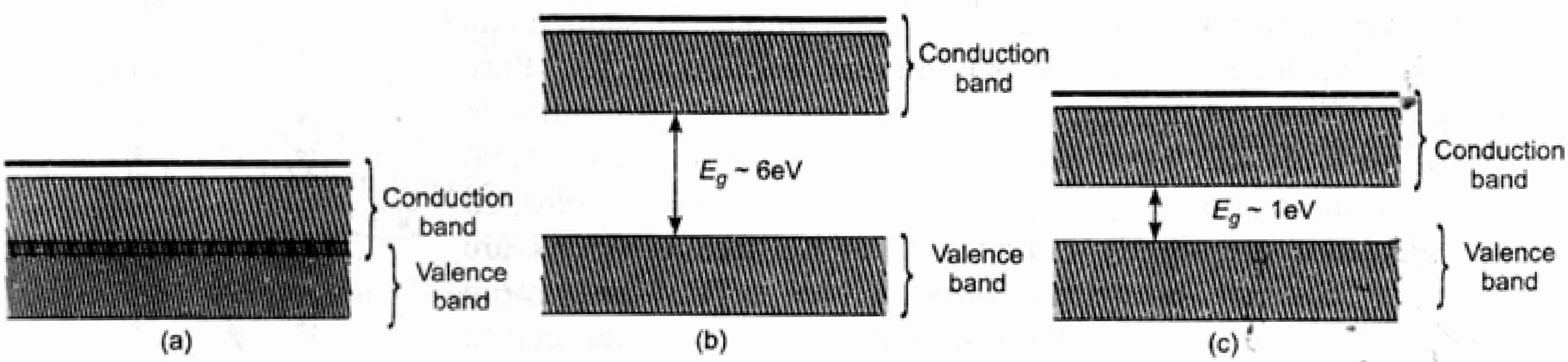


Fig 32.2 Energy band diagram for a (a) metal, (b) insulator and (c) semiconductor Note that one can have a metal either when the conduction band is partially filled or when the conduction and valence bands overlap in energy.

Insulators The energy band structure of an insulator is shown in figure (b). The conduction band is separated from the valence band by a wide energy gap (*e.g.*, 6 eV for diamond). But at any non-zero temperature, some electrons can be excited to the conduction band.

Semiconductors The energy band structure of a semiconductor is shown in figure (c). It is similar to that of an insulator but with a comparatively small energy gap. At absolute zero temperature, the conduction band of semiconductors is totally empty, and all the energy states in the valence band are filled. The absence of electrons in the conduction band at absolute zero does not allow current to flow under the influence of an electric field. Therefore, they are insulators at low temperatures. However at room temperatures some valence electrons acquire thermal energy greater than the energy gap E_g and move to the conduction band where they are free to move under the influence of even a small electric field. Thus, a semiconductor originally an insulator at low temperatures becomes slightly conducting at room temperature. Unlike conductors the resistance of semiconductors decreases with increasing temperature. We are generally concerned with only the highest valence band and the lowest conduction band. So, when we say valence band, it means the highest valence band. Similarly, when we say conduction band, it means the lowest conduction band.

Sample Example 32.1 *What is the energy band gap of : (i) silicon and (ii) germanium?*

Solution The energy band gap of silicon is 1.1 eV and of germanium is about 0.7 eV.

Sample Example 32.2 *In a good conductor, what is the energy gap between the conduction band and the valence band.*

Solution In a good conductor, conduction band overlaps with the valence band. Therefore, the energy gap between them is zero.

32.3 Intrinsic and Extrinsic Semiconductors

As discussed above, in semiconductors the conduction band and the valence band are separated by a relatively small energy gap. For silicon, this gap is 1.1 eV and for germanium it is 0.7 eV.

Silicon has an atomic number 14 and electronic configuration $1s^2, 1s^2, 2p^6, 3s^2, 3p^2$.

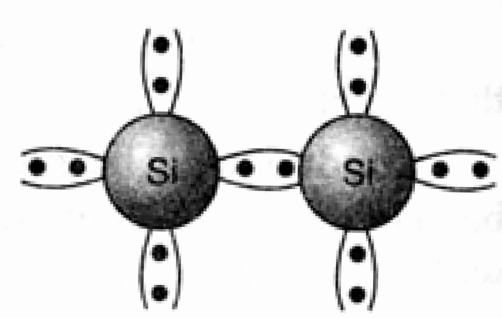


Fig. 32.3

The chemistry of silicon tells us that it has a valency 4. Each silicon atom makes covalent bonds with the four neighbouring silicon atoms. On the basis of bonds the atoms make with their neighbouring atoms, semiconductors are divided in two groups.

Intrinsic Semiconductors A pure (free from impurity) semiconductor which has a valency 4 is called an intrinsic semiconductor. Pure germanium, silicon or carbon in their natural state are intrinsic semiconductors. As discussed above each atom makes four covalent bonds with their neighbouring atoms. At temperature close to zero, all valence electrons are tightly bound and so no free electrons are available to conduct electricity through the crystal. At room temperature, however a few of the covalent bonds are broken due to thermal agitation and thus some of the valence electrons become free. Thus, we can say that a valence electrons is shifted to conduction band leaving a **hole** (vacancy of electron) in valence band.

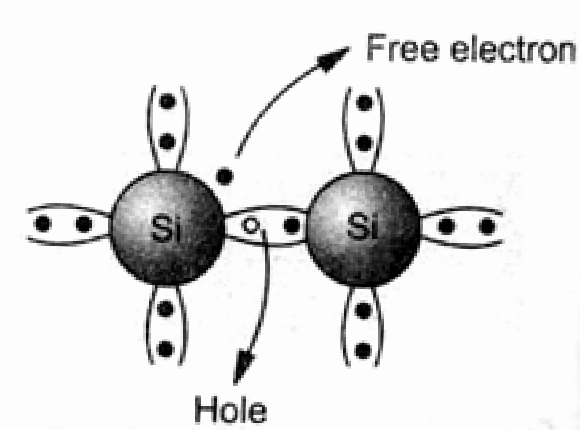


Fig. 32.4

In intrinsic semiconductors,

$$\text{Number of holes} = \text{Number of free electrons}$$

or

$$n_h = n_e$$

Extrinsic Semiconductors The conductivity of an intrinsic semiconductor is very poor (unless the temperature is very high). At ordinary temperature, only one covalent bond breaks in 10^9 atoms of Ge. Conductivity of an intrinsic (pure) semiconductor is significantly increased, if some pentavalent or trivalent impurity is mixed with it. Such impure semiconductors are called extrinsic or doped semiconductors. Extrinsic semiconductors are again of two types (i) *p*-type and (ii) *n*-type.

(i) ***p*-type semiconductors** When a trivalent (*e.g.*, boron, aluminium, gallium or indium) is added to a germanium or silicon crystal it replaces one of the germanium or silicon atom. Its three valence electrons form covalent bonds with neighbouring three Ge (or Si) atoms while the fourth valence electron of Ge (or Si) is not able to form the bond. Thus, there remains a hole (an empty space) on one side of the impurity atom.

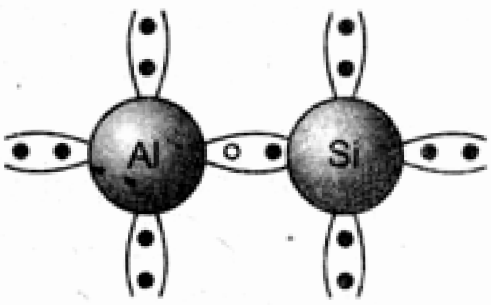


Fig. 32.5

The trivalent impurity atoms are called **acceptor atoms** because they create holes which accept electrons. Following points are worthnoting regarding *p*-type semiconductors

(a) Holes are the majority charge carriers and electrons are minority charge carriers in case of *p*-type semiconductors or number of holes are much greater than the number of electrons.

$$n_h >> n_e$$

(b) *p*-type semiconductor is electrically neutral.

(c) *p*-type semiconductor can be shown as

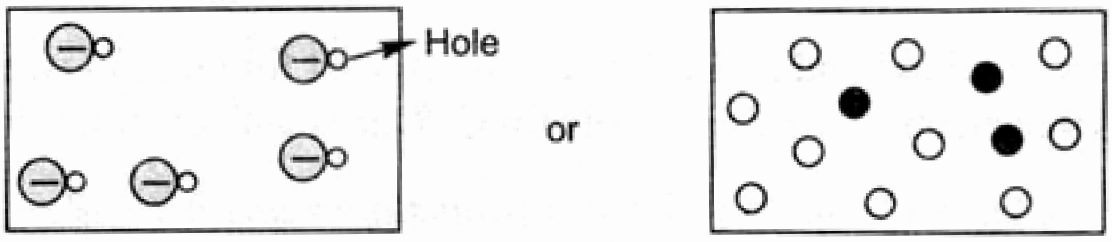


Fig. 32.6

(ii) ***n*-type semiconductors** When a pentavalent impurity atom (antimony, phosphorus or arsenic is added to a Ge (or Si) crystal it replaces a Ge (or Si) atom. Four of the five valence electrons of the impurity atom form covalent bonds with four neighbouring Ge (or Si) atoms and the fifth valence electron becomes free to move inside the crystal lattice. Thus, by doping pentavalent impurity number of free electrons increases.

The impurity (pentavalent) atoms are called **donor atoms** because they donate conduction electrons inside the crystal. Following points are worthnoting regarding *n*-type semiconductors

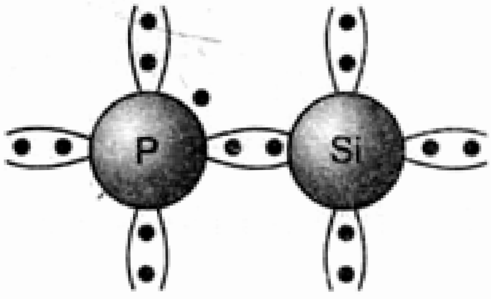


Fig. 32.7

(a) Electrons are the majority charge carriers and holes are minority or number of electrons are much greater than the number of holes

$$n_e >> n_h$$

(b) *n*-type semiconductor is also electrically neutral.

(c) *n*-type semiconductor can be shown as

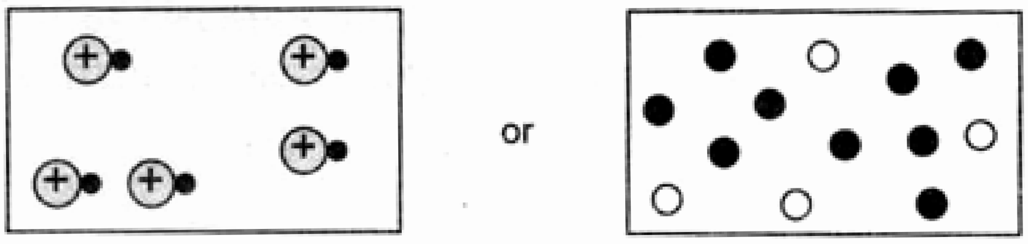


Fig. 32.8

Electrical Conduction through Semiconductors When a battery is connected across a semiconductor (whether intrinsic or extrinsic) a potential difference is developed across its ends. Due to the potential difference an electric field is produced inside the semiconductor. A current (although very small) starts flowing through the semiconductor. This current may be due to the motion of (i) free electrons and (ii) holes. Electrons move in opposite direction of electric field while holes move in the same direction.

The motion of holes towards right (in the figure) take place because electrons from right hand side come to fill this hole, creating a new hole in their own position. Thus, we can say that holes are moving from left to right. Thus, current in a semiconductor can be written as,

$$i = i_e + i_h$$

But it should be noted that mobility of holes is less than the mobility of electrons.

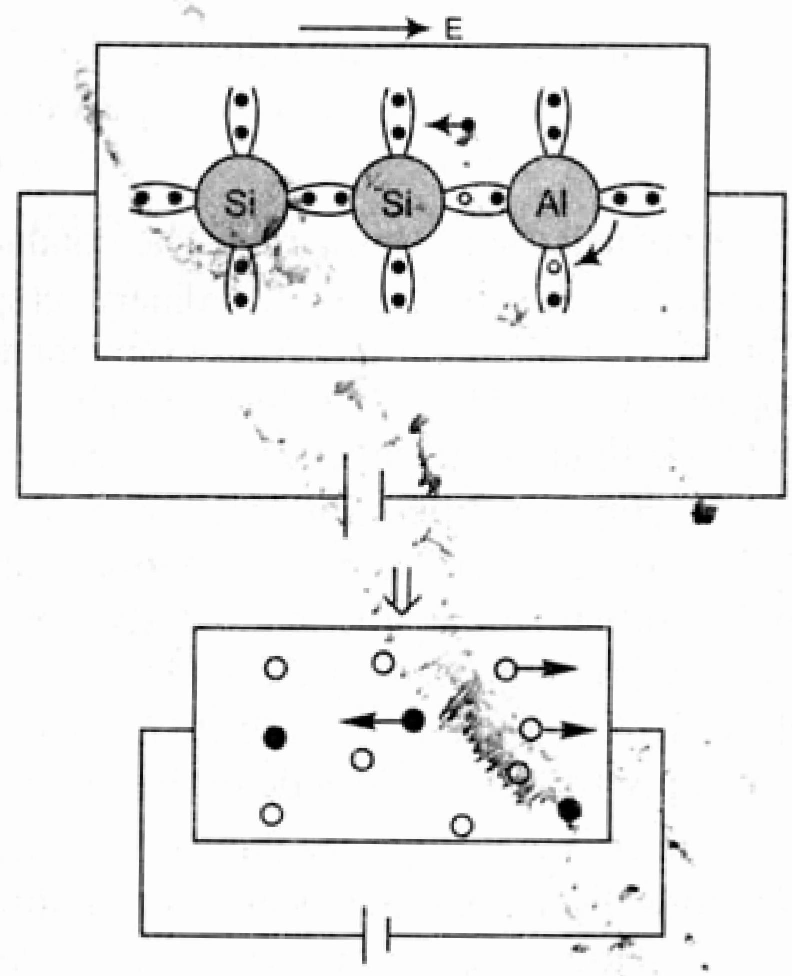


Fig. 32.9

Sample Example 32.3 *C, Si and Ge have same lattice structure. Why is C insulator while Si and Ge intrinsic semiconductors?*

Solution The energy gap between conduction band and valence band is least for Ge, followed by Si and and highest for C. Hence number of free electrons are negligible for C. This is why carbon is insulator.

Sample Example 32.4 *In an n-type silicon, which of the following statements is true?*

(a) Electrons are majority carriers and trivalent atoms are the dopants.

(b) Electrons are minority carriers and pentavalent atoms are the dopants.

(c) Holes are minority carriers and pentavalent atoms are the dopants.

(d) Holes are majority carriers and trivalent atoms are the dopants.

Solution (c) Holes are minority charge carriers and pentavalent atoms are the dopants in an n-type silicon.

Sample Example 32.5 *Which of the statements given in above example is true for p-type semiconductors?*

Solution (d) Holes are majority carriers and trivalent atoms are the dopants in an p-type semiconductors.

Introductory Exercise 32.1

1. Carbon, silicon and germanium have four valence electrons each. These are characteried by valence and conduction bands separated by energy band-gap respectively equal to $(E_g)_C$, $(E_g)_{Si}$ and $(E_g)_{Ge}$. Which of the following statements is true?

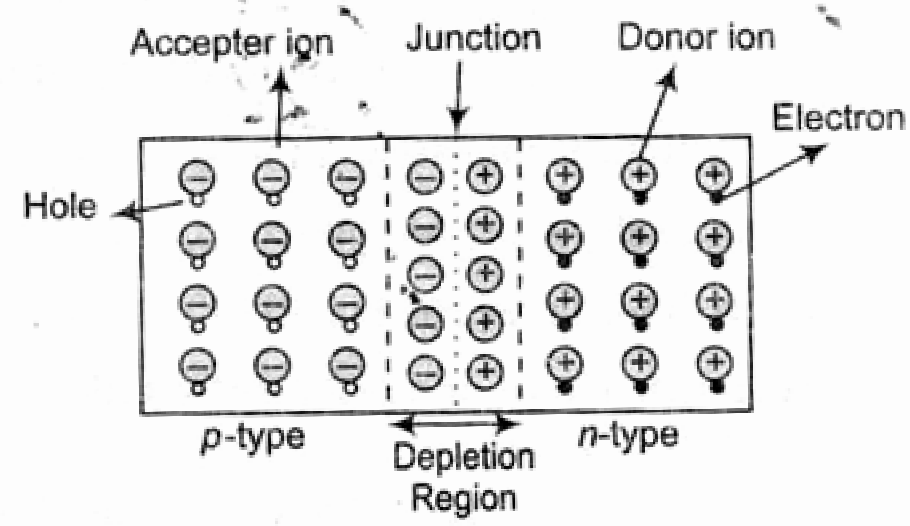
   (a) $(E_g)_{Si} < (E_g)_{Ge} < (E_g)_C$
   (b) $(E_g)_C < (E_g)_{Ge} > (E_g)_{Si}$
   (c) $(E_g)_C > (E_g)_{Si} > (E_g)_{Ge}$
   (d) $(E_g)_C = (E_g)_{Si} = (E_g)_{Ge}$

32.4 *p-n* Junction Diode

A *p*-type or *n*-type silicon crystal can be made by adding appropriate impurity as discussed above. These crystals are cut into thin slices called the wafer. Semiconductor devices are usually made of these wafers.

If on a wafer of *n*-type silicon, an aluminium film is placed and heated to a high temperature, aluminium diffuses into silicon.

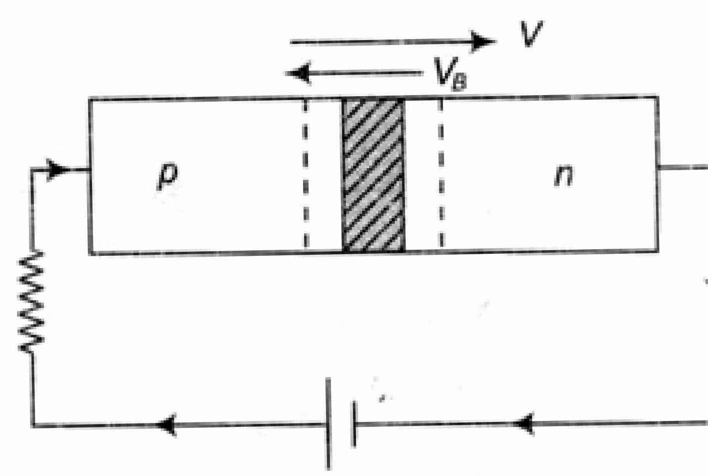
In this way a *p*-type semiconductor is formed on an *n*-type semiconductor. Such a formation of *p*-region on *n*-region is called the *p-n*-junction. Another way to make a *p-n* junction is by diffusion of phosphorus into a *p*-type semiconductor. Such *p-n* junctions are used in a host of semiconductor devices of practical applications. The simplest of the semiconductor devices is a *p-n* junction diode.



(a) Formation of *p-n* junction

Biasing of a diode In a *p-n* junction diode holes are majority carriers on *p*-side and electrons on *n*-side. Holes, thus diffuse to *n*-side and electrons to *p*-side.

