SEMESTER-TWO

PERIOD-4

P12CH4

TOPIC 4

Alternating Current (AC) and Electronics

4.1 ALTERNATING CURRENT

Alternating current *is that current which continuously varies in magnitude and periodically reverses its direction.* The same is true of alternating voltage.

Symbol of ac source

Note that polarity is not marked on ac source.

During one cycle, the current (or voltage) first rises from zero to maximum in one direction, falls to zero, then becomes maximum in the reverse direction and again falls to zero.

4.2 AVERAGE VALUE OF AC OVER HALF CYCLE

Average or mean value of alternating current over half cycle *is that steady current which will send the same amount of charge in a circuit in the time of half cycle* $\left(i.e., \frac{T}{2}\right)$ *as is sent by the given alternating current in the same circuit in the same time* $\left(i.e., \frac{T}{2}\right)$.

Let the alternating current be represented by $i = i_m \sin \omega t$.

Mean value of ac, $I_{\text{mean}} = \frac{2}{\pi} i_m = \mathbf{0.637}\ \boldsymbol{i_m}$ or $\boxed{I_{\text{mean}} = 63.7\%\ i_m}$

So, the mean value of alternating current for half cycle is 0.637 times the peak value of ac. [The same is true of the alternating voltage.]

4.3 ROOT MEAN SQUARE VALUE AND PEAK VALUE OF ALTERNATING CURRENT

Root Mean Square value (rms value) or Virtual value or Effective value of ac *is that steady current which would produce the same heat in given resistance in a given time as is done by the alternating current when passed through the same resistance for the same time. It is represented by* I *or* I_{rms} *or* I_v *or* I_{eff}.

Let the alternating current be represented by $i = i_m \sin \omega t$.

We have,
$$I = \frac{i_m}{\sqrt{2}} = 0.707\ i_m$$

The root mean square or virtual value of alternating current is 0.707 times the peak value of alternating current.

Example 1: *The peak value of an alternating current is 5 A and its frequency is 60 Hz. Find its rms value.*

Solution:
$$I_{\text{rms}} = \frac{i_m}{\sqrt{2}} = \frac{5}{\sqrt{2}}\ \text{A} = \mathbf{3.536\ A}$$

Example 2: *In the previous question, how long will the current take to reach the peak value, starting from zero?*

Solution:
$$T = \frac{1}{\nu} = \frac{1}{60}\ \text{s}$$
$$t = \frac{T}{4} = \frac{1}{4 \times 60}\ \text{s} = \frac{1}{240}\ \text{s} = \mathbf{4.167\ ms}$$

Example 3: *The instantaneous current from an ac source is I = 6 sin 314t. What is the rms value of the current ?*

Solution: Comparing the given equation with $i = i_m \sin \omega t$, we get
$$i_m = 6\ \text{A}$$
$$I_{\text{rms}} = \frac{i_m}{\sqrt{2}} = \frac{6}{\sqrt{2}}\ \text{A} = 3\sqrt{2}\ \text{A} = \mathbf{4.24\ A}$$

4.4 AC VOLTAGE APPLIED TO A RESISTOR

Figure 4.1 shows a resistor connected to a source ε of ac voltage. The symbol for an ac source in a circuit diagram is ⏦. We consider a source which produces sinusoidally varying potential difference across its terminals. Let this potential difference, also called ac voltage, be given by

$$v = v_m \sin \omega t \qquad \text{...(1)}$$

where v_m is the amplitude of the oscillating potential difference and ω is its angular frequency.

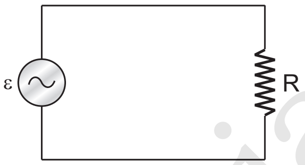


Fig. 4.1. AC voltage applied to a resistor.

Applying Kirchhoff's loop rule to the circuit shown in Fig. 4.1, we get

$$v_m \sin \omega t = i\text{R}$$

or

$$i = \frac{v_m}{\text{R}} \sin \omega t$$

or

$$i = i_m \sin \omega t \qquad \text{...(2)}$$

where the current amplitude i_m is given by

$$i_m = \frac{v_m}{\text{R}} \qquad \text{...(3)}$$

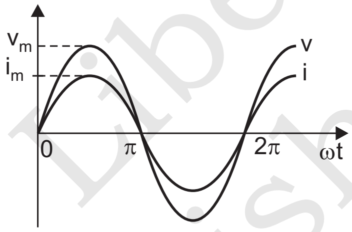


Fig. 4.2. In a pure resistor, the voltage and current are in phase. The minima, zero and maxima occur at the same respective times.