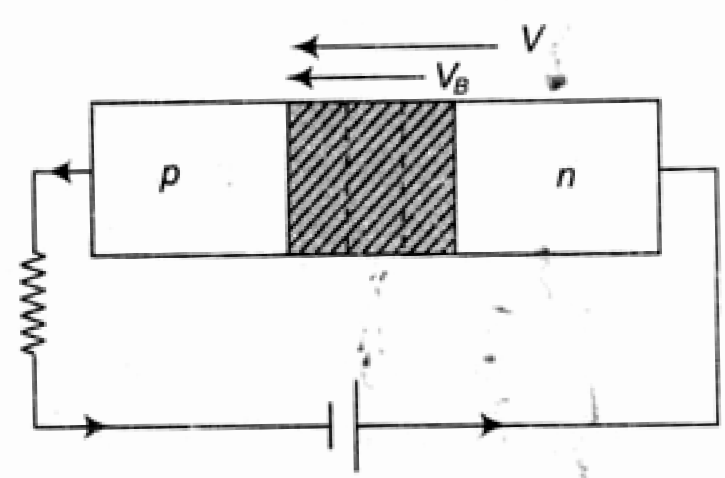
This diffusion causes an excess positive charge in the *n* region and an excess negative charge in the *p* region near the junction. This double layer of charge creates an electric field which exerts a force on the electrons and holes, against their diffusion. In the equilibrium position, there is a barrier, for charge motion with the *n*-side at a higher potential than the *p*-side.



(b) Forward biased *p-n* junction

The junction region has a very low density of either *p* or *n*-type carriers, because of inter diffusion. It is called **depletion region.** There is a barrier V_B associated with it, as described above. This is called **potential barrier.**

Now suppose a DC voltage source is connected across the *p-n* junction. The polarity of this voltage can lead to an electric field across the *p-n* junction that is opposite to the already present electric field. The potential drop across the junction decreases and the diffusion of electrons and holes is thereby increased, resulting in a current in the circuit. This is called **forward biasing.**



(c) Reverse biased *p-n* junction

Fig. 32.10

The depletion layer effectively becomes smaller. In the opposite case, called **reverse biasing** the barrier increases, the depletion region becomes larger, current of electrons and holes is greatly reduced.

Thus, the *p-n* junction allows a much larger current flow in forward biasing than in reverse biasing. This is crudely, the basis of the action of a *p-n* junction as a rectifier. The symbol of *p-n* junction diode is (p —▷— n)

Diffusion Current and Drift Current

Because of concentration difference, holes try to diffuse from the *p*-side to the *n*-side at the *p-n* junction. This diffusion give rise to a current from *p*-side to *n*-side called **diffusion current.** Because of thermal collisions, electron-hole pair are created at every part of a diode.

However, if an electron-hole pair is created in the depletion region, the electron is pushed by the electric field towards the *n*-side and the hole towards the *p*-side. This gives rise to a current from *n*-side to *p*-side called the **drift current.**

Thus, $I_{df} \longrightarrow$ from *p*-side to *n*-side

$I_{dr} \longrightarrow$ from *n*-side to *p*-side

When diode is unbiased $I_{df} = I_{dr}$ or $I_{net} = 0$

When diode is forward biased $I_{df} > I_{dr}$ or I_{net} is from *p*-side to *n*-side

When diode is reverse biased $I_{dr} > I_{df}$ or I_{net} is from *n*-side to *p*-side.

Characteristic curve of a *p-n* junction diode

(a) Circuit for obtaining the characteristics of a forward biased diode and (b) Circuit for obtaining the characteristics of a reverse bias diode

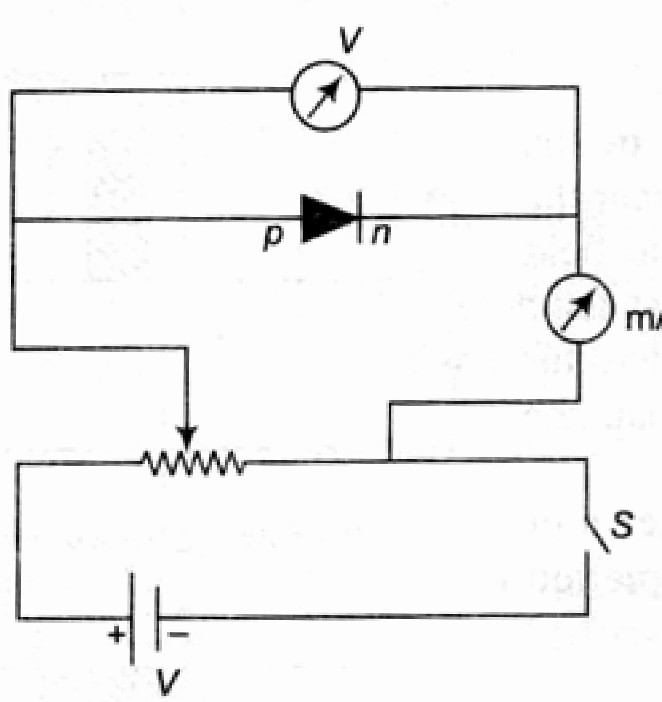


Fig. 32.11

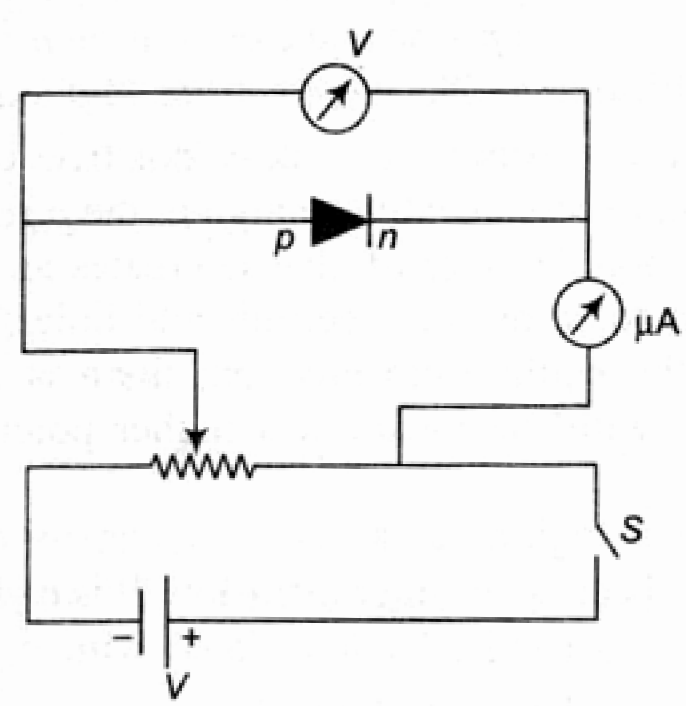


Fig. 32.12

When the diode is forward biased *i.e.*, *p*-side is kept at higher potential, the current in the diode changes with the voltage applied across the diode. The current increases very slowly till the voltage across the diode crosses a certain value.

After this voltage, the diode current increases rapidly, even for very small increase in the diode voltage. This voltage is called the **threshold voltage or cut-off voltage.** The value of the cut off voltage is about 0.2 V for a germanium diode and 0.7 V for a silicon diode.

When the diode is reverse biased, a very small current (about a few micro amperes) produces in the circuit which remains nearly constant till a characteristic voltage called the breakdown voltage, is reached. Then the reverse current suddenly increases to a large value. This phenomenon is called **avalanche breakdown**. The reverse voltage beyond which current suddenly increases is called the **breakdown voltage**.

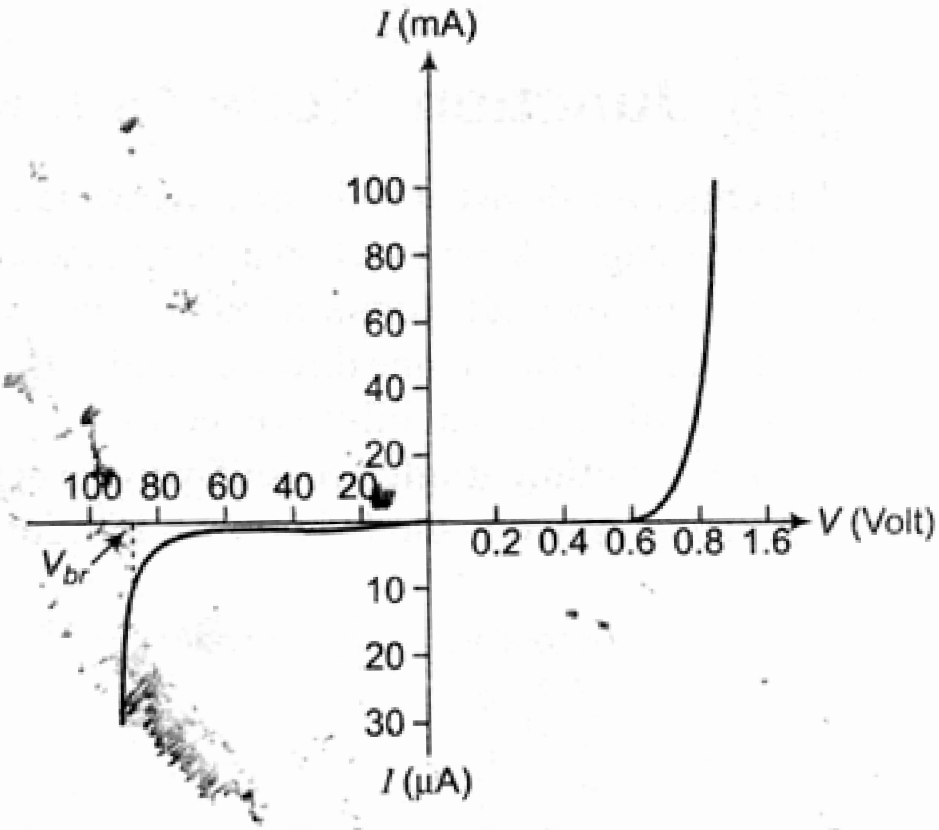


Fig. 32.13

Sample Example 32.6 *Can we take one slab of p-type semiconductor and physically join it to another n-type semiconductor to get p-n junction?*

Solution No. Any slab will have some roughness. Hence continuous contact at the atomic level will not be possible. For the charge carriers the junction will behave as a discontinuity.

Sample Example 32.7 *Find current passing through* $2\,\Omega$ *and* $4\,\Omega$ *resistance in the circuit shown in figure.*

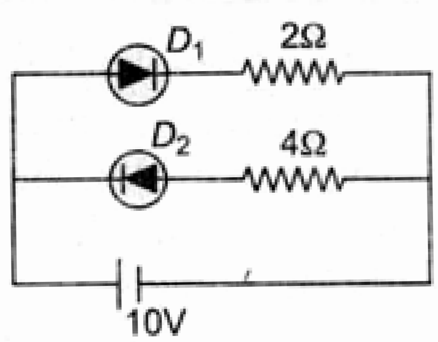


Fig. 32.14

Solution In the given circuit diode D_1 is forward biased and D_2 reverse biased. Hence, D_1 will conduct but D_2 not. Therefore, current through $4\,\Omega$ resistance will be zero while through $2\,\Omega$ resistance will be, $\frac{10}{2} = 5\text{ A}$.

Introductory Exercise 32.2

1. In an unbiased p - n junction, holes diffuse from the p-region to n-region because
   (a) free electrons in the n-region attract them
   (b) they move across the junction by the potential difference
   (c) hole concentration in p-region is more as compared to n-region
   (d) All of the above
2. When a forward bias is applied to a p - n junction. It
   (a) raises the potential barrier
   (b) reduces the majority carrier current to zero
   (c) lowers the potential barrier
   (d) All of the above

32.5 Junction Diode As A Rectifier

A rectifier is a device which converts an alternating current (or voltage) into a direct (or unidirectional) current (or voltage). A *p-n* junction diode can work as an excellent rectifier. It offers a low resistance for the current to flow when it is forward biased, but a very high resistance when reverse biased. Thus, it allows current through it only in one direction and acts as a rectifier. The junction diode can be used either as an half-wave rectifier or as a full-wave rectifier.

(i) ***p-n* junction diode as half-wave rectifier** A simple rectifier circuit called the half-wave rectifier, using only one diode is shown in figure.

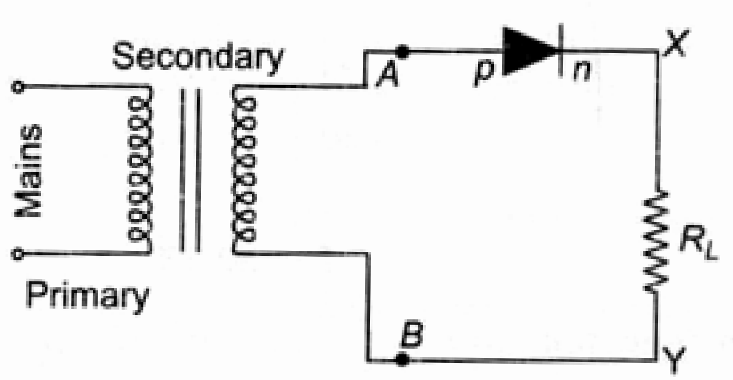


Fig. 32.15

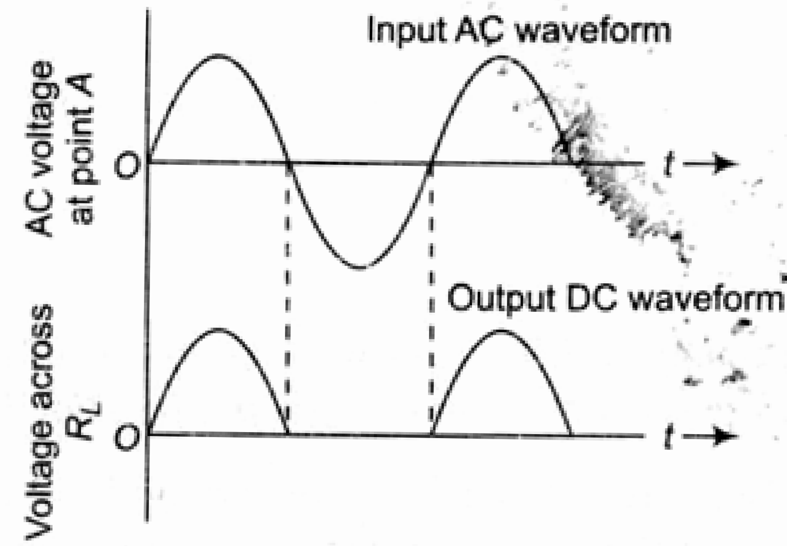
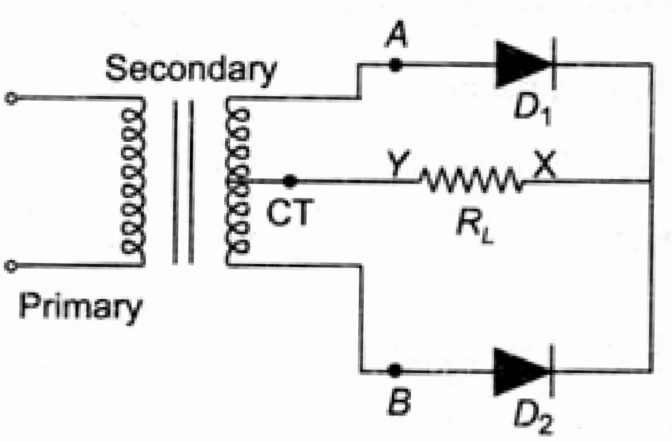


Fig. 32.16

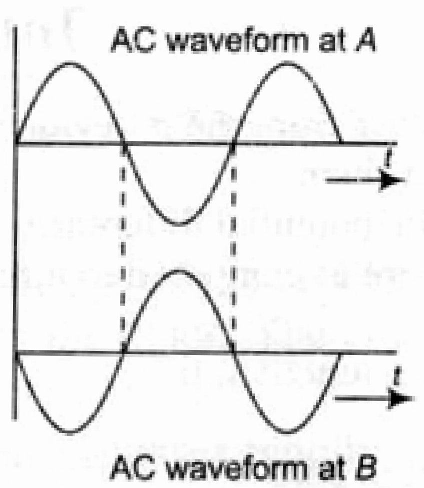
When the voltage at A is positive, the diode is forward biased and it conducts and when the voltage at A is negative, the diode is reverse biased and does not conduct. Since, the diode conducts only in the positive half cycles, the voltage between X and Y or across R_L will be DC but in pulses. When this is given to a circuit called filter (normally a capacitor), it will smoothen the pulses and will produce a rather steady DC voltage.

(ii) ***p-n* junction diode as full-wave rectifier** Figure shows a circuit which is used in full-wave rectification. Two diodes are used for this purpose.

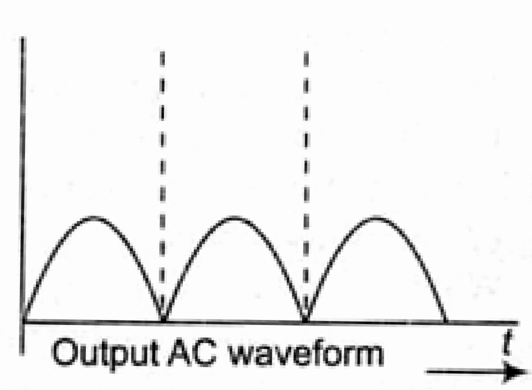
The secondary coil of the transformer is wound in two parts and the junction is called a Centre-Tap (CT). During one-half cycle D_1 is forward biased and D_2 is reverse biased. Therefore, D_1 conducts but D_2 does not, current flows from X to Y through load resistance R_L. During another half cycle D_2 is forward biased and D_1 reverse biased. Therefore, D_2 conducts and D_1 does not. In this half cycle also current through R_L flows from X to Y. Thus, current through R_L in both the half cycles is in one direction, *i.e.*, from X to Y.



(a) Full wave rectifier



(b) AC voltage waveforms at point A and B



(c) Output DC wave forms of a full-wave rectifier.

Fig. 32.17

Bridge rectifier Another full-wave rectifier called the bridge rectifier which uses four diodes is shown in figure.

For one-half cycle diodes D_1 and D_3 are forward biased and D_2 and D_4 are reverse biased. So, D_1 and D_3 conduct but D_2 and D_4 don't. Current through R_L flows from X to Y. In another half cycle D_2 and D_4 are forward biased and D_1 and D_3 are reverse biased. So, in this half cycle D_2 and D_4 conduct but D_1 and D_3 do not. Current again flows from X to Y through R_L. Thus, we see that current through R_L always flows in one direction from X to Y.

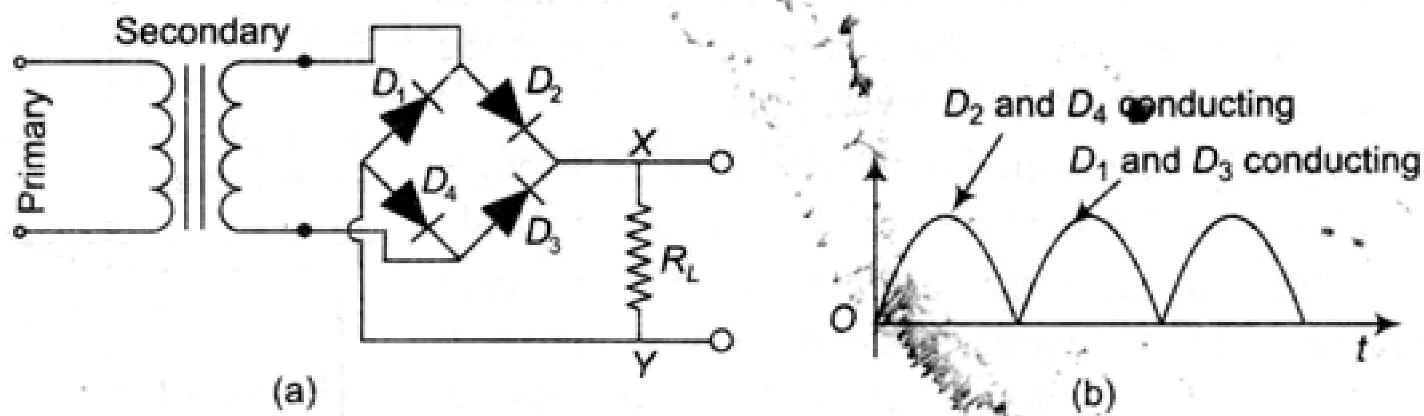


Fig. 32.18 (a) Bridge rectifier and (b) output waveforms for a bridge rectifier

Note *Even after rectification ripples are present in the output which can be removed upto great extent by a filter circuit. A filter circuit consists of a capacitor.*

Sample Example 32.8 *In half-wave rectification, what is the output frequency, if the input frequency is 50 Hz. What is the output frequency of a full-wave rectifier for the same input frequency?*

Solution A half-wave rectifier conducts once during a cycle. Therefore frequency of AC output is also the frequency of AC input i.e. 50 Hz. A full-wave rectifier rectifies both the half cycles of the AC output i.e., it conducts twice during a cycle.

So, Frequency of AC output $= 2 \times$ frequency of AC input

$$= 2 \times 50 = 100 \text{ Hz}$$ **Ans.**

Sample Example 32.9 *In the figure, the input is across the terminals A and C and the output is across B and D. Then the output is*

(a) *zero*

(b) *same as the input*

(c) *full-wave rectified*

(d) *half-wave rectified*

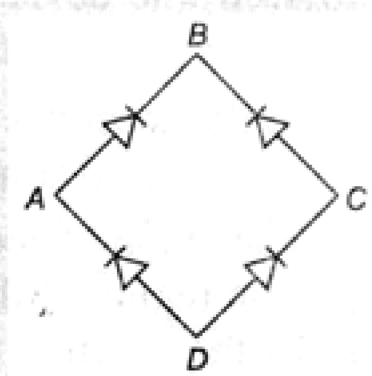


Fig. 32.19

Solution (*c*) During the half cycle when $V_M > V_N$, D_1 and D_3 are forward biased. Hence, the path of current is $MABPQDCNM$.

In the second half cycle when $V_N > V_M$, D_2 and D_4 are forward biased while D_1 and D_3 are reverse biased. Hence the path of current is $NCBPQDAMN$.

Therefore in both half cycles current flows from P to Q from load resistance R_L. Or, it is a full-wave rectifier.

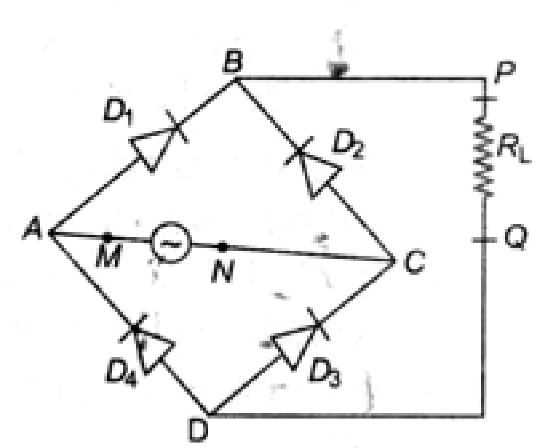


Fig. 32.20

32.6 Applications of p-n Junction Diodes

(i) Zener Diode

A diode meant to operate under reverse bias in the breakdown region is called an **avalanche diode** or a **zener diode**. Such diode is used as a voltage regulator. The symbol of zener diode is shown in figure.

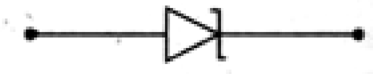


Fig. 32.21

Once the breakdown occurs, the potential difference across the diode does not increase even if, there is large change in the current. Figure shows a zener diode in reverse biasing.

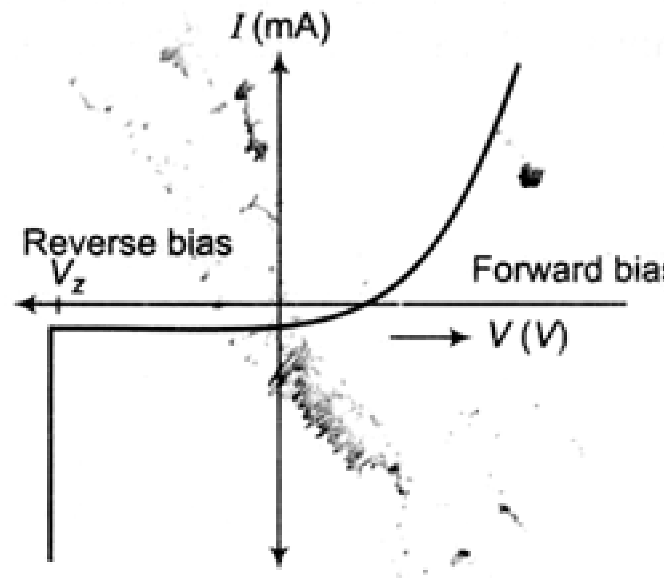


Fig. 32.22

An input voltage V_i is connected to the zener diode through a series resistance R such that the zener diode is reverse biased.

If the input voltage increases, the current through R and zener diode also increases. This increases the voltage drop across R without any change in the voltage across the zener diode. Similarly if the input voltage decreases the current through R and zener diode also decreases. The voltage drop across R decreases without any change in the voltage across the zener diode.

Thus any increase/decrease in the input voltage results in increase/decrease of the voltage drop across R without any change in voltage across the zener diode (and hence across load resistance R_L). Thus the zener diode acts as a voltage regulator.

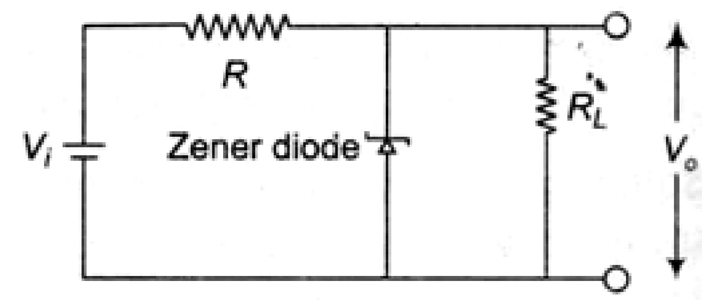


Fig. 32.23

We have to select the zener diode according to the required output voltage and accordingly the series resistance R.

(ii) Optoelectronic Devices

Semiconductor diodes in which carriers are generated by photons (photo excitation) are called optoelectronic devices. Examples of optoelectronic devices are, photodiodes, Light Emitting Diodes (LED) and photovoltaic devices etc.

(a) Photodiodes Photodiodes are used as photodetector to detect optical signals. They are operated in reverse biased connections.

When light of energy greater than the energy gap falls on the depletion region of the diode, electron-hole pairs are generated. Due to the electric field of junction, electrons and holes are separated before they recombine. Electrons reach n-side and holes reach p-side giving rise to an emf. When an external load is connected, current flows. The magnitude of the photocurrent depends on the intensity of incident light.

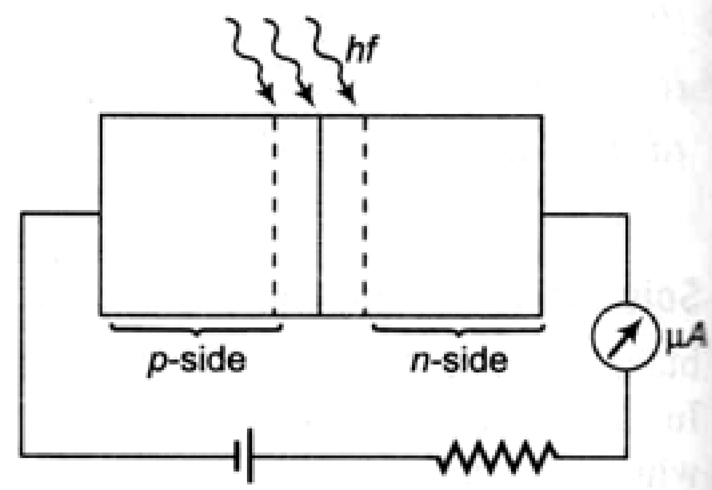


Fig. 32.24

(b) Light Emitting Diode (LED) It is heavily doped p-n junction diode which under forward bias emits spontaneous radiation. LEDs that can emit red, yellow, orange, green and blue light are commercially available. These LEDs find extensive use in remote controls, burglar alarm systems, optical communications etc.

Extensive research is being done for developing white LEDs which can replace incandescent lamps. LED have the following advantages over conventional incandescent power lamps.

(i) long life
(ii) low operational voltage and less power
(iii) no warm up time is required. So fast on-off switching capability.

(c) Solar Cell It works on the same principle as the photodiode. It is basically a $p-n$ junction which generates emf when solar radiation falls on the *p-n* junction. The difference between a photodiode and a solar cell is that no external bias is applied and the junction area is kept much larger for solar radiation to be incident because we require more power.

The generation of emf by a solar cell (when light falls on it) is due to the following three processes.

(i) generation Generation of electron-hole pairs due to light ($hf > E_g$) falling on it.

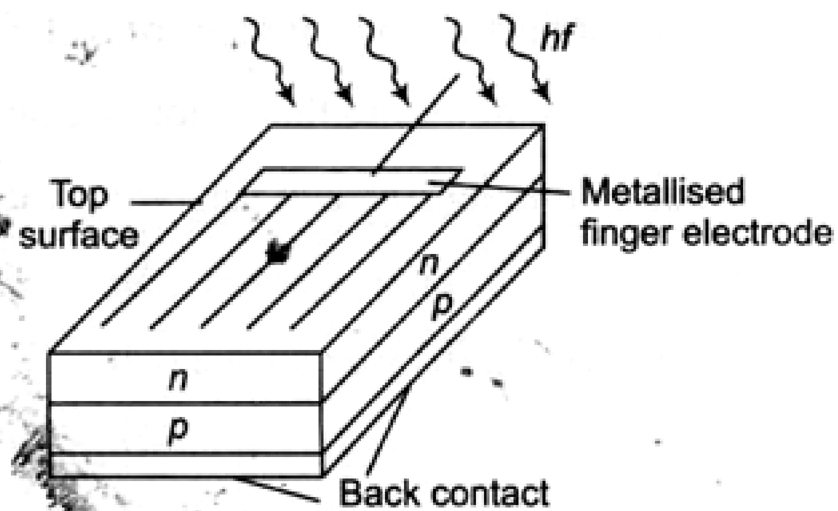


Fig. 32.25 Typical p-n junction Solar cell

(ii) separation Separation of electrons and holes due to electric field of the depletion region.

(iii) collection Electrons are swept to n –side and holes to p-side. Thus p-side becomes positive and n-side becomes negative giving rise to photovoltage.

Solar cells are used to power electronic devices in satellites and space vehicles and also as power supply to some calculators.

Sample Example 32.10 *In a zener regulated power supply a Zener diode with $V_Z = 6.0$ V is used for regulation. The load current is to be 4.0 mA and the unregulated input is 10.0 V. What should be the value of series resistor R?*

Solution Zener current I_Z should be sufficiently larger than load current I_L.

Given, $I_L = 4.0$ mA

So, let us take I_Z to be five times I_L or $I_Z = 20$ mA

Total current $I = I_Z + I_L = 24.0$ mA

Input voltage $V_{in} = 10$ Volt

Zener diode voltage $V_Z = 6$ Volt

$\therefore$ Voltage drop across resistance, $V_R = V_{in} - V_Z$

or $V_R = (10-6)$ Volt

$= 4$ Volt

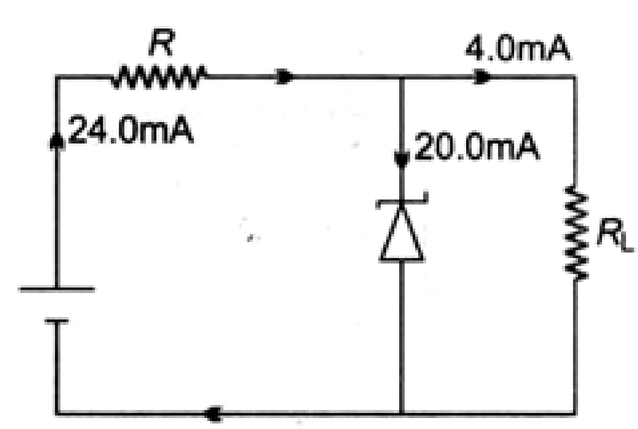


Fig. 32.26

Now, $$R = \frac{V_R}{I_R} = \frac{4}{24 \times 10^{-3}} = 167\ \Omega$$

The nearest value of carbon resistor is 150 Ω. So, a series resistor of 150 Ω is appropriate.

Sample Example 32.11 *The current in the forward bias is known to be more* (in *mA*) *than the current in the reverse bias* (in μ*A*). *What is the reason then to operate the photodiodes in reverse bias?*

Solution Let us take an example of *p*- type semiconductor.

Without illumination

number of holes (n_h) >> number of electrons (n_e) ...(i)

This is because holes are the majority charge carriers in *p*-type semiconductor.

On illumination, let Δn_e and Δn_h are the excess electrons and holes generated.

$$\Delta n_e = \Delta n_h \quad \text{...(ii)}$$

From Eqs. (i) and (ii) we can see that

$$\frac{\Delta n_e}{n_e} >> \frac{\Delta n_h}{n_h}$$

From here we can say that the fractional change due to illumination on the minority carrier dominated reverse bias current is more easily measurable than the fractional change in the forward bias current.

32.7 Junction Transistors

A junction transistor is formed by sandwiching a thin wafer of one type of semiconductor between two layers of another type. The *n-p-n* transistor has a *p*-type wafer between two *n*-type layers. Similarly the *p-n-p* transistor has a *n*-type wafer between two *p*-type layers.

(i) *p-n-p* Transistor

Figure shows a *p-n-p* transistor, in which a thin layer of *n*-type semiconductor is sandwiched between two *p*-type semiconductors. The middle layer (called the base) is very thin (of the order of 1 μm) as compared to the widths of the two layers at the sides. Base is very lightly doped. One of the side layer (called emitter) is heavily doped and the other side layer (called collector) is moderately doped. Figure (c) shows the symbol of *p-n-p* transistor.

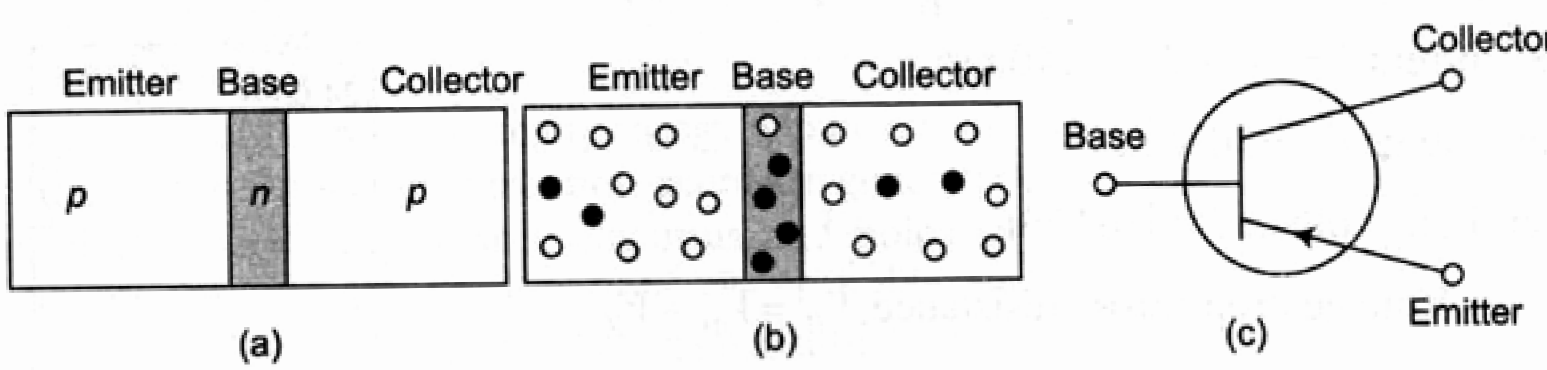


Fig. 32.27

(ii) *n-p-n* Transistor

In *n-p-n* transistor *p*-type semiconductor is sandwiched between two *n*-type semiconductors. Symbol of *p-n-p* transistor is shown in figure (f).

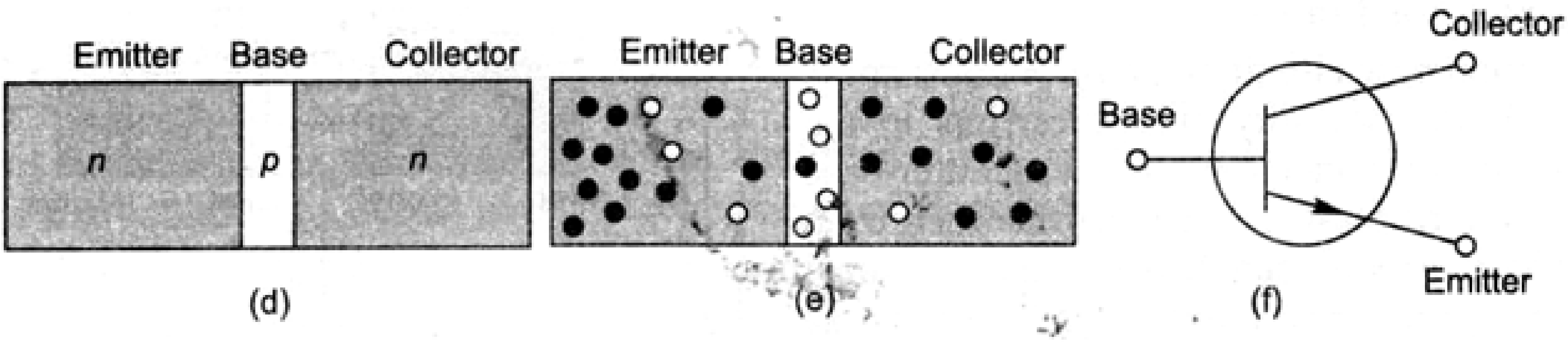


Fig. 32.28

More points about a transistor A transistor is basically a three-terminal device. Terminals come out from the emitter, base and the collector for external connections. In normal operation of a transistor, the emitter-base junction is always forward biased and collector-base junction is reverse biased.