Equation (3) is just Ohm's law which for resistors works equally well for both ac and dc voltages. The voltage across a pure resistor and the current through it, given by Eqs. (1) and (2) are plotted as a function of time in Fig. 4.2. Note, in particular that both v and i reach zero, minimum and maximum values at the same time. Clearly, *the voltage* and *current are in phase with each other.*

4.5 REPRESENTATION OF AC CURRENT AND VOLTAGE BY ROTATING VECTORS–PHASORS

We know that the current through a resistor is in phase with the voltage. But this is not so in the case of an inductor, a capacitor or a combination of these circuit elements. In order to show phase relationship between voltage and current in an ac circuit, we use the notion of *phasors.* A phasor is a vector which rotates about the origin with angular speed ω as shown in Fig. 4.3. The vertical components of phasors $\vec{\text{V}}$ and $\vec{\text{I}}$ represent the sinusoidally varying quantities v and i. Figure 4.3 shows the voltage and current phasors and their relationship at time t_1 for the case of an ac source connected to a resistor *i.e.*, corresponding to the purely resistive circuit. From Fig. 4.3 we see that phasors $\vec{V}$ and $\vec{I}$ for the case of a resistor are in the same direction. This is so for all times. This means that the phase angle between the voltage and the current is zero.

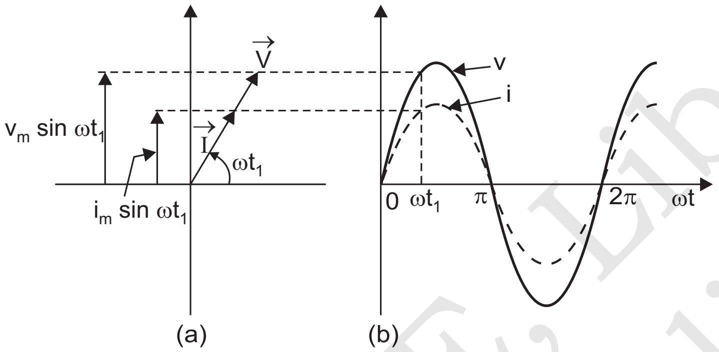


Fig. 4.3. (*a*) A phasor diagram for the purely resistive circuit (*b*) Graph of *v* and *i* versus ω*t*.

4.6 INDUCTIVE REACTANCE (X_L)

We know that $i_m = \dfrac{v_m}{\omega L}$

Comparing with Ohm's law equation $\left(I = \dfrac{V}{R}\right)$, we find that ωL plays the same role in ac circuit as is played by R in dc circuit. The term ωL is called *inductive reactance*. The inductive reactance limits the current in a purely inductive circuit in the same way as the resistance limits the current in a purely resistive circuit.

Inductive reactance is defined as the opposition offered by an inductor to the flow of alternating current through it. It is denoted by X_L.

$$X_L = \omega L = 2\pi f L$$

where f is the frequency of ac supply. *The inductive reactance is directly proportional to the inductance and to the frequency of the current.*

For a given coil, L is constant. $\therefore \quad X_L \propto f$

So, higher the frequency of ac supply, greater will be the value of inductive reactance Fig. 4.4.

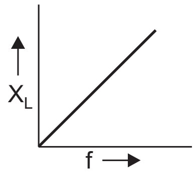


Fig. 4.4. Variation of X_L with f.

The dimensions of inductive reactance are the same as those of resistance. The SI unit of inductive reactance is ohm (Ω).

Example 4: *A pure inductor of 25.0 mH is connected to a source of 220 V. Find the inductive reactance and rms current in the circuit if the frequency of the source is 50 Hz.*

Solution:

$$X_L = 2\pi\nu L = 2 \times 3.14 \times 50 \times 25 \times 10^{-3}\ \Omega$$

$$= 7.85\ \Omega$$

$$I_{rms} = \frac{V_{rms}}{X_L} = \frac{220\ \text{V}}{7.85\ \Omega} = \mathbf{28.03\ A}$$

Example 5: *Calculate the value of the current through an inductance of 1 henry and of negligible resistance when connected to an ac source of 200 V and 50 Hz.*

Solution:

$$I_v = \frac{V_v}{\omega L} = \frac{V_v}{2\pi f\,L} = \frac{200}{2 \times 3.14 \times 50 \times 1}\text{A}$$

$$= \frac{220}{314}\text{A} = \mathbf{0.637\ A}$$

4.7 AC VOLTAGE APPLIED TO A CAPACITOR

Figure 4.5 shows an ac source ε connected to a capacitor only, a purely capacitive ac circuit.

It generates a voltage given by:

$$v = v_m \sin \omega t \qquad \text{...(1)}$$

When a capacitor is connected to a voltage source in a dc circuit, current will flow for the short time required to charge the capacitor. As charge accumulates on the capacitor plates, the voltage across them increases, opposing the current. That is, a capacitor in a dc circuit will limit or oppose the current as it charges. When the capacitor is fully charged, the current in the circuit falls to zero.

Fig. 4.5. An ac source connected to a capacitor.

When the capacitor is connected to an ac source, as in Fig. 4.5, it limits or regulates the current, but does not completely prevent the flow of charge. The capacitor is alternately charged and discharged as the current reverses each half cycle.