The arrow on the emitter-base line shows the direction of current between emitter and base. In an *n-p-n* transistor for example, there are a large number of conduction electrons in the emitter and a large number of holes in the base. If the junction is forward biased the electrons will diffuse from emitter to the base and holes will diffuse from the base to the emitter. The direction of electric current at this junction is therefore from the base to the emitter. A transistor can be operated in three different modes.

(i) common emitter (or grounded-emitter)
(ii) common collector (or grounded-collector) and
(iii) common base (or grounded-base)

In common emitter mode, emitter is kept at zero potential. Similarly in common collector mode collector is at zero potential and so on.

Working of a *p-n-p* Transistor

Let us consider the working of a *p-n-p* transistor in common base mode. In emitter (*p* type) holes are in majority. Since, emitter-base is forward biased, holes move toward base. Few of them combine with electrons in the base and rest go to the collector. Since, base-collector is reverse biased, holes coming from base move toward the terminal of collector. They combine with equal number of electrons entering from collector terminal.

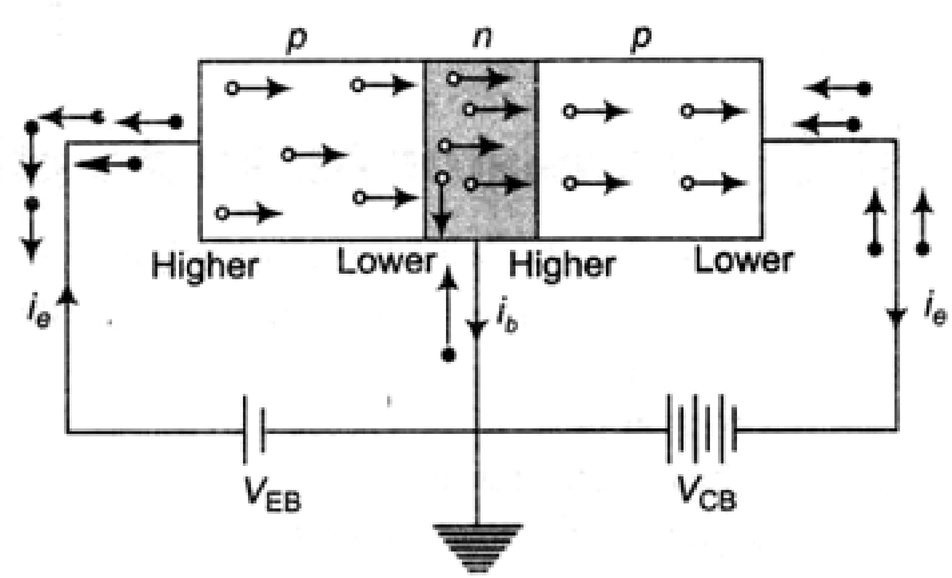


Fig. 32.29

Let us take an example with some numerical values.

Suppose 5 holes enter from emitter to base. This deficiency of 5 holes in emitter is compensated when 5 electrons emit from emitter and give rise to i_e. One out of five holes which reach the base combine with one electron entering from base (the equivalent current is i_b). Rest four holes enter the collector and move towards its terminal. On the other hand 5 electrons which leave the emitter (as i_e) come to the base, emitter and collector junction. One electron of it goes to base and rest four to collector. These four electrons give rise to i_c (the collector current) and combine with the four holes coming from the base, and thus circuit is complete. From the figure we can see that,

$$i_e = i_c + i_b$$

Note *that i_b is only about 2% of i_e, or roughly around 2% of holes coming from emitter to base combine with the electrons. Rest 98% move to collector.*

Working of *n-p-n* Transistor

A common base circuit of an *n-p-n* transistor is shown in figure. Majority charge carriers in the emitter (*n*-type) are electrons. Since, emitter-base circuit is forward biased. The electrons rush from emitter to base. Few of them leave the base terminal (comprising i_b) and rest move to collector. These electrons finally leave the collector terminal (give rise to i_c). Electrons coming from base and from collector meet at junction *O* and they jointly move to emitter, which gives rise to i_e.

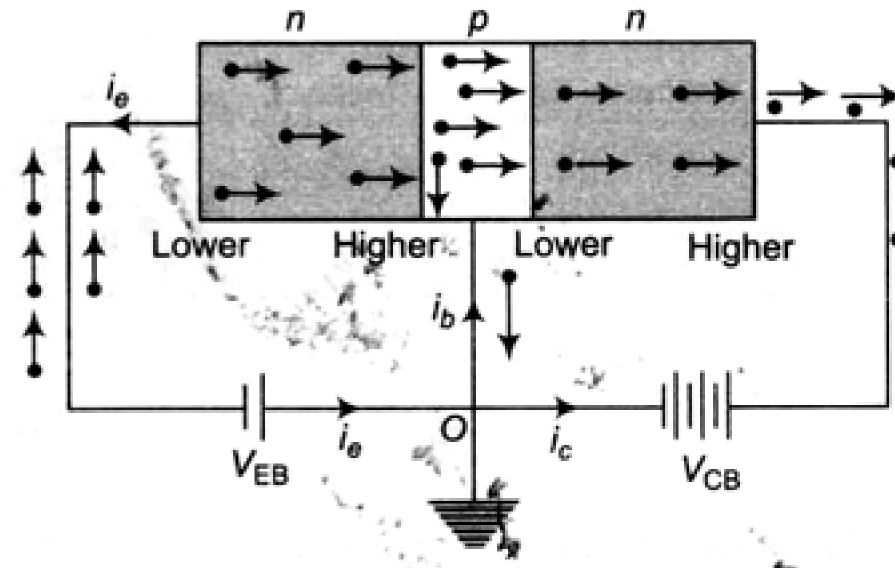


Fig. 32.30

Thus, here also we can see that $i_e = i_b + i_c$

Note *that although the working principle of p-n-p and n-p-n transistors are similar but the current carriers in p-n-p transistor are mainly holes whereas in n-p-n transistors the current carriers are mainly electrons. Mobility of electrons are however more than the mobility of holes, therefore n-p-n transistors are used in high frequency and computer circuits where the carriers are required to respond very quickly to signals.*

α and β-parameters: α and β-parameters of a transistor are defined as,

$$\alpha = i_c / i_e \quad \text{and} \quad \beta = i_c / i_b$$

As i_b is about 1 to 5% of i_e, α is about 0.95 to 0.99 and β is about 20 to 100. By simple mathematics we can prove that,

$$\beta = \frac{\alpha}{1-\alpha}$$

32.8 Transistor As An Amplifier

A transistor can be used for amplifying a weak signal.

When a transistor is to be operated as amplifier, three different basic circuit connections are possible. These are

(i) common base,
(ii) common emitter and
(iii) common collector circuits.

Whichever circuit configuration, the emitter-base junction is always forward biased while the collector-base junction is always reverse biased.

(a) **Common base amplifier using a *p-n-p* transistor** In common base amplifier, the input signal is applied across the emitter and the base, while the amplified output signal is taken across the collector and the base. This circuit provides a very low input resistance, a very high output resistance and a current gain of just less than 1. Still it provides a good voltage and power amplification. There is no phase difference between input and output signals.

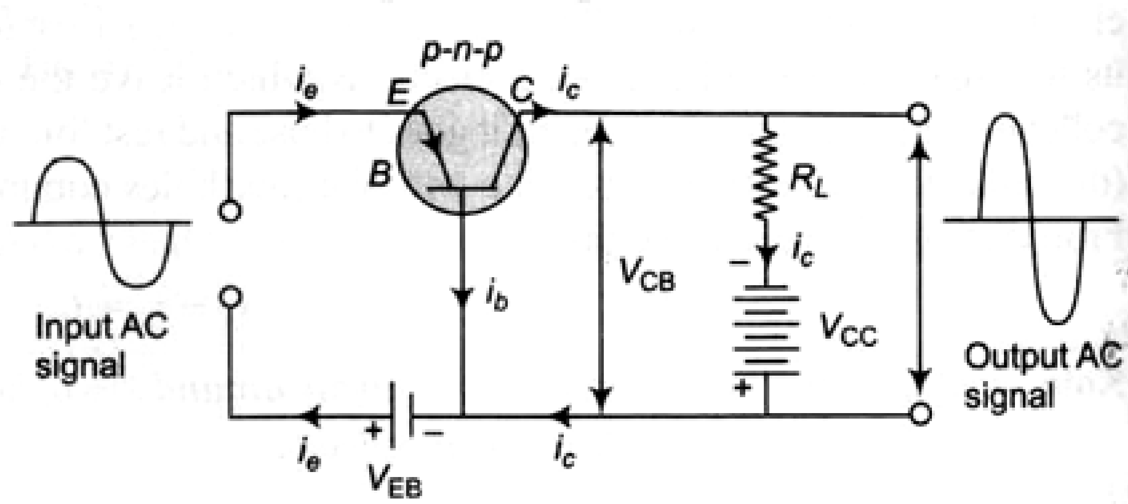


Fig. 32.31

The common base amplifier circuit using a *p-n-p* transistor is shown in figure. The emitter base input circuit is forward biased by a low voltage battery V_{EB}. The collector base output circuit is reversed biased by means of a high voltage battery V_{CC}. Since, the input circuit is forward biased, resistance of input circuit is small. Similarly, output circuit is reverse biased, hence resistance of output circuit is high.

The weak input AC voltage signal is superimposed on V_{EB} and the amplified output signal is obtained across collector-base circuit. In the figure we can see that,

$$V_{CB} = V_{CC} - i_c R_L$$

The input AC voltage signal changes net value of V_{EB}. Due to fluctuations in V_{EB}, the emitter current i_e also fluctuates which in turn fluctuates i_c. In accordance with the above equation there are fluctuations in V_{CB}, when the input signal is applied and an amplified output is obtained.

Current gain, Voltage gain and Power gain

(i) **Current gain** Also called AC current gain (α_{ac}), is defined as the ratio of the change in the collector current to the change in the emitter current at constant collector-base voltage.

Thus, α_{ac} or simply $\alpha = \dfrac{\Delta i_c}{\Delta i_e}$ (V_{CB} = constant)

As stated earlier also, α is slightly less than 1.

(ii) **Voltage gain** It is defined as the ratio of change in the output voltage to the change in the input voltage. It is denoted by A_V. Thus,

$$A_V = \frac{\Delta i_c \times R_{out}}{\Delta i_e \times R_{in}}$$

but $\dfrac{\Delta i_c}{\Delta i_e} = \alpha$, the current gain.

$$\therefore \quad A_V = \frac{a\, R_{out}}{R_{in}}$$

Since, $R_{out} >> R_{in}$, A_V is quite high, although α is slightly less than 1.

(iii) **Power gain** It is defined as the change in the output power to the change in the input power. Since,

$$P = Vi$$

Therefore, power gain = current gain × voltage gain

or $$\text{Power gain} = \alpha^2 \cdot \frac{R_{out}}{R_{in}}$$

• Important points in common base amplifier

1. The output voltage signal is in phase with the input voltage signal.
2. The common base amplifier is used to amplify high (radio)-frequency signals and to match a very low source impedance (~20 Ω) to a high load impedance (~100 k Ω).

(b) **Common emitter amplifier using a *p-n-p* transistor** Figure shows a *p-n-p* transistor as an amplifier in common emitter mode. The emitter is common to both input and output circuits. The input (base-emitter) circuit is forward biased by a low voltage battery V_{BE}. The output (collector-emitter) circuit is reverse biased by means of a high voltage battery V_{CC}.

Since, the base-emitter circuit is forward biased, input resistance is low. Similarly, collector-emitter circuit is reverse biased, therefore output resistance is high. The weak input AC signal is superimposed on V_{BE} and the amplified output signal is obtained across the collector-emitter circuit.

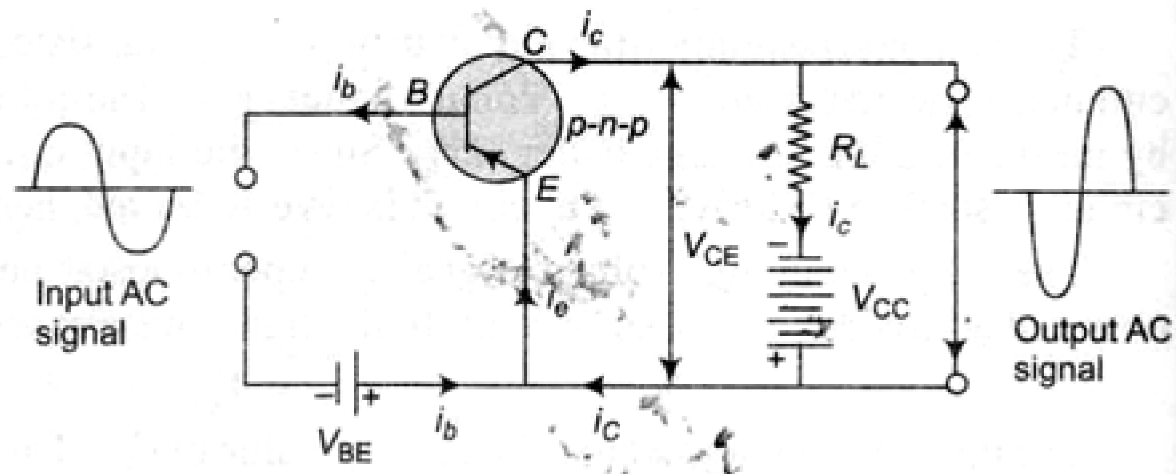


Fig. 32.32

In the figure we can see that,

$$V_{CE} = V_{CC} - i_c R_L$$

When the input AC voltage signal is applied across the base-emitter circuit, it fluctuates V_{BE} and hence the emitter current i_e. This in turn changes the collector current i_c consequently V_{CE} varies in accordance with the above equation. This variation in V_{CE} appears as an amplified output.

Current gain, Voltage gain and Power gain

(i) **Current gain** Also called ac current gain (β_{ac}), is defined as the ratio of the collector current to the base current at constant collector to emitter voltage.

$$\beta_{ac} \text{ or simply } \beta = \left(\frac{\Delta i_c}{\Delta i_b}\right) \qquad (V_{CE} = \text{constant})$$

(ii) **Voltage gain** It is defined as the ratio of the change in the output voltage to the change in the input voltage. It is denoted by A_V. Thus,

$$A_V = \frac{\Delta i_c \times R_{out}}{\Delta i_b \times R_{in}} \quad \text{or} \quad A_V = \beta\left(\frac{R_{out}}{R_{in}}\right)$$

(iii) **Power gain** It is defined as the ratio of change in output power to the change in the input power. Since,

$$P = Vi$$

Therefore, power gain = current gain × voltage gain

or

$$\text{Power gain} = \beta^2 \left(\frac{R_{out}}{R_{in}}\right)$$

• Important Points in Common Emitter Amplifier

(i) The value of current gain β is from 15 to 50 which is much greater than α.

(ii) The voltage gain in common-emitter amplifier is larger compared to that in common base amplifier.

(iii) The power gain in common-emitter amplifier is extremely large compared to that in common base amplifier.

(iv) The output voltage signal is 180° out of phase with the input voltage signal in the common emitter amplifier.

Transconductance (g_m) There is one more term called transconductance (g_m) in common emitter mode. It is defined as the ratio of the change in the collector current to the change in the base to emitter voltage at constant collector to emitter voltage. Thus,

$$g_m = \left(\frac{\Delta i_c}{\Delta V_{BE}}\right) \qquad (V_{CE} = \text{constant})$$

The unit of g_m is Ω^{-1} or siemen (S).
By simple calculation we can prove that,

$$g_m = \frac{\beta}{R_{in}}$$

Advantages of a transistor over a triode valve A transistor is similar to a triode valve in the sense that both have three elements. While the elements of a triode are, cathode, plate and grid the three elements of a transistor are emitter, collector and base. Emitter of a transistor can be compared with the cathode of the triode, the collector with the plate and the base with the grid.

Transistor has following advantages over a triode valve

(i) A transistor is small and cheap as compared to a triode valve. They can bear mechanical shocks.
(ii) A transistor has much longer life as compared to a triode valve.
(iii) Loss of power in a transistor is less as it operates at a much lower voltage.
(iv) In a transistor no heating current is required. So, unlike a triode valve, a transistor starts functioning immediately as soon as the switch is opened. In case of valves, they come in operation after some time of opening the switch (till cathode gets heated).

Drawbacks of a transistor over a triode valve Transistor have following drawbacks as comparedto valves

(i) Since, the transistors are made of semiconductors they are temperature sensitive. We cannot work on transistors at high temperatures.
(ii) In transistors noise level is high. Keeping all the factors into consideration, transistors have replaced the valve from most of the modern electronic devices.

Sample Example 32.12 *The current gain of a transistor in a common base arrangement in 0.98. Find the change in collector current corresponding to a change of 5.0 mA in emitter current. What would be the change in base current?*

Solution Given, $\alpha = 0.98$ and $\Delta i_e = 5.0$ mA

From the definition of,

$$\alpha = \frac{\Delta i_c}{\Delta i_e}$$

Change in collector current,

$$\Delta i_c = (\alpha)(\Delta i_e) = (0.98)(5.0) \text{ mA} = 4.9 \text{ mA}$$

Further, change in base current,

$$\Delta i_b = \Delta i_e - \Delta i_c = 0.1 \, mA$$ **Ans.**

Sample Example 32.13 *A transistor is connected in common emitter configuration. The collector supply is 8 V and the voltage drop across a resistor of* 800 Ω *in the collector circuit is 0.5 V. If the current gain factor* (α) *is 0.96, find the base current.*

Solution

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$

The collector current is,

$$i_c = \frac{\text{voltage drop across collector resistor}}{\text{resistance}}$$

$$= \frac{0.5}{800}\ \Omega = 0.625 \times 10^{-3}\ \text{A}$$

From the definition of
$$\beta = \frac{i_c}{i_b}$$

the base current
$$i_b = \frac{i_c}{\beta} = \frac{0.625 \times 10^{-3}}{24}\ \text{A}$$

$$= 26\ \mu\text{A}$$

Ans.

Sample Example 32.14 *In a common emitter amplifier, the load resistance of the output circuit is 500 times the resistance of the input circuit. If $\alpha = 0.98$, then find the voltage gain and power gain.*

Solution Given $\alpha = 0.98$ and $\dfrac{R_{\text{out}}}{R_{\text{in}}} = 500$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = 49$$

(i) Voltage gain $= (\beta)\dfrac{R_{\text{out}}}{R_{\text{in}}} = (49)\,(500) = 24500$

(ii) Power gain $= (\beta^2)\dfrac{R_{\text{out}}}{R_{\text{in}}} = (49)^2\,(500) = 1200500$

Introductory Exercise 32.3

1. For transistor action, which of the following statements are correct?
   (a) Base, emitter and collector regions should have similar size and doping concentrations
   (b) The base region must be very thin and lightly doped
   (c) The emitter junction is forward biased and collector junction is reverse biased
   (d) Both the emitter junction as well as the collector junction are forward biased
2. For a transistor amplifier, the voltage gain
   (a) remains constant for all frequencies
   (b) is high at high and low frequencies and constant in the middle frequency range
   (c) is low at high and low frequencies and constant at mid frequencies
   (d) None of the above
3. For a CE-transistor amplifier, the audio signal voltage across the collector resistance of 2 kΩ is 2 V. Suppose the current amplification factor of the transistor is 100. Find the input signal voltage and base current, if the base resistance is 1 kΩ.

32.9 Digital Electronics and Logic Gates

(i) **Binary system** There are a number of questions which have only two answers Yes or No. A statement can be either True or False. A switch can be either ON or OFF. These values may be represented by two symbols 0 and 1. In a number system, in which we have only two digits is called a binary system. (decimal system for example has ten digits).

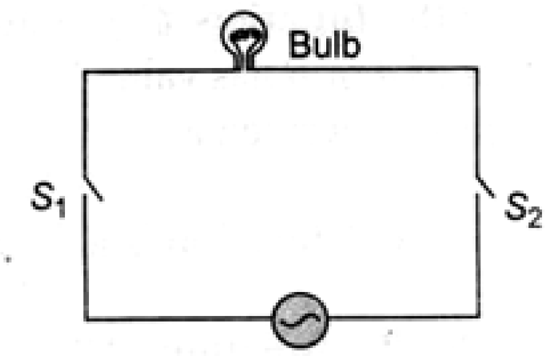


Fig. 32.33

In binary system usually we write 1 for positive response (*e.g.*, when a switch is ON) and 0 for negative (when switch is OFF).

(ii) **Truth table** To understand the concept of truth table let us take an example. A bulb is connected to an AC source *via* two switches S_1 and S_2.

In binary system, we will write 0, if the switch (or bulb) is off and write 1 if it is on. Further let us write

A for state of switch S_1

B for state of switch S_2

and C for state of the bulb.

Now, let us make a table (called truth table) which is self explanatory.

Table 32.3

Switch S_1	Switch S_2	Bulb	A	B	C
Off	On	Off	0	1	0
On	Off	Off	1	0	0
Off	Off	Off	0	0	0
On	On	On	1	1	1

Exercise *Make a truth table corresponding to the circuit shown in figure.*

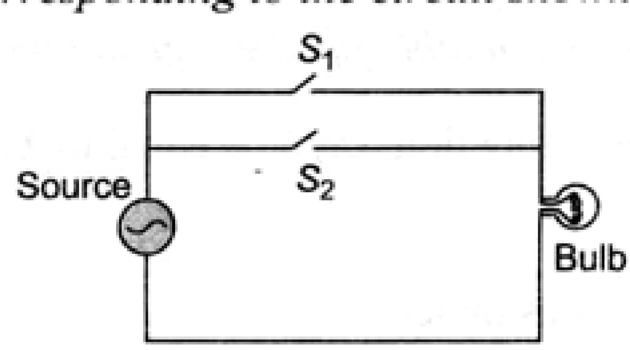


Fig. 32.34

Table 32.4

Switch S_1	Switch S_2	Bulb	A	B	C
On	Off	On	1	0	1
Off	On	On	0	1	1
Off	Off	Off	0	0	0
On	On	On	1	1	1

(iii) **Logical function** A variable (*e.g.*, state of a switch or state of a bulb) which can assume only two values (0 and 1) is called a logical variable. A function of logical variables is called a logical function. **AND, OR** and **NOT** represent three basic operation on logical variables.

'AND' function Suppose C is a function of A and B, then it will be said an 'AND' function when C has value 1 when both A and B have value 1. Truth table corresponding to Table 32.3 is an example of 'AND' function. The function is written as,

$$C = A \text{ and } B$$

AND function is also denoted as $C = A \cdot B$

'OR' function C, a function of A and B will be said an 'OR' function when C has value 1 when either of A or B has value 1. Truth table corresponding to Table 32.4 is an example of 'OR' function. The function is written as,

$$C = A \text{ OR } B$$

OR function is also denoted as,

$$C = A + B$$

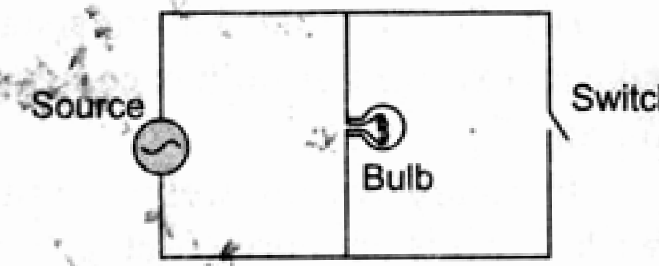


Fig. 32.35

'NOT' function 'NOT' function is a function of a single variable.

A bulb is short circuited by a switch. If the switch is open, the current goes through the bulb and it is on. If the switch is closed the current goes through the switch and the bulb is off. The truth table corresponding to the above situation (or NOT function) is as under.

Table 32.5

Switch	Bulb	A	B
Open	On	0	1
Closed	Off	1	0

'NOT' function is denoted as,

$$B = \text{NOT } A \text{ or } B = \overline{A}$$

Sample Example 32.15 *Write the truth table for the logical function $D = (A \text{ OR } B) \text{ AND } B$.*

Solution A OR B is a logical function, say it is equal to X, *i.e.*,

$$X = A \text{ OR } B$$

Now, $D = X \text{ AND } B$

The corresponding truth table is as under.

Table 32.6

A	B	$X = A$ OR B	$D = (A$ OR $B)$ AND B
1	0	1	0
0	1	1	1
0	0	0	0
1	1	1	1

Note *that the given function can also be written as,*

$$D = (A + B) \cdot B$$

(iv) **Logic gates** Logic gates are important building blocks in digital electronics. These are circuits with one or more inputs and one output. The basic gates are OR, AND, NOT, NAND, NOR and XOR. As we know, in digital electronics only two voltage levels are

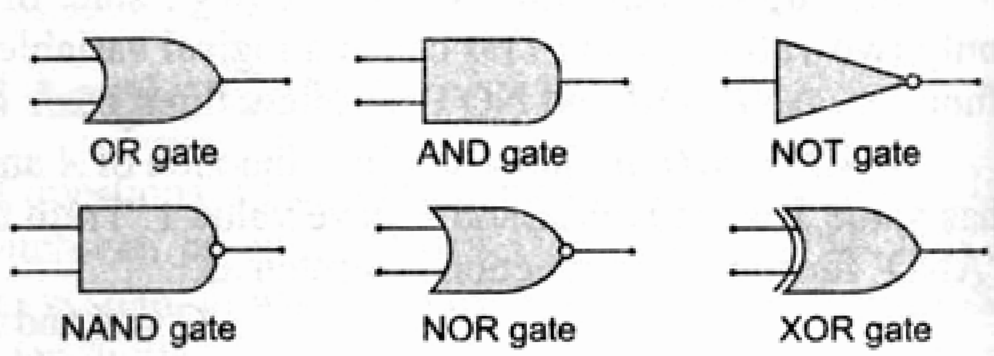


Fig. 32.36

present. Conventionally, these are 5V and 0V, referred to as 1 and 0 respectively or *vice-versa*. They are also referred as high and low.

Figure given are the symbols of six basic gates:

OR gate The truth table of 'OR' gate is given below.

Table 32.7

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

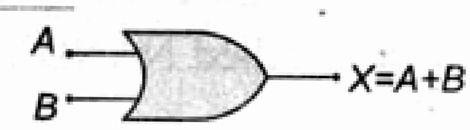


Fig. 32.37

The output X will be 1 (*i.e.*, 5V) when the A input is 1, OR when the B input is 1, OR when both are 1. This is written as,

$$X = A + B$$

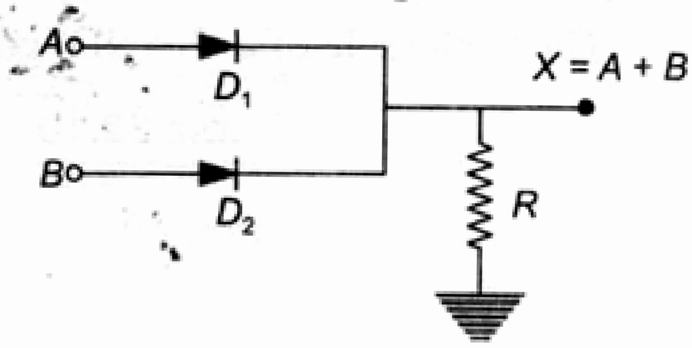


Fig. 32.38

Figure shows construction of an OR gate using two diodes.

When either of point A or point B (or both) has potential +5V, diodes D_1 or D_2 (or both) are forward biased and the potential at X is the same as the common potential at A and B which is 5V.

AND gate The truth table of 'AND' gate is given below.

Table 32.8

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

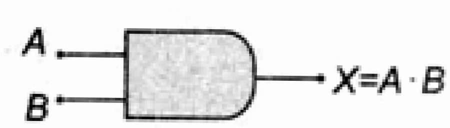


Fig. 32.39

The output X will be 1 (*i.e.*, 5V) when both the inputs A and B is 1. This is written as,

$$X = A \cdot B$$

Figure shows construction for an AND gate using two diodes D_1 and D_2.

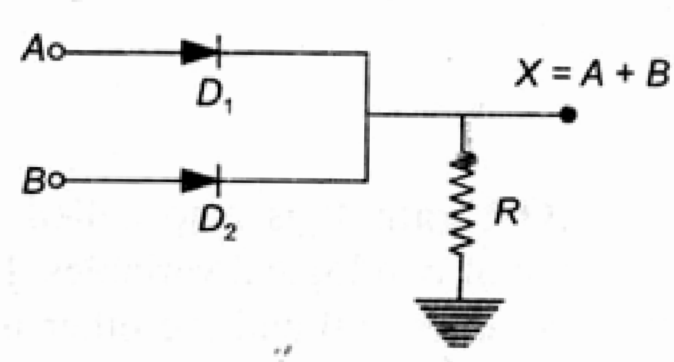


Fig. 32.40

When potentials at A and B both are zero, then both the diodes are forward biased and offer no resistance. The potential at X in this position is equal to the potential at A or B *i.e.*, 0. Thus $X = 0$, when both A and B are zero. Now suppose potential at A is zero but at B is 5V, then D_1 is forward biased. In this situation potential at X is also zero.

Thus, $X = 0$ when $A = 0$. Similarly, we can see that $X = 0$ when $B = 0$. Lastly when potentials at both A and B are 5V, so that both the diodes are unbiased and there will be no current through R and the potential at X will be equal to 5V. Thus, $X = 1$ when A and B both are 1.

Fig. 32.41

NOT gate This has one input and one output. The output is the inverse of the input. When the input A is 1, the output X will be 0 and *vice-versa.* The truth table for 'NOT' gate is given below.

Table 32.9

A	X
0	1
1	0

Note *A NOT gate cannot be constructed with diodes. Transistor is used for realisation of a NOT gate, but at this stage students do not require it. A NOT gate is written as* $X = \bar{A}$.

NAND gate The function, X = NOT (A and B) of two logical variables A and B is called NAND function. It is written as $X = A$ NAND B. It is also written as,

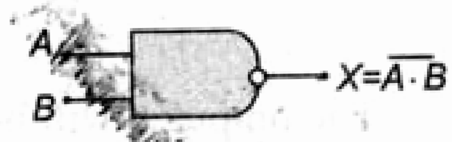


Fig. 32.42

$$X = \overline{A \cdot B} \quad \text{or} \quad X = \overline{AB}$$

The truth table of a 'NAND' gate is given.

Table 32.10

A	B	$A \cdot B$	$X = \overline{A \cdot B}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

NOR gate The function X = NOT (A OR B) is called a NOR function and is written as $X = A$ NOR B. It is also written as, $X = \overline{A + B}$. The truth table for a NOR gate is given below.

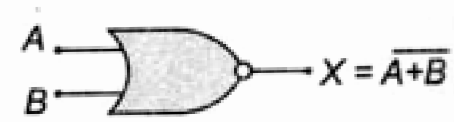


Fig. 32.43

Table 32.11

A	B	$A + B$	$X = \overline{A + B}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

XOR gate It is also called the exclusive OR function. It is a function of two logical variables A and B which evaluates to 1 if one of two variables is 0 and the other is 1. The function is zero, if both the variables are 0 or 1.

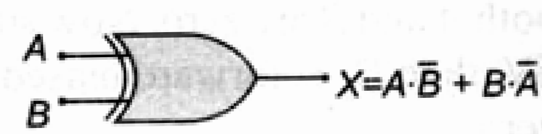


Fig. 32.44

$$A \text{ XOR } B = A \cdot \bar{B} + \bar{A} \cdot B$$

The truth table for XOR is given below.

Table 32.12

A	B	$\overline{A}$	$\overline{B}$	$A\cdot\overline{B}$	$\overline{A}\cdot B$	$A = A\cdot\overline{B}+\overline{A}\cdot B$
0	0	1	1	0	0	0
0	1	1	0	0	1	1
1	0	0	1	1	0	1
1	1	0	0	0	0	0

Sample Example 32.16 *Construct the truth table for the function X of A and B represented by figure shown here.*

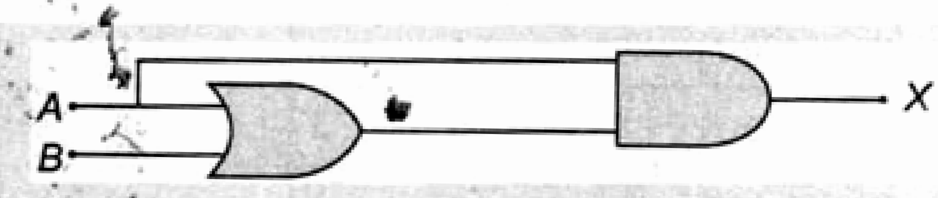


Fig. 32.45*

Solution The output X in terms of the input A and B can be written as, $X = A\cdot(A+B)$

Let us make the truth table corresponding to this function.

Table 32.13

A	B	$A+B$	$X = A\cdot(A+B)$
0	0	0	0
0	1	1	0
1	0	1	1
1	1	1	1

Sample Example 32.17 *Make the output waveform (Y) of the OR gate for the following inputs A and B.*

Table 32.14

Time	A	B
For $t < t_1$	0	0
From t_1 to t_2	1	0
From t_2 to t_3	1	1
From t_3 to t_4	0	1
From t_4 to t_5	0	0
From t_5 to t_6	1	0
For $t > t_6$	0	1

Solution Output value Y corresponding to OR gate is given in the following table.

Table 32.15

Time	A	B	Y = A + B
For $t < t_1$	0	0	0
From t_1 to t_2	1	0	1
From t_2 to t_3	1	1	1
From t_3 to t_4	0	1	1
From t_4 to t_5	0	0	0
From t_5 to t_6	1	0	1
For $t > t_6$	0	1	1

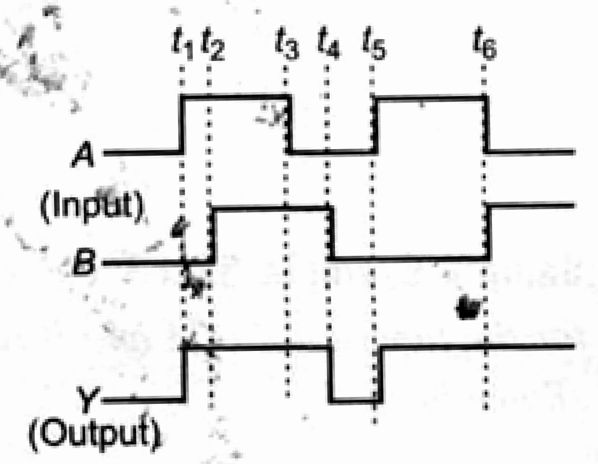


Fig. 32.46

Therefore, the waveform Y will be as shown in the figure.

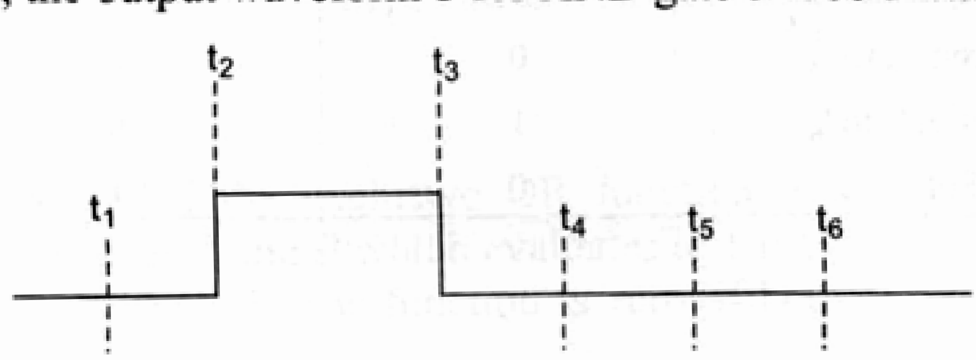
Sample Example 32.18 *Take A and B inputs similar to that in above example. Sketch the output waveform obtained from NAND gate.*

Solution Output value, Y corresponding to AND gate is given in the following table.

Table 32.16

Time	A	B	Y = A · B
For $t < t_1$	0	0	0
From t_1 to t_2	1	0	0
From t_2 to t_3	1	1	1
From t_3 to t_4	0	1	0
From t_4 to t_5	0	0	0
From t_5 to t_6	1	0	0
For $t > t_6$	0	1	0

Based on the above table, the output waveform Y for AND gate can be drawn as in figure 32.47.



Introductory Exercise 32.4

1. Make the output waveform Y of the NAND gate for the following inputs A and B.

Table 32.17

Time	A	B
For $t < t_1$	1	1
From t_1 to t_2	0	0
From t_2 to t_3	0	1
From t_3 to t_4	1	0
From t_4 to t_5	1	1
From t_5 to t_6	0	0
For $t > t_6$	0	1

2. You are given two circuits. Identify the logic operation carried out by the two circuits.

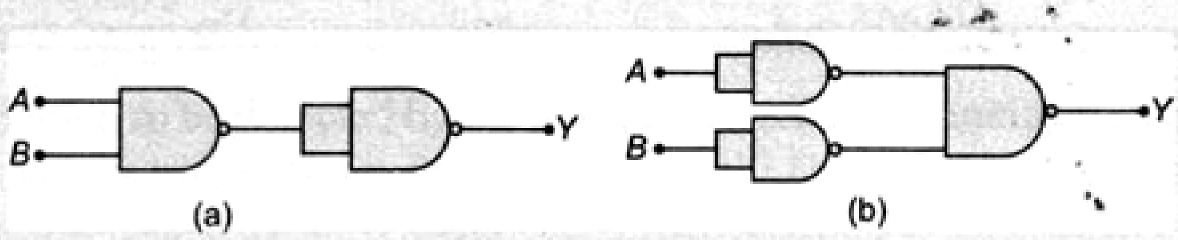


Fig. 32.48

Extra points

1. **Integrated Circuits** The short form of integrated circuit is IC. It is revolutionised the electronics technology. The entire electronic circuit (consisting of many passive components like R and C and active devices like diode and transistor) is fabricated on a small single block (called chip) of a semiconductor. Such circuits are more reliable and less shock proof compared to conventional circuits used before. The chip dimensions are as small as 1 mm × 1 mm or it could be even smaller than this.

   Depending on the nature of input signals, ICs are of two types.
   (i) linear or analogue IC
   (ii) digital IC

   Linear ICs process analogue signals which change over a range of values between a maximum and a minimum. The digital ICs process signals that have only two values. They contain circuits such as logic gates.