We can write,

$$i_m = \frac{v_m}{(1/\omega C)}$$

The quantity $\frac{1}{\omega C}$ is analogous to the resistance. It is called *capacitive reactance* and is denoted by X_C.

$$X_C = 1/\omega C$$

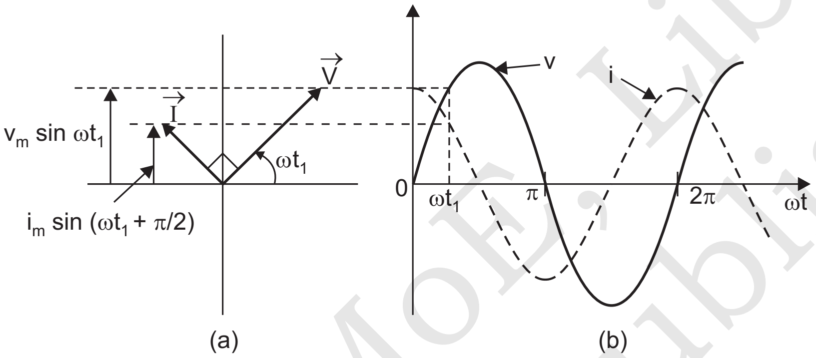


Fig. 4.6. (*a*) A phasor diagram for the purely capacitive circuit (*b*) Graph of v and i versus ωt.

The amplitude of the current is

$$i_m = \frac{v_m}{X_C}$$

Figure 4.6(a) shows the phasor diagram at an instant t_1. Here the current phasor $\vec{I}$ is $\pi/2$ ahead of the voltage phasor $\vec{V}$ as they rotate counterclockwise. Figure 4.6(*b*) shows the variation of voltage and current with time. We see that the current reaches its maximum value earlier than the voltage by one-fourth of a period.

4.8 CAPACITIVE REACTANCE

We know that $$i_m = \frac{v_m}{\frac{1}{\omega C}}$$

Comparing this equation with Ohm's law equation, we find that $\frac{1}{\omega C}$ plays the same role in ac circuit as is played by resistance R in dc circuit. The term $\frac{1}{\omega C}$ is called *capacitive reactance.*

The capacitive reactance limits the amplitude of the current in a purely capacitive circuit in the same way as the resistance limits the current in a purely resistive circuit.

Capacitive reactance is defined as the opposition offered by a capacitor to the flow of alternating current through it. It is denoted by X_C.

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

Capacitive reactance is inversely proportional to the frequency and the capacitance.

For constant C, $X_C \propto \frac{1}{f}$.

So, the capacitive reactance is inversely proportional to frequency [Fig. 4.7].

For direct current, $f = 0$. $\therefore$ $X_C = \infty$

So, a capacitor offers infinite opposition to the flow of direct current through it. In other words, a capacitor blocks dc.

The dimensions of capacitive reactance are the same as those of resistance. The SI unit of capacitive reactance is ohm.

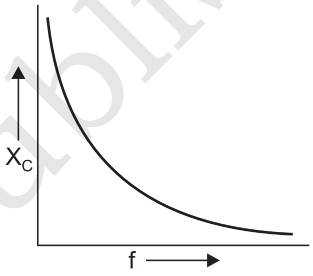


Fig. 4.7. Variation of X_C with f.

4.9 AC VOLTAGE APPLIED TO A SERIES LCR CIRCUIT

Figure 4.8 shows a series LCR circuit connected to an ac source ε. This circuit is a series combination of a pure inductance L, an ideal capacitor of capacitance C and a pure resistance R. Let the voltage across the source be :

$$v = v_m \sin \omega t$$

where v_m is the amplitude of the oscillating potential difference and ω is its angular frequency.

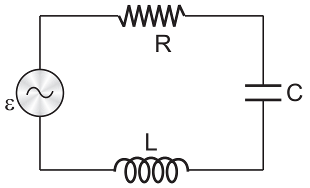


Fig. 4.8. A series LCR circuit connected to an ac source.

If q is the charge on the capacitor and i the current at time t, we have, from Kirchhoff's loop rule:

$$L\frac{di}{dt} + iR + \frac{q}{C} = v \qquad \text{...(1)}$$

By analogy to the resistance in a circuit, we introduce the *impedance Z* in an ac circuit:

$$i_m = \frac{v_m}{Z}$$

where $$Z = \sqrt{R^2 + (X_C - X_L)^2} = \sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2} \qquad \text{...(5)}$$

Impedance of LCR circuit is defined as the effective opposition (resistance) offered by LCR circuit to the flow of alternating current through it.

The reciprocal of impedance is called admittance. It is measured in mho *i.e.,* ohm^{-1} or siemen. Admittance = $\frac{1}{Z}$.

Special Cases

Case I. If $X_C > X_L$, then ϕ is positive and the circuit is predominantly capacitive. Consequently, the current in the circuit leads the source voltage.

Case II. If $X_C < X_L$, then ϕ is negative and the circuit is predominantly inductive. Consequently, the current in the circuit lags the source voltage.

Case III. If $X_L = X_C$, then

$$\tan\phi = 0 \text{ or } \phi = 0°.$$

In this case, the current and the voltage are in the same phase.

Again, $$Z = \sqrt{R^2 + (X_L - X_L)^2} = R$$

So, the LCR circuit behaves like a purely resistive circuit. The impedance is now independent of the frequency of alternating current.

Due to minimum value of impedance, the current in LCR series circuit is maximum. This condition is called **resonance**.

4.10 ADVANTAGES OF ALTERNATING CURRENT OVER DIRECT CURRENT

1. The ac is available in a wide range of voltages. These voltages can be easily stepped up or stepped down with the help of transformers.

2. The cost of generation of ac is less than that of dc.

3. The ac can be conveniently converted into dc with the help of rectifiers.

4. The ac appliances are simple, robust and require less care as compared to dc devices.

5. By supplying ac at high voltages, we can minimise line losses.

4.11 DISADVANTAGES OF ALTERNATING CURRENT OVER DIRECT CURRENT

1. The ac is more dangerous than dc.

2. The maximum voltage of ac is higher than the effective value indicated by ac voltmeter.

3. The ac is transmitted more by the surface of the conductor. This is called *skin effect*. It is for this reason that several strands of thin insulated wire, instead of a simple thick wire, need be used.

4. For electroplating, electrorefining, electrotyping etc., only dc can be used and not ac.

4.12 ENERGY BANDS IN SOLIDS (BAND THEORY OF SOLIDS)

According to Bohr's atomic model, the electrons have well-defined energy levels in an isolated atom. However, if an atom belongs to a crystal, then the energy levels are modified because of the presence of neighbouring atoms. This modification is not appreciable in the case of energy levels of electrons in the inner shells. But it is considerable in the case of the energy levels of the electrons in the outermost shell. This is because the electrons in the outermost shell are shared by more than one atom in the crystal. In order to understand the modification in the energy levels, consider the case of silicon because of the predominance of silicon devices. Its electronic configuration is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$.

Consider a single crystal of silicon having N atoms. Each atom in the crystal is situated at a lattice site. In 4.9, the interatomic spacing r is plotted along x-axis and the energy is plotted along y-axis. The distance $r = a \approx 1$ Å corresponds to the actual crystal lattice spacing. It is the equilibrium distance between atoms.

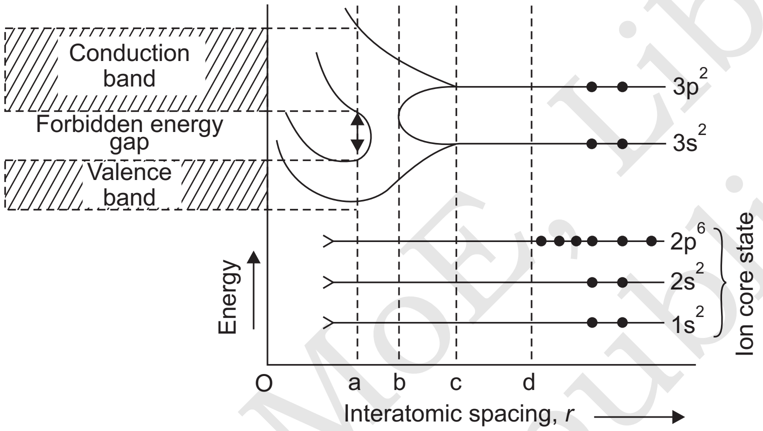


Fig. 4.9. Formation of energy bands in silicon.

In order to understand the process of splitting of energy levels for silicon, let us consider different situations.

(*i*) **When r = d >> a.** In this situation, the interatomic spacing is supposed to be infinite and each atom may be regarded as an isolated atom. Each of N atoms has its own energy levels. The energy levels of the N atoms are identical. The energy levels of each atom remain unmodified. Moreover, the energy levels are sharp, discrete and distinct.

The outer two sub-shells ($3s$ and $3p$ sub-shells of the M or $n = 3$ shell) of silicon atom contain two s electrons and two p electrons. So, in the silicon crystal under consideration, there are 2N electrons completely filling 2N possible $3s$ levels, all of which are at the same energy.

(*ii*) **When c < r < d.** When the interatomic spacing r is between d and c, there is no visible splitting of energy levels. However, there develops a tendency for the splitting of energy levels.

(*iii*) **When r = c.** When the interatomic spacing is equal to c, the interaction between the outermost shell electrons of neighbouring silicon atoms becomes appreciable. Consequently, the splitting of the energy levels commences.

(*iv*) **When b < r < c.** The interatomic spacing *r* is between *c* and *b*. The energy of electrons corresponding to the 3*s* and 3*p* levels of each atom gets slightly changed. Instead of a single 3*s* or 3*p* level, we get a large number of closely spaced levels. Corresponding to a single 3*s* level of an isolated atom, we get 2N levels. Similarly, we get 6N levels for a single 3*p* level of an isolated atom. The spreading of energy corresponding to the 3*s* and 3*p* levels reduces the energy gap that existed between the 3*s* and 3*p* levels of an isolated atom. This energy gap is called *Forbidden energy gap.*

Since N is a very large number ($\approx 10^{29}$ atoms/m^3) and energy of 3*s* and 3*p* levels is of the order of a few *e*V, therefore, the levels due to the spreading of energy of 3*s* or 3*p* levels are very closely spaced. This collection of very closely spaced levels (spacing $\approx 10^{-23}$ *e*V for 1 cm^3 crystal) is called an energy band.