   IC is the heart of all computer systems. It is used in almost all electronic devices like, cell phones, televisions, cars etc.

   It was first invented in 1958 by **Jack Kilky** and he was awarded Nobel prize for this in the year 2000. Growth of semiconductor industry is very fast. From current trends it is expected that by 2020 computers will operate at 40 GHz and would be much smaller, more efficient and less expensive than present day computers.

2. **Feedback amplifier and transistor oscillator** In an amplifier, a sinusoidal input is given which gets amplified as an output. Hence, an external input is necessary to sustain AC signal in the output.

   In an oscillator we get AC output without any external input signal. A portion of the output power is returned back (feedback) to the input (in phase) with the starting power. In other words, the output in an oscillator is self sustained.

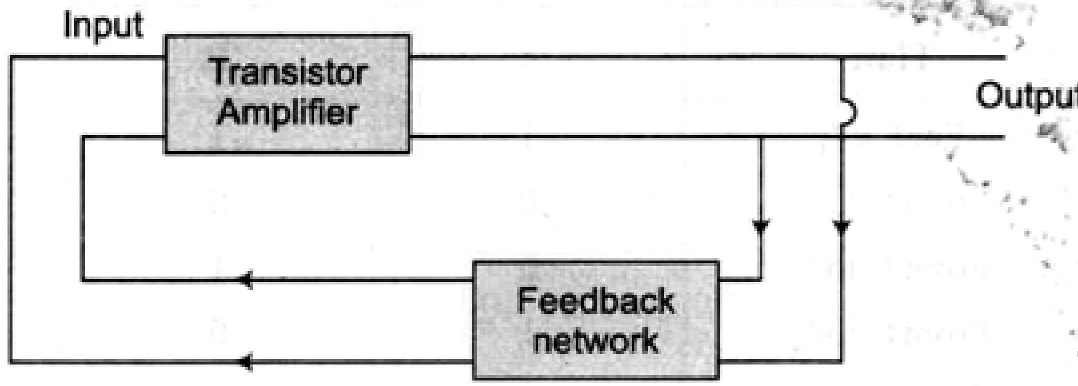


Fig. 32.49 Principle of a transistor amplifier with positive feedback working as an oscillator

3. In transistors, the base region is narrow and lightly doped, otherwise the electrons or holes coming from the input side (say emitter in CE-configuration) will not be able to reach the collector.

Solved Examples

Example 1 *Sn, C, Si and Ge are all group XIV elements. Yet, Sn is a conductor, C is an insulator while Si and Ge are semiconductors. Why ?*

Solution It all depends on energy gap between valence band and conduction band. The energy gap for Sn is 0 eV, for caris 5.4 eV, for Si is 1.1 eV and for Ge is 0.7 eV.

Example 2 *Three photodiodes D_1, D_2 and D_3 are made of semiconductors having band gaps of 2.5 eV, 2 eV and 3 eV respectively. Which one will be able to detect light of wavelength 6000 Å ?*

Solution Energy of incident light

$$E\text{ (in eV)} = \frac{12375}{\lambda\text{ (in Å)}}$$

$$E = \frac{12375}{6000}\text{ eV} \qquad \text{or} \qquad E = 2.06\text{ eV}$$

For the incident radiation to be detected by the photodiode energy of incident radiation should be greater than the band gap. This is true only for D_2. Therefore only D_2 will detect this radiation.

Example 3 *What is the range of energy gap (E_g) in insulators, semiconductors and conductors?*

Solution For insulators $E_g > 3$ eV, for semiconductors, $E_g = 0.2$ eV to 3eV while for conductors (or metals) $E_g = 0$.

Example 4 *n-type extrinsic semiconductor is negatively charged, while p-type extrinsic semiconductor is positively charged. Is this statement true or false?*

Solution False. Intrinsic as well as extrinsic semiconductors are electrically neutral.

Example 5 *What is resistance of an intrinsic semiconductor at 0K?*

Solution At 0K number of holes (or number of free electrons) in an intrinsic semiconductor become zero. Therefore resistance of an intrinsic semiconductor becomes infinite at 0 K.

Example 6 *Consider an amplifier circuit using a transistor. The output power is several times greater than the input power. Where does the extra power come from?*

Solution The extra power required for amplified output is obtained from the DC source.

Example 7 *A piece of copper and the other of germanium are cooled from the room temperature to 80 K. What will happen to their resistance?*

Solution Copper is conductor and germanium is semiconductor. With decrease in temperature resistance of a conductor decreases and that of semiconductor increases. Therefore resistance of copper will decrease and that of semiconductor will increase.

Example 8 *A transistor has three impurity regions, emitter, base and collector. Arrange them in order of increasing doping levels.*

Solution The order of increasing doping levels is

base > collector > emitter.

Example 9 *Name two gates which can be used repeatedly to produce all the basic or complicated gates.*

Solution NAND and NOR gates can be used repeatedly to produce all the basic or complicated gates. This is why these gates are called digital building blocks.

Example 10 *A change of 8.0 mA in the emitter current brings a change of 7.9 mA in the collector current. How much change in the base current is required to have the same change 7.9 mA in the collector current? Find the values of α and β.*

Solution We know that,

$$i_e = i_b + i_c$$

$$\therefore \quad \Delta i_e = \Delta i_b + \Delta i_c$$

$$\text{or} \quad \Delta i_b = \Delta i_e - \Delta i_c$$

Substituting the given values of the question,

We have

$$\Delta i_b = (8.0 - 7.9)\,\text{mA} = 0.1\,\text{mA}$$

Hence, a change of 0.1 mA in the base current is required to have a change of 7.9 mA in the collector current.

Further,

$$\alpha = \frac{i_c}{i_e} \quad \text{or} \quad \frac{\Delta i_c}{\Delta i_e}$$

$$= \frac{7.9}{8.0} = 0.99$$ **Ans.**

$$\beta = \frac{i_c}{i_b} \quad \text{or} \quad \frac{\Delta i_c}{\Delta i_b}$$

$$= \frac{7.9}{0.1} = 79$$ **Ans.**

Example 11 *A transistor is used in common-emitter mode in an amplifier circuit. When a signal of 20 mV is added to the base-emitter voltage, the base current changes by 20 μA and the collector current changes by 2 mA. The load resistance is 5 kΩ. Calculate (a) the factor β (b) the input resistance R_{in} (c) the transconductance and (d) the voltage gain.*

Solution (a) **Factor β**

$$\beta = \frac{\Delta i_c}{\Delta i_b}$$

Substituting the given values, we have

$$\beta = \frac{2\times10^{-3}}{20\times10^{-6}} = 100$$ **Ans.**

(b) **Input Resistance R_{in}**

$$R_{in} = \frac{\Delta V_{BE}}{\Delta i_b}$$

$$= \frac{20\times10^{-3}}{20\times10^{-6}} = 10^3\ \Omega$$

$$= 1\ \text{k}\Omega$$ **Ans.**

(c) **Transconductance g_m**

$$g_m = \frac{\Delta i_c}{\Delta V_{BE}} = \frac{2\times10^{-3}}{20\times10^{-3}}$$

$$= 0.1\ \text{mho}$$ **Ans.**

(d) **Voltage Gain A_V**

$$A_V = \beta\left(\frac{R_{\text{out}}}{R_{\text{in}}}\right)$$

Substituting the values we have,

$$A_V = (100)\left(\frac{5\times10^3}{1\times10^3}\right)$$

$$= 500$$ **Ans.**

Example 12 *An n-p-n transistor is connected in common emitter configuration in which collector supply is 8V and the voltage drop across the load resistance of 800 Ω connected in the collector circuit is 0.8 V. If current amplification factor is 25, determine collector-emitter voltage and base current. If the internal resistance of the transistor is 200 Ω, calculate the voltage gain and the power gain.*

Solution The corresponding circuit is shown in figure.

Voltage across $R_L = i_c R_L = 0.8$ V (given)

$$\therefore \quad i_c = \frac{0.8}{R_L} = \frac{0.8}{800}\ \text{A} = 1\ \text{mA}$$

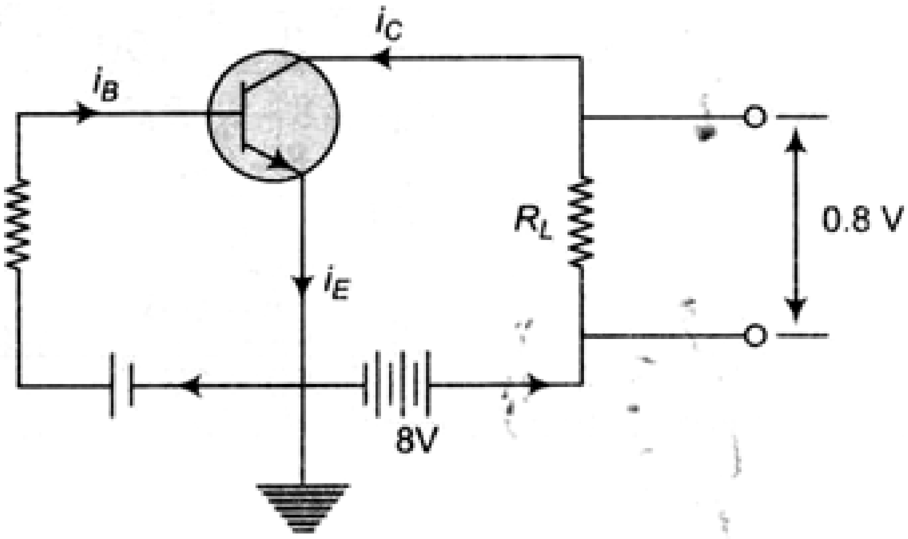


Fig. 32.50

Further it is given that,

$$\beta = 25 = \frac{i_c}{i_b}$$

$$\therefore \quad i_b = \frac{i_c}{25} = 40\ \mu\text{A}$$ **Ans.**

Collector-Emitter Voltage (V_{CE})

Applying Kirchhoff's second law in emitter-collector circuit, we have

$$V_{CE} = (8 - 0.8)\ \text{V} = 7.2\ \text{V}$$ **Ans.**

Voltage gain (A_V)

Voltage gain, $$A_V = \beta\left(\frac{R_{\text{out}}}{R_{\text{in}}}\right)$$

or $$A_V = 25\left(\frac{800}{200}\right) = 100$$ **Ans.**

Power gain

$$\text{Power gain} = \beta^2\left(\frac{R_{\text{out}}}{R_{\text{in}}}\right) = (25)^2\left(\frac{800}{200}\right) = 2500$$ **Ans.**

Note *Kirchhoff's laws can be applied in a transistor circuit in the similar manner as is done in normal circuits.*

Example 13 *An n-p-n transistor in a common emitter mode is used as a simple voltage amplifier with a collector current of 4 mA. The positive terminal of a 8 V battery is connected to the collector through a load resistance R_L and to the base through a resistance R_B. The collector-emitter voltage $V_{CE} = 4V$, the base-emitter voltage $V_{BE} = 0.6\ V$ and the current amplification factor $\beta = 100$. Calculate the values of R_L and R_B.*

Solution Given, $i_c = 4$ mA

Applying Kirchhoff's second law in loop 1, we have

$$V_{CE} = 8 - i_c R_L$$

$$\therefore \quad R_L = \frac{8 - V_{CE}}{i_c} = \frac{8-4}{4\times 10^{-3}}$$

$$= 1000\ \Omega$$

$$= 1\ \text{k}\Omega$$ **Ans.**

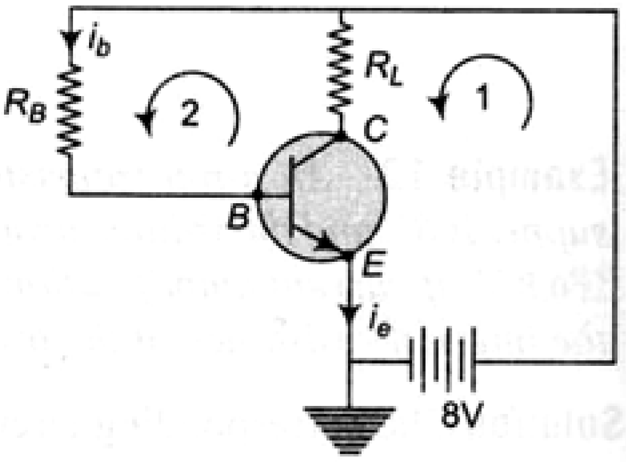


Fig. 32.51

Further, $$\beta = \frac{i_c}{i_b}$$

$$\therefore \quad i_b = \frac{i_c}{\beta} = \frac{4\times 10^{-3}}{100}\ \text{A} = 40\ \mu\text{A}$$

Now, $$V_{BE} = 8 - i_b R_B$$

$$\therefore \quad R_B = \frac{8 - V_{BE}}{i_b}$$

$$= \frac{8 - 0.6}{40\times 10^{-6}} = 1.85\times 10^5\ \Omega$$ **Ans.**

Example 14 *Let $X = A \cdot \overline{BC}$. Evaluate X for*

(a) $A = 1, B = 0, C = 1$,

(b) $A = B = C = 1$ and

(c) $A = B = C = 0$.

Solution (a) When, $A = 1, B = 0$ and $C = 1$

$$BC = 0$$

∴ $$\overline{BC} = 1$$

or $$A \cdot \overline{BC} = 1$$ **Ans.**

(b) When, $$A = B = C = 1$$

Then, $$BC = 1$$

or $$\overline{BC} = 0$$

∴ $$A \cdot \overline{BC} = 0$$ **Ans.**

(c) When, $$A = B = C = 0$$

Then, $$BC = 0$$

∴ $$\overline{BC} = 1$$

or $$A \cdot \overline{BC} = 0$$ **Ans.**

Example 15 *Show that given circuit (a) acts as OR gate while the given circuit (b) acts as AND gate.*

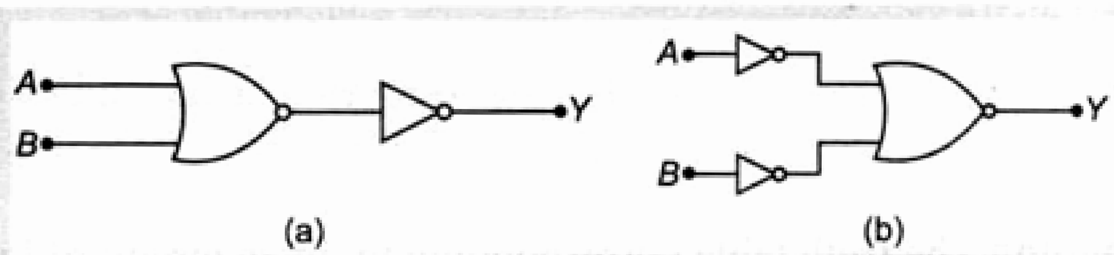


Fig. 32.52

Solution (a) The first gate is NOR gate then NOT gate

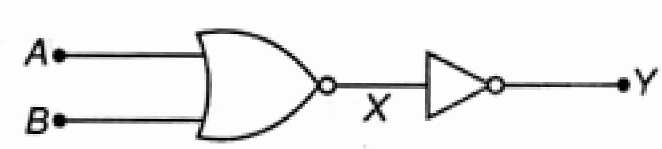


Fig. 32.53

Thus, $X = \overline{A + B}$ and $Y = \overline{X}$

The truth table can be made as under.7

Table 32.18

A	B	A + B	$X = \overline{A+B}$	$Y = \overline{X}$
1	0	1	0	1
0	1	1	0	1
1	1	1	0	1
0	0	0	1	0

The last column of Y is similar to third column of $A + B$ which is the truth table corresponding to OR gate.

(b) First two gates are NOT gates and the last gate is NOR gate.

Thus, $C = \overline{A}$, $D = \overline{B}$ and $X = \overline{C + D}$

The truth table corresponding to this can be made as under.

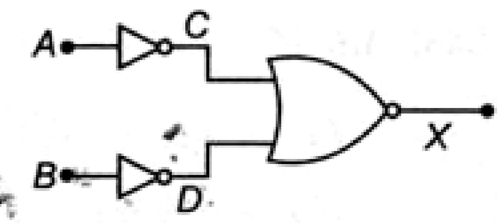


Fig. 32.54

Table 32.19

A	B	$A \cdot B$	$C = \overline{A}$	$D = \overline{B}$	$C + D$	$X = \overline{C + D}$
1	0	0	0	1	1	0
0	1	0	1	0	1	0
1	1	1	0	0	0	1
0	0	0	1	1	1	0

The last column of X is similar to third column of $A \cdot B$, which is the truth table corresponding to AND gate.

Example 16 *Write the truth table for the circuit given in figure consisting of NOR gates. identify the logic operations (OR, AND, NOT) performed by the the circuits.*

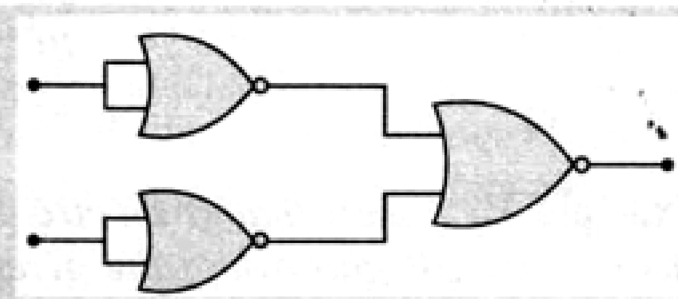


Fig. 32.55

Solution The truth table corresponding to given circuit of logic gates is

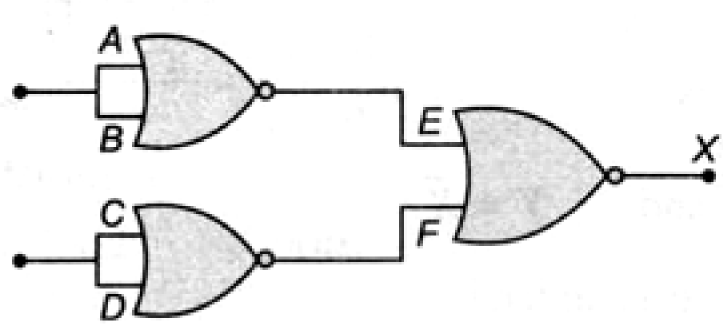


Fig. 32.56

Table 32.20

A	B	$A + B$	$E = \overline{A + B}$	C	D	$C + D$	$F = \overline{C + D}$	E + F	$X = \overline{E + F}$
1	1	1	0	1	1	1	0	0	1
0	0	0	1	0	0	0	1	1	0

Corresponding to input columns of A, B, C and D we can see that output column of X is of AND gate,

$$X = A + B + C + D$$

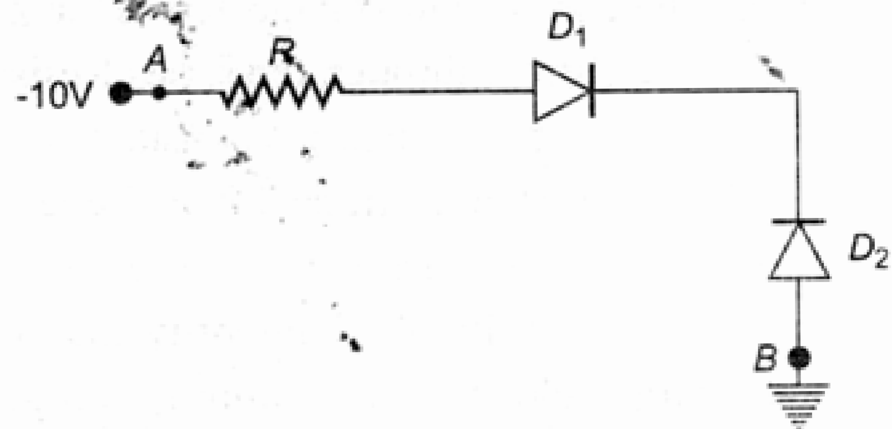
EXERCISES

Objective Questions

Single Correct Option

1. The conductivity of a semiconductor increases with increase in temperature because
   (a) number density of free current carriers increases.
   (b) relaxation time increases
   (c) both number density of carriers and relaxation time decreases but effect of decrease in relaxation time is much less than increase in number density.
   (d) number density of current carriers increases, relaxation time decreases but effect of decrease in relaxation time is much less than increase in number density

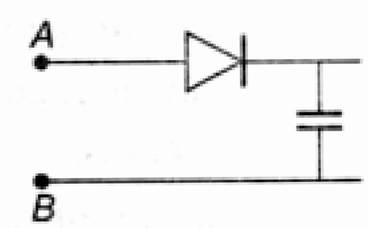
2. In figure, assuming the diodes to be ideal,



   (a) D_1 is forward biased and D_2 is reverse biased and hence current flows from A to B.
   (b) D_2 is forward biased and D_1 is reverse biased and hence no current flows from B to A and *vice-versa*.
   (c) D_1 and D_2 are both forward biased and hence current flows from A to B.
   (d) D_1 and D_2 are both reverse biased and hence no current flows from A to B and *vice-versa*.