(*v*) **When r = b.** When the interatomic spacing is equal to *b*, the energy gap between 3*s* and 3*p* levels disappears completely. The 8N energy levels are continuously distributed. It is not possible to distinguish between the electrons belonging to 3*s* and 3*p* subshells.

(*vi*) **When r = a.** When the interatomic spacing is equal to a (actual spacing in the crystal), the band of 8N levels splits into two bands, band of 4N energy levels completely filled with electrons and the band of 4N unfilled levels. The lower energy band of 4N filled levels is called the **valence band**. The upper band of 4N empty levels is called the **conduction band**. The gap between top of valence band and bottom of conduction band is called **forbidden gap** or **energy gap** or **band gap**. No allowed energy levels for electrons can exist in the forbidden gap.

4.13 ENERGY BANDS IN CONDUCTORS, SEMICONDUCTORS AND INSULATORS (*QUALITATIVE IDEAS ONLY*)

Depending upon the energy gap between valence band and conduction band, the solids behave as conductors, semiconductors or insulators as explained below:

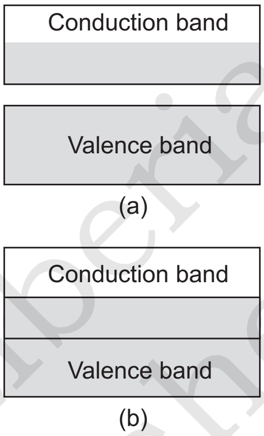
1. Conductors. The energy band structure in conductors has two possibilities :

(*i*) There is an extremely small energy gap between the completely filled valence band and the partially filled conduction band

[Fig. 4.10 (*a*)]. This band structure, is met in alkali metals (Li, Na, K etc.), noble metals (Cu, Ag, Au) and third group elements like Al, Ga, In and Tl.

(*ii*) The valence band is completely filled and the conduction band is empty but the two partially overlap each other [Fig. 4.10(*b*)]. This band structure is seen in metals like Be, Mg, Zn etc.

In both the situations, it can be assumed that there is a single energy band which is partially filled. Therefore, on applying even a small electric field, the conductors conduct electricity.



(a)

(b)

Fig. 4.10

The highest energy level occupied by electrons in a crystal, at absolute zero of temperature, is called Fermi level. The energy corresponding to this level is called the Fermi energy. Under an applied field, the electrons get enough energy to go beyond Fermi energy and thus permit electrical conduction to take place.

2. Semiconductors. Semiconductors are solids for which valence band is completely filled and conduction band is completely empty. There is a small band gap (Eg < 3 eV) between the valence band and the conduction band [Fig. 4.11]. For germanium, band gap is 0.72 eV and for silicon it is 1.1 eV.

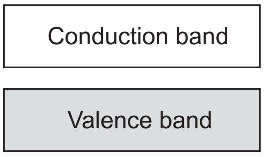


Fig. 4.11

At absolute zero of temperature, electrons are not able to cross the band gap. So, conduction band is totally empty. Thus, no current can flow in semiconductors at 0 K and they behave like insulators.

At room temperature, some valence electrons acquire thermal energy greater than the energy gap. They move to the conduction band where they are free to move under the influence of even a weak electric field. This is the specific property of the crystal which is known as a semiconductor. Higher the temperature, greater are the chances of electrons to jump to conduction band and greater is the conductivity. Clearly, the resistance of semiconductors decreases with increase in temperature.

3. Insulators. In insulators, the valence band is completely filled while the conduction band is empty. There is a large energy gap ($E_g > 3$ eV) between the valence and conduction bands [Fig. 4.12]. For example, in case of diamond, the energy gap is of 6 eV. Since energy gap is large therefore no electron is able to go from valence band to the conduction band even if electric field is applied. Thus, electrical conduction is not possible through an insulator.

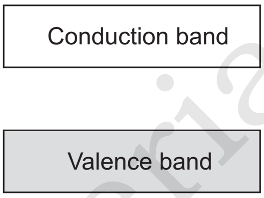
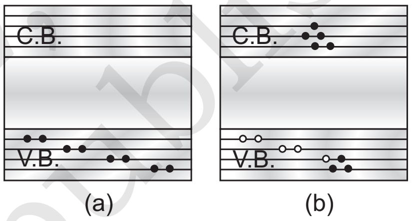


Fig. 4.12

4.14 ELECTRONS AND HOLES IN SEMICONDUCTORS

Figure 4.13 shows the energy band diagram of an intrinsic semiconductor (pure semiconductor). Fig. 4.13 (*a*) shows some charge carriers at absolute zero of temperature. Fig. 4.13 (*b*) shows the situation at room temperature. At room temperature, some electrons are in conduction band leaving an equal number of holes (o) in valence band. Note that each horizontal line represents an energy level. In each energy level, there can be at the most two electrons.



(a) (b)

Fig. 4.13. Electrons and holes in semiconductors.

Those electrons in an intrinsic semiconductor which move to the conduction band at high temperatures are called intrinsic carriers. In the valence band, a vacancy is created at the place where the electron was present before moving to the conduction band. This vacancy is called a hole.

The creation of a hole can also be understood by referring to Fig. 4.14. On receiving an additional energy, one of the electrons contributing to a covalent bond breaks and is free to move in the crystal lattice. While coming out of the covalent bond, it leaves behind a hole which is shown as an open circle. An electron from the neighbouring atom can break away

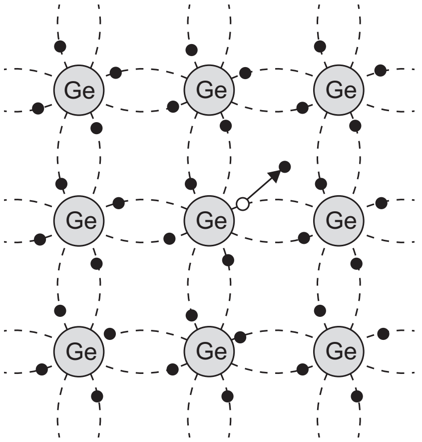


Fig. 4.14. Creation of a hole.

and can come to the place of the missing electron (or hole) completing the covalent bond and creating a hole at another place. The holes move randomly in a crystal lattice.

The completion of a bond may not be necessarily due to an electron from a bond of a neighbouring atom. The bond may be completed by a conduction band electron i.e., free electron and this case is referred to as electron-hole recombination.

The breaking of bonds or generation of electron-hole pairs, and completion of bonds due to recombination is taking place all the time. At equilibrium, the rate of generation becomes equal to the rate of recombination, giving a fixed number of free electrons and holes.

4.15 INTRINSIC SEMICONDUCTOR

It is a pure semiconductor *i.e.,* it is free from impurities. The energy gap in the case of silicon is 1.1 eV. In the case of Germanium, it is 0.74 eV.

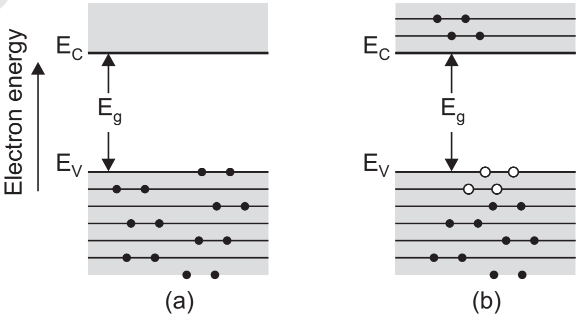
Silicon and Germanium are the best examples of semiconductors because these are the most widely used semiconductors.

In intrinsic semiconductors, the number of free electrons, n_e is equal to the number of holes, n_h. That is

$$n_e = n_h = n_i \qquad ...(1)$$

where n_i is called intrinsic carrier concentration.

Semiconductors posses the unique property in which, apart from electrons, the holes also move.



(a) (b)

Fig. 4.15. (*a*) An intrinsic semiconductor at T = 0 K behaves like insulator. (*b*) At T > 0 K, four thermally generated electron-hole pairs. The filled circles (•) represent electrons and empty circles (○) represent holes.

An intrinsic semiconductor will behave like an insulator at T = 0 K as shown in Fig. 4.15(*a*). It is the thermal energy at higher temperatures (T > 0 K), which excites some electrons from the valence band to the conduction band. These thermally excited electrons at T > 0 K, partially occupy the conduction band. Therefore, the energy-band diagram of an intrinsic semiconductor will be as shown in Fig. 4.15(*b*). Here, some electrons are shown in the conduction band. These have come from the valence band leaving equal number of holes there.

4.16 EXTRINSIC SEMICONDUCTORS

An ***extrinsic semiconductor*** *is one in which an impurity with a valency higher or lower than the valency of the semiconductor atoms is deliberately introduced, thereby drastically influencing the electrical properties of the semiconductor.*

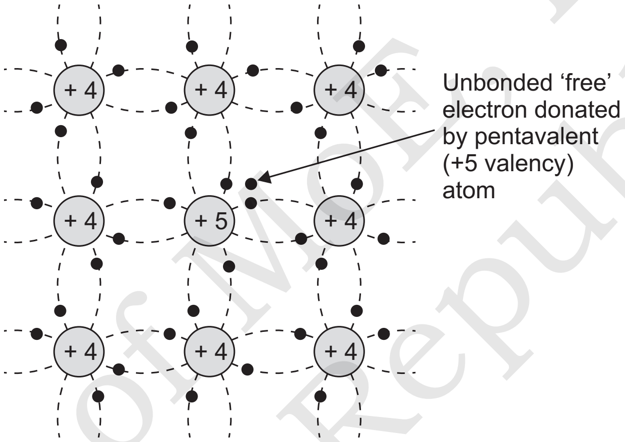


Fig. 4.16. Pentavalent donor atom (As, Sb, P, etc.) doped for tetravalent Si or Ge giving *n*-type semiconductor.