3. Hole is
   (a) an anti-particle of electron
   (b) a vacancy created when an electron leaves a covalent bond
   (c) absence of free electrons
   (d) an artificially created particle

4. A 220 V AC. supply is connected between points A and B. What will be the potential difference V across the capacitor?



   (a) 220V (b) 110V
   (c) 0V (d) $220\sqrt{2}$ V

More than One Correct Option

5. When an electric field is applied across a semiconductor,
   (a) electrons move from lower energy level to higher energy level in the conduction band.
   (b) electrons move from higher energy level to lower energy level in the conduction band.
   (c) holes in the valence band move from higher energy level to lower energy level.
   (d) holes in the valence band move from lower energy level to higher energy level.

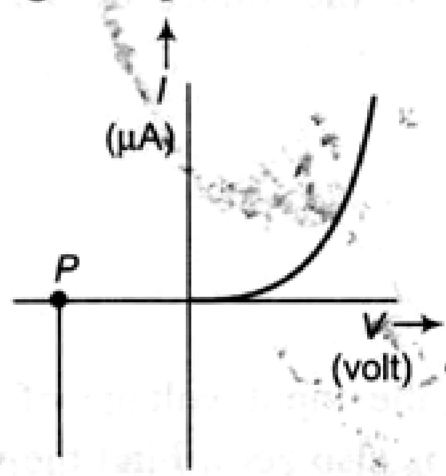
6. Consider an *n-p-n* transistor with its base-emitter junction forward biased and collector base junction reverse biased. Which of the following statements are true?
   (a) Electrons crossover from emitter to collector.
   (b) Holes move from base to collector.
   (c) Electrons move from emitter to base.
   (d) Electrons from emitter move out of base without going to the collector.

7. In a n-p-n transistor circuit, the collector current is 10 mA. If 95 per cent of the electrons emitted reach the collector, which of the following statements are true?
   (a) The emitter current will be 8 mA.
   (b) The emitter current will be 10.53 mA.
   (c) The base current will be 0.53 mA.
   (d) The base current will be 2 mA.
8. In the depletion region of a diode
   (a) there are no mobile charges
   (b) equal number of holes and electrons exist, making the region neutral
   (c) recombination of holes and electrons has taken place
   (d) immobile charged ions exist.
9. What happens during regulation action of a Zener diode?
   (a) The current and voltage across the Zener remains fixed.
   (b) The current through the series Resistance (R) changes.
   (c) The Zener resistance is constant.
   (d) The resistance offered by the Zener changes.
10. The breakdown in a reverse biased p-n junction diode is more likely to occur due to
   (a) large velocity of the minority charge carriers if the doping concentration is small
   (b) large velocity of the minority charge carriers if the doping concentration is large
   (c) strong electric field in a depletion region if the doping concentration is small
   (d) strong electric field in the depletion region if the doping concentration is large.

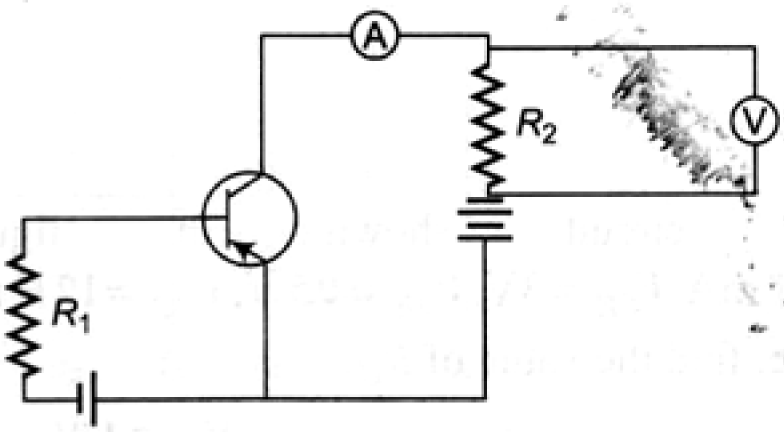
Subjective Questions

11. Can the potential barrier across a p-n junction be measured by simply connecting a voltmeter across the junction?
12. Two car garages have a common gate which needs to open automatically when a car enters either of the garages or cars enter both. Devise a circuit that resembles this situation using diodes for this situation.
13. Two amplifiers are connected one after the other in series (cascaded). The first amplifier has a voltage gain of 10 and the second has a voltage gain of 20. If the input signal is 0.01 V, calculate the output AC signal.
14. A p-n photodiode is fabricated from a semiconductor with band-gap of 2.8 eV. Can it detect a wavelength of 6000 nm?
15. The amplifiers X, Y and Z are connected in series. If the voltage gains of X, Y and Z are 10, 20 and 30, respectively and the input signal is 1 mV peak value, then what is the output signal voltage (peak value)
   (i) if DC supply voltage is 10V?
   (ii) if DC supply voltage is 5V?

16. (i) Name the type of a diode whose characteristics are shown in figure.
(ii) What does the point P in figure represent?

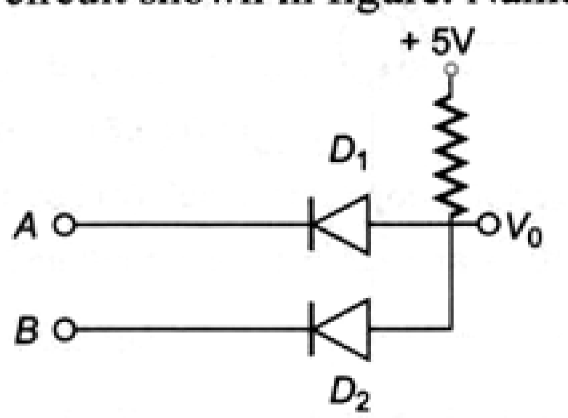


17. If the resistance R_1 is increased, how will the readings of the ammeter and voltmeter change?

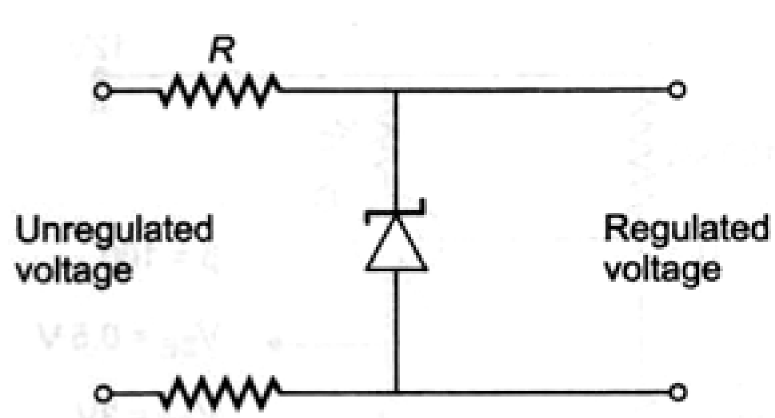


18. How would you set up a circuit to obtain NOT gate using a transistor?

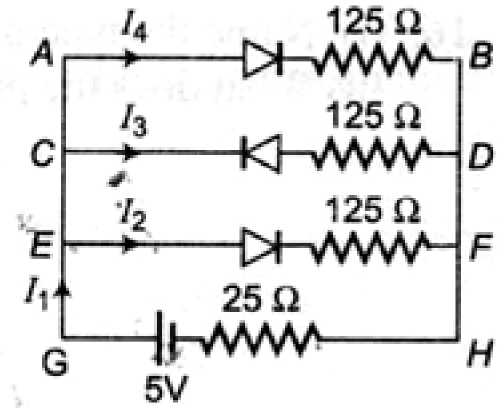
19. Write the truth table for the circuit shown in figure. Name the gate that the circuit resembles.



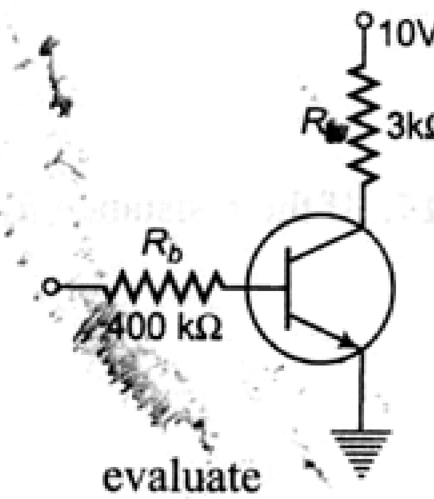
20. A Zener of power rating 1 W is to be used as a voltage regulator. If Zener has a breakdown of 5V and it has to regulate voltage which fluctuated between 3V and 7V, what should be the value of R for safe operation.



21. If each diode in figure has a forward bias resistance of 25 Ω and infinite resistance in reverse bias, what will be the values of the current I_1, I_2, I_3 and I_4?

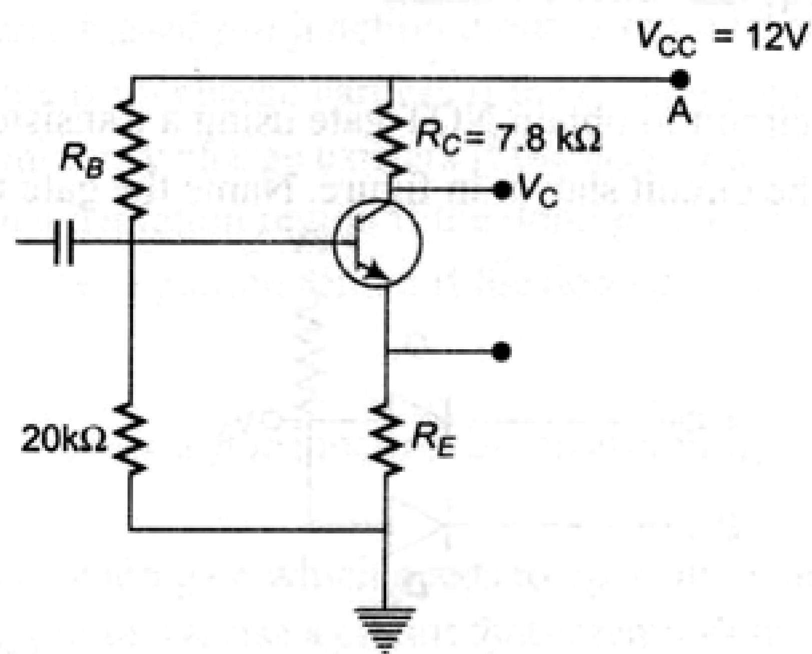


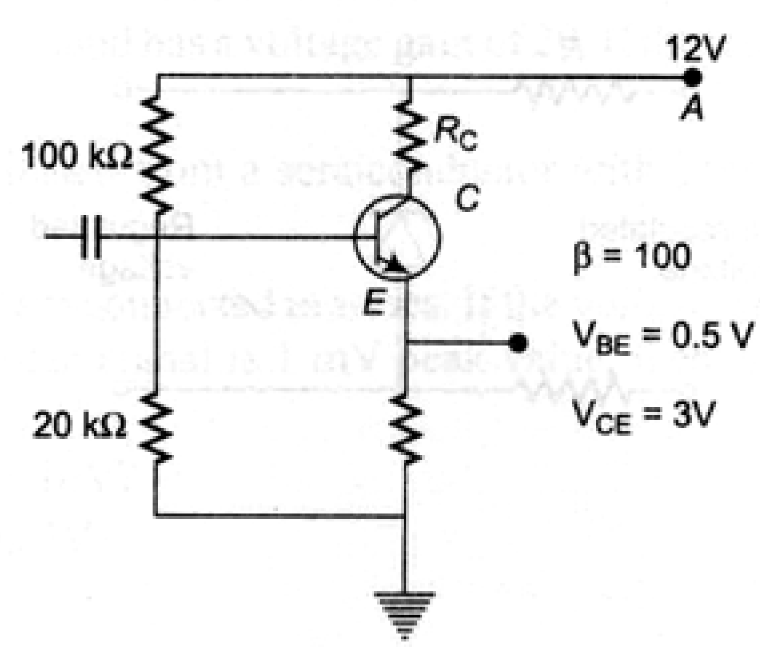
22. In the circuit shown in figure when the input voltage of the base resistance is 10V, V_{be} is zero and V_{ce} is also zero. Find the values of I_b, I_c and β.



23. For the transistor circuit shown in figure, evaluate V_E, R_B and R_E. Given $I_C = 1$ mA, $V_{CE} = 3$V, $V_{BE} = 0.5$ V, $V_{CC} = 12V$ and $\beta = 100$

24. In the circuit shown in figure, find the value of R_C.





ANSWERS

Introductory Exercise 32.1

1. (c)

Introductory Exercise 32.2

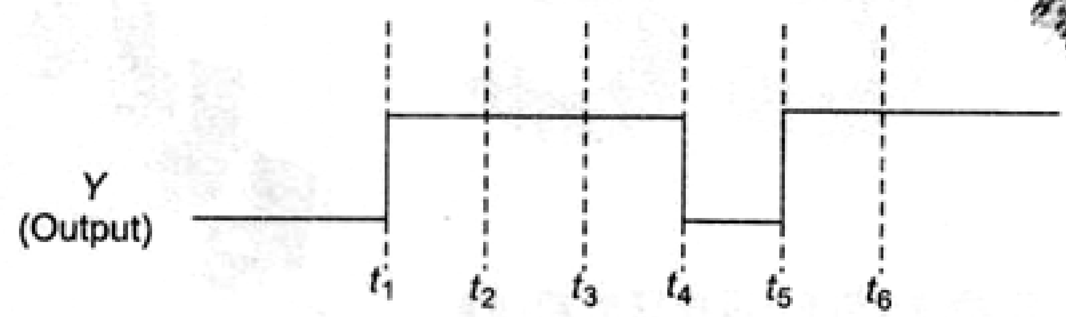
1. (c) 2. (c)

Introductory Exercise 32.3

1. (b,c) 2. (c) 3. $V_i = 0.01$ V, $i_b = 10\,\mu$ A

Introductory Exercise 32.4

1.



2. (a) AND (b) OR

Exercises

1. (d) 2. (b) 3. (b) 4. (d) 5. (a,c) 6. (a,c) 7. (b,c) 8. (a,b,d) 9. (b,d) 10. (a,d)

11. No 12. OR gate 13. 2V 14. No 15. (i) 6V (ii) 5 V

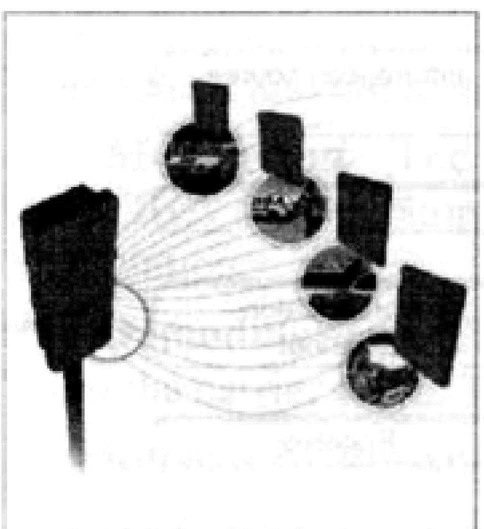
16. (i) Zener junction diode and solar cell (ii) Zener breakdown voltage

17. Both readings will decrease 18. See the hints 19. AND gate 20. 10 Ω

21. $I_1 = 0.05$A, $I_2 = 0.025$A, $I_3 = 0$, $I_4 = 0.025$A

22. $I_b = 25\,\mu$A, $I_c = 3.33$ mA, $\beta = 133$ 23. $V_E = 1.2$ V, $R_B = 108$ kΩ, $R_E = 1.2$ kΩ

24. 0.56 kΩ



33

COMMUNICATION SYSTEM

Chapter Contents

33.1 Introduction

Communication refers to the transfer of information or message from one point to another point. In modern communication systems, the information is first converted into electrical signals and then sent electronically. This has the advantage of speed, reliability and possibility of communicating over long distances. We are using these every day such as telephones, TV and radio transmission, satellite communication etc. Historically, long distance communication started with the advent of telegraphy in early nineteenth century. The milestone in trans-atlantic radio transmission in 1901 is credited to **Marconi.** However, the concept of radio transmission was first demonstrated by Indian physicist **JC Bose**. Satellite communication started in 1962 with the launching of **Telstar** satellite. The first geostationary satellite **Early Bird** was launched in 1965. Around 1970, optical fibre communication entered in USA, Europe and Japan. The basic units of any communication systems are shown in Fig. 33.1

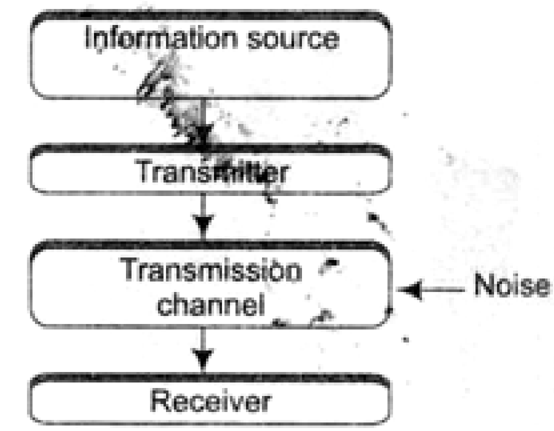


Fig. 33.1. Block diagram of communication system

The transmitter is located at one place. The receiver is located at some other place. Transmission channel connects the transmitter and the receiver. A channel may be in the form of wires or cables or it may be wireless. Transmitter converts message signals produced by the source of information into a form suitable for transmission through the channel.