When a small amount, say, a few parts per million (ppm), of a suitable impurity is added to the pure semiconductor, the conductivity of the semiconductor is increased manifold. Such materials are known as *extrinsic semiconductors* or *impurity semiconductors*. The deliberate addition of a desirable impurity is called *doping* and the impurity atoms are called *dopants*. Such a material is also called a *doped semiconductor*.

There are two types of dopants used in doping the tetravalent Si or Ge:

(*i*) Pentavalent (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

(*ii*) Trivalent (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.

Depending upon the type of dopant present in the semiconductor, an extrinsic semiconductor may be classified as *n*-type or *p*-type.

4.16.1 n-Type Semiconductor

When an elemental semiconductor of Group IV such as Si or Ge is doped with a pentavalent impurity (an element of group V such as phosphorus, arsenic or antimony), we get n-type semiconductor.

Si or Ge with a pentavalent element is shown in Fig. 4.16. When an atom of +5 valency element occupies the position of an atom in the crystal lattice of Si, four of its electrons bond with the four silicon neighbours while the fifth remains very weakly bound to its parent atom.

In the energy band picture, the energy state corresponding to the fifth valence electron is in the forbidden gap and is slightly below the conduction band. The energy level is indicated by the dashed line in Fig. 4.17. This level is called the *donor level.*

When the *fifth valence electron is transferred to the conduction band,* the parent impurity atom *becomes positively charged* immobile ion. In this way, each impurity atom donates a free electron to the semiconductor. The pentavalent dopant is donating one extra electron for conduction and hence is known as *donor* impurity. It is for this reason that *n*-type semiconductor is sometimes called donor-type semiconductor.

The number of electrons made available for conduction by dopant atoms depends strongly upon the doping level and is independent of any increase in ambient temperature. On the other hand, the number of free electrons (with an equal number of holes) generated by Si atoms, increases weakly with temperature.

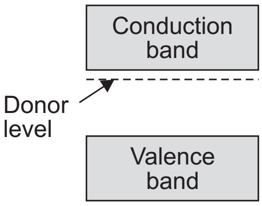


Fig. 4.17. Donor energy level.

Thus, with proper level of doping, the number of conduction electrons can be made much larger than the number of holes. Hence in an extrinsic semiconductor doped with pentavalent impurity, electrons become the *majority carriers* and holes the *minority carriers*. These semiconductors are, therefore, known as *n-type semiconductors*. For *n*-type semiconductors, we have

$$n_e >> n_h$$

4.16.2 p-Type Semiconductor

When an elemental semiconductor of Group IV such as Si or Ge is doped with a trivalent impurity (an element of Group III such as Indium, Boron or Gallium), we get p-type semiconductor.

When Si or Ge is doped with a trivalent impurity like Al, B, In etc, we get *p*-type semiconductor. The dopant has one valence electron less than Si or Ge and, therefore, this atom can form covalent bonds with neighbouring three Si atoms but does not have any electron to offer to the fourth Si atom. So the bond between the fourth neighbour and the trivalent atom has a vacancy or hole as shown in Fig. 4.18. It is obvious that one *acceptor* atom gives one *hole*. These holes are in addition to the intrinsically generated holes while the source of conduction electrons is only intrinsic generation. Thus, for such a material, the holes are the majority carriers and electrons are minority carriers. Therefore, extrinsic semiconductors doped with trivalent impurity are called *p-type semiconductors*.

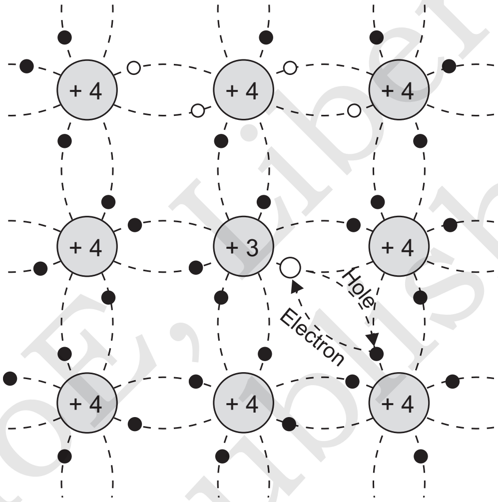


Fig. 4.18. Trivalent acceptor atom (In. Al, B etc.) doped in tetravalent Si or Ge lattice giving *p*-type semiconductor.

In a *p*-type semiconductor, holes are the majority charge carriers and the free electrons are the minority charge carriers.

Like in an *n*-type semiconductor, a *p*-type semiconductor also satisfies the relation

$$pn = p_i\, n_i = n_i^2$$

For each impurity atom, there is a free hole in the valence band but there is no corresponding generation of free electron in the conduction band. So, $p > p_i$ but $n < n_i$.

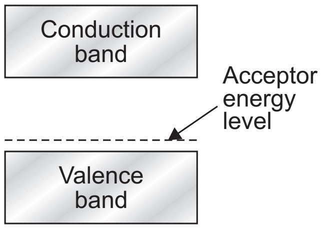


Fig. 4.19. Acceptor energy level.