In any communication system a non-electrical signal (like voice signal) is first converted into an electrical signal by a device called **transducer.** Most of the speech or information signal cannot be directly transmitted to long distances. For this an intermediate step of **modulation** is necessary in which the information signal is loaded or superimposed on a high frequency wave which acts as a carrier wave.

• Important Point

1. There are basically two communication modes : point to point and broadcast.

   Point to point In this mode, communication takes place between a single receiver and transmitter. For example : telephonic call between two persons is a point to point communication.

   Broadcast In this mode, there are a large number of receivers corresponding to a single transmitter. Radio and television are examples of this type of communication.

33.2 Different Terms Used in Communication System

Following basic terminology is used in any communication system. Now let us discuss them in detail.

Electrical Transducer As discussed earlier also a transducer converts a non-electrical signal (like a voice signal) into an electrical signal.

Signal Any information in electrical form suitable for transmission is called a signal. Signals can be either analog or digital. Analog signals are continuous variations of voltage or current. Sine functions of time are fundamental analog signal. Digital signals are those which can take only discrete values. Binary system is extensively used in digital electronics. In binary system 0 corresponds to low level and 1 corresponds to high level of voltage or current.

Noise Unwanted signals which are mixed with the main signals are referred as noise.

Transmitter A transmitter makes the incoming message signal suitable for transmission through a channel.

Receiver The signal sent by transmitter through channels is received by the receiver.

Attenuation When the signal propagates from transmitter to receiver it loses some strength and it becomes weaker. This is known as attenuation.

Amplification The signal received by receiver is weaker than the signal sent by transmitter (due to attenuation). The amplitude of this signal is increased by an amplifier (in chapter-20, we have learned that a transistor can be used as an amplifier). The energy needed for additional signal is obtained from a DC power source.

Range This is the largest distance from the transmitter up to which signal can be received with sufficient strength.

Bandwidth This is the width of the range of frequencies that an electronic signal uses on a given transmission medium. It is expressed in terms of the difference between the highest frequency signal component and the lowest frequency signal component.

Modulation The low frequency message signals cannot be transmitted to long distances by their own. They are superimposed on a high frequency wave (also called a carrier wave). This process is called modulation.

Demodulation This is reverse process of modulation. At the receiver end information is retrieved from the carrier wave. This process is known as demodulation.

Repeater Repeaters are used to extend the range of a communication system. It is a combination of a receiver and a transmitter. Receiver (or a repeater) first receives the original signals, then amplifies it and retransmits it to other places (sometimes with a different carrier frequency).

33.3 Bandwidth of Signals

Message signals (such as voice, picture or computer data) have different range of frequencies. The type of communication system depends on the bandwidth (discussed in the above article). Some frequency range and their corresponding bandwidth are given below.

(i) **For telephonic communication** A bandwidth of 2800 Hz is required. As, the signals range from 300 Hz to 3100 Hz and their difference is 2800 Hz.

(ii) **For music channels** A bandwidth of approximately 20 kHz is required. Because, the audible range of frequencies extends from 20 Hz to 20 kHz and their difference is approximately 20 kHz.

(iii) **For TV signals** A TV signal consists both audio and video. A bandwidth of approximately 6 MHz is required for its transmission.

33.4 Bandwidth of Transmission Medium

Like bandwidths of message signals different types of transmission media offer different bandwidths. Commonly used transmission media are optical fibres, free space and wire. The International Telecommunication Union (ITU) administers the present system of frequency allocations.

(i) Coaxial cables offers a bandwidth of approximately 750 MHz.

(ii) Optical fibres offers a frequency range of 1 THz to 1000 THz.

(iii) Communication through free space (using radio waves) offers a bandwidth varying from few hundreds of kHz to a few GHz. These frequencies are further subdivided for various services as given in following table.

Table 33.1

S.No.	Service	Frequency Bands
1.	AM radio broadcast	540 – 1600 kHz
2.	FM radio broadcast	88 – 108 MHz
3.	Television	54 – 890 MHz
4.	Cellular Phones	840 – 935 MHz
5.	Satellite communication	3.7 – 6.425 GHz

33.5 Propagation of Electromagnetic Waves or Communication Channels

Physical medium through which signals propagate between transmitting and receiving station is called the communication channel. There are basically two types of communications.

(i) Space communication

(ii) Line communication

As per syllabus we are here discussing only space communication.

Space Communication

Consider two friends playing with a ball in a closed room. One friend throws the ball (transmitter) and the other receives the ball (receiver). There are three ways in which the ball can be sent to the receiver.

(a) By rolling it along the ground

(b) Throwing directly and

(c) Throwing towards roof and then reflected towards the receiver. Similarly, there are three ways of transmitting an information from one place to the other using physical space around the earth.

(a) Along the ground (ground waves).

(b) Directly in a straight line through intervening topographic space (space wave, or tropospheric wave or surface wave) and

(c) Upwards in sky followed by reflection from the ionosphere (sky wave).

These three modes are discussed below.

(i) **Ground Wave or Surface Wave Propagation** Information can be transmitted through this mode when the transmitting and receiving antenna are close to the surface of the earth.

The radio waves which progress along the surface of the earth are called ground waves or surface waves. These waves are vertically polarised in order to prevent short-circuiting of the electric component. The electrical field due to the wave induce charges in the earth's surface as shown in figure. As the wave travels, the induced charges in the earth also travel along it. This constitutes a current in the earth's surface. As the ground wave passes over the surface of the earth, it is weakened as a result of energy absorbed by the earth. Due to these losses the ground waves are not suited for very long range communication. Further these losses are higher for high frequency. Hence, ground wave propagation can be sustained only at low frequencies (500 kHz to 1500 kHz).

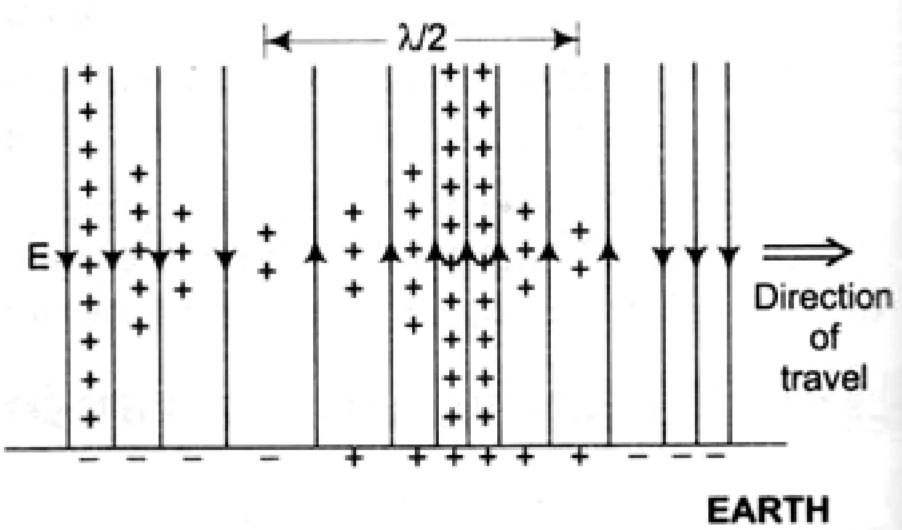


Fig. 33.2. Vertically polarised wave travelling over the surface of the earth. The solid lines represent the electric field (E) of the electromagnetic wave.

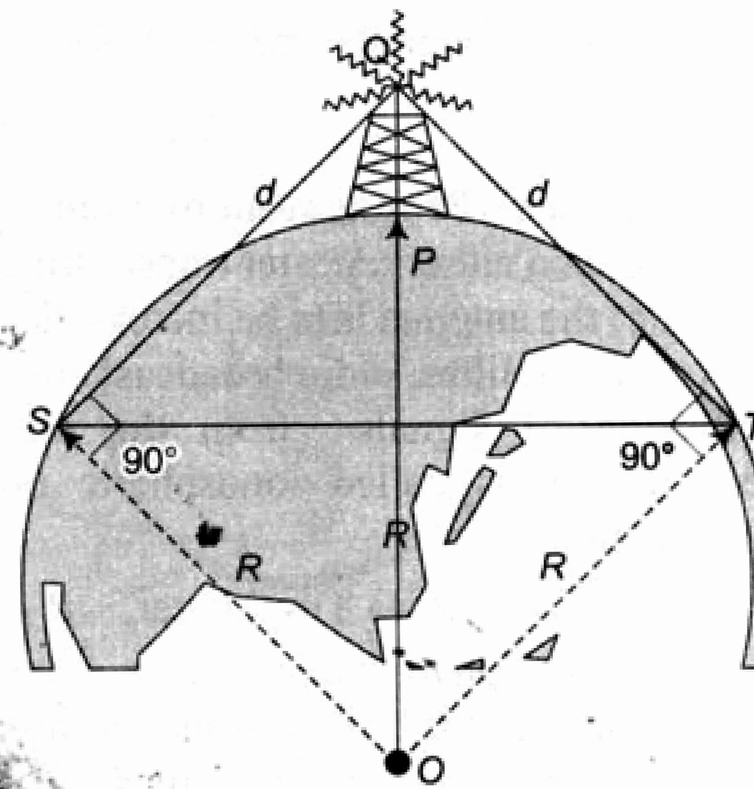


Fig. 33.3

Space Wave Propagation or Tropospheric Wave Propagation Television signal (80 MHz to 200 MHz) waves neither follow the curvature of the earth nor get reflected by ionosphere. Surface wave or sky wave cannot be employed in television communication. Television signals can be reflected from geostationary satellite or tall receiver antennas.

Height of Transmitting Antenna The transmitted waves, travelling in a straight line, directly reach the receiver end and are then picked up by the receiving antenna as shown in figure. Due to finite curvature of the earth, such waves cannot be seen beyond the tangent points S and T.

Suppose h is the height of antenna PQ. Let R be the radius of earth.

Further, let $QT = QS = d$, $PQ = h$, $OQ = R + h$

From the right angled triangle OQT,

$$OQ^2 = OT^2 + QT^2$$

$$\therefore \quad (R + h)^2 = R^2 + d^2$$

$$\therefore \quad d^2 = h^2 + 2Rh$$

Since, $R >> h$, $h^2 + 2Rh \approx 2Rh$

$$\therefore \quad d \approx \sqrt{2Rh}$$

This distance is of the order of 40 km. Area covered for TV transmission

$$A = \pi d^2 = 2\pi Rh$$

If height of receiving antenna is also given in the question then the maximum line of sight distance d_M is given by

$$d_M = \sqrt{2Rh_T} + \sqrt{2Rh_R}$$

where, h_T = height of transmitting antenna

and h_R = height of receiving antenna

Further population covered = population density × area covered.

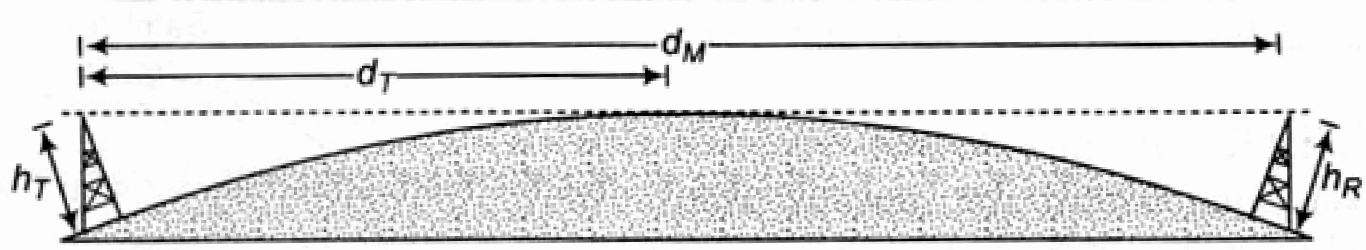


Fig. 33.4 Line of sight communication by space waves

Sample Example 33.1 *A TV tower has a height of 60 m. What is the maximum distance and area up to which TV transmission can be received? (Take radius of earth as 6.4×10^6 m.)*

Solution (i) Distance

$$d = \sqrt{2Rh}$$

$$= \sqrt{2 \times 6.4 \times 10^6 \times 60} \text{ m} = 27.7 \text{ km}$$ **Ans.**

(ii) Area covered $= \pi d^2 = 2\pi Rh$

$$(2\times 3.14\times 6.4\times 10^6 \times 60)\ \text{m}^2 = 2411\ \text{km}^2$$ **Ans.**

Sky Wave Propagation or Ionospheric Propagation If one wishes to send signals at far away stations, then either repeater transmitting stations are necessary or height of the antenna is to be increased. However much before the advent of satellites, radio broadcast covered long distances by the reflection of signals from the ionosphere. This mode of transmission is called ionospheric propagation or sky wave propagation.

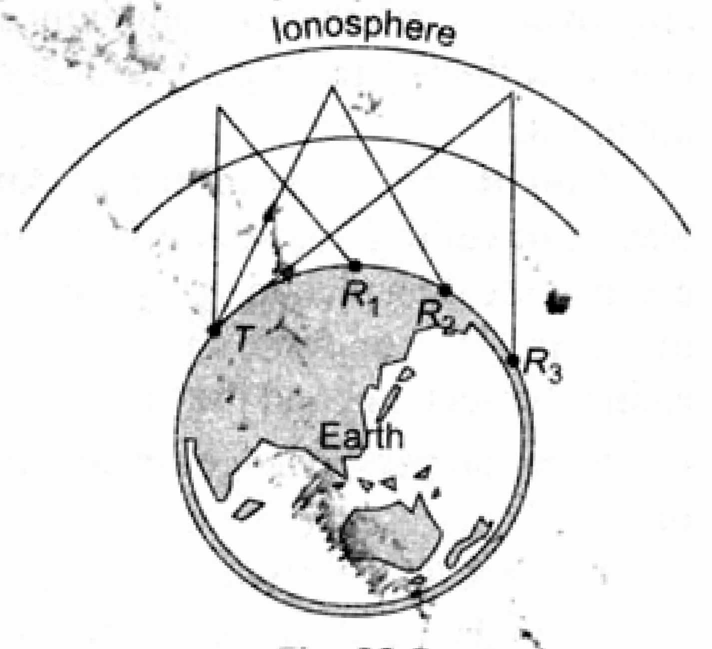


Fig. 33.5

$T \rightarrow$ Transmitter, $R \rightarrow$ Receiver

The ionosphere extends from a height of 80 km to 300 km. The refractive index of ionosphere is less than its free space value. That is, it behaves as a rare medium. As we go deep into the ionosphere, the refractive index keeps on decreasing. The bending of beam (away from the normal) will continue till it reaches critical angle after which it will be reflected back. The different points on earth receive signals reflected from different depths of the ionosphere. There is a critical frequency f_c (5 to 100 MHz) beyond which the waves cross the ionosphere and do not return back to earth.

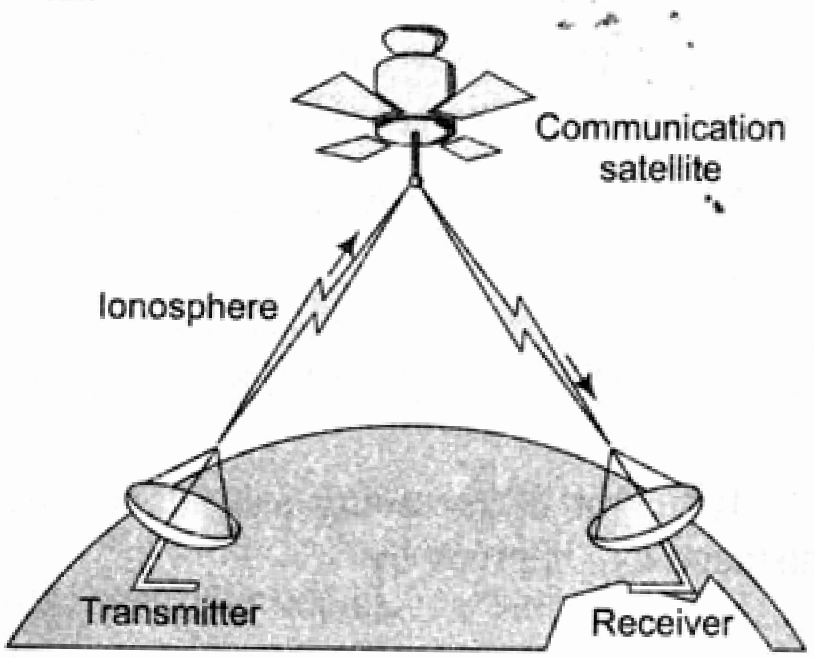


Fig. 33.6 Principle of satellite communication

Satellite Communication Long distance communication beyond 10 to 20 MHz was not possible before 1960 because all the three modes of communication discussed above failed (ground waves due to conduction losses, space wave due to limited line of sight and sky wave due to the penetration of the ionosphere by the high frequencies beyond f_c), satellite communication made this possible.

The basic principle of satellite communication is shown in figure. A communication satellite is a spacecraft placed in an orbit around the earth. The frequencies used in satellite communication lie in UHF/microwave regions. These waves can cross the ionosphere and reach the satellite.

For steady, reliable transmission and reception it is preferred that satellite should be geostationary. A geostationary satellite is one that appears to be stationary relative to the earth. It has a circular orbit lying in the equatorial plane of the earth at an approximate height of 36,000 km. Its time period is 24 hours.

If we use three geostationary satellites placed at the vertices of an equilateral triangle as shown in figure. The entire earth can be covered by the communication network.

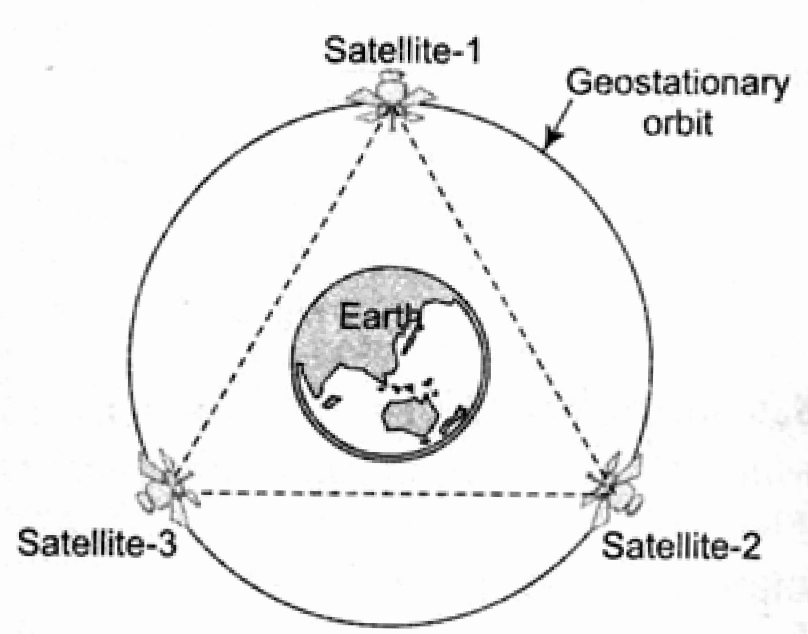


Fig. 33.7