4.17 DISTINCTION BETWEEN N-TYPE SEMICONDUCTORS AND p-TYPE SEMICONDUCTORS

n-Type Semiconductors	*p-Type Semiconductors*
1. These are extrinsic semiconductors obtained by doping impurity atoms of group V to Ge or Si crystal.	**1.** These are extrinsic semiconductors obtained by doping impurity atoms of group III to Ge or Si crystal.
2. The impurity atoms are called donors. These provide free electrons.	**2.** The impurity atoms are called acceptors. These create vacancies of electrons (or holes).
3. The donor energy level lies just below the conduction band.	**3.** The acceptor energy level lies just above the valence band.
4. The electrons are majority charge carriers and holes are minority charge carriers.	**4.** The holes are majority charge carriers and electrons are minority charge carriers.
5. The free electron density is much greater than hole density *i.e.*, $n_e >> n_h$.	**5.** The hole density is much greater than free electron density *i.e.*, $n_h >> n_e$.
6. The fermi energy level lies in between the donor energy level and the conduction band.	**6.** The fermi energy level lies in between the acceptor energy level and valence band.

4.18 *p-n* JUNCTION

A *p-n* junction is the basic building block of many semiconductor devices like diodes, transistors, etc. A clear understanding of the junction behaviour is important to analyse the working of other semiconductor devices.

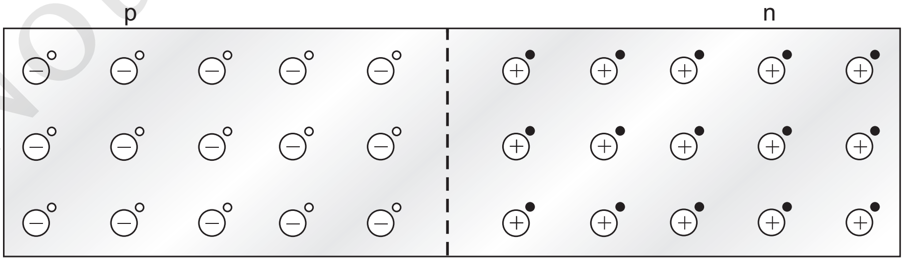


Fig. 4.20. (*a*) *p-n* junction.

Formation of p-n Junction

Consider a thin *p*-type silicon (*p*-Si) semiconductor wafer. By adding precisely a small quantity of pentavalent impurity, part of the *p*-Si wafer can be converted into *n*-Si. The wafer now contains *p*-region and *n*-region and a metallurgical junction between *p*-, and *n*-regions.

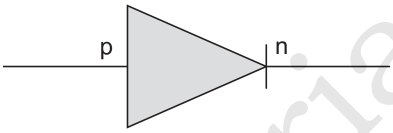


Fig. 4.20. (*b*) Symbol for *p-n* junction diode.

Structural Details

p-type and *n*-type semiconductors, taken individually, have practically not much of a use. However, if the two are joined together, they become very useful.

A p-n junction is a single semiconductor crystal that has been selectively doped so that one region is n-type material and the adjacent region is p-type material.

Formation of Depletion Region

When an electron diffuses from $n \rightarrow p$, it leaves behind an ionised donor on *n*-side. This ionised donor (positive charge) is immobile as it is bonded to the surrounding atoms. As the electrons continue to diffuse from $n \rightarrow p$, a layer of positive charge (or positive space-charge region) on *n*-side of the junction is developed.

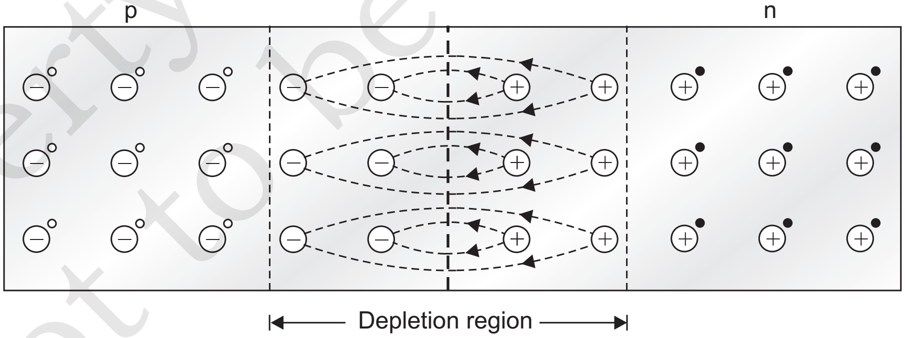


Fig. 4.21. Formation of depletion region in *p-n* junction diode.

Similarly, when a hole diffuses from $p \rightarrow n$ due to the concentration gradient, it leaves behind an ionised acceptor (negative charge) which is immobile. As the holes continue to diffuse, a layer of negative charge (or negative space-charge region) on the *p*-side of the junction is developed. This space-charge region on either side of the junction together is known as *depletion region* as the electrons and holes taking part in the initial movement across the junction *depleted* the region of its free charges (Fig. 4.21). The thickness of depletion region is of the order of one-tenth of a micrometre.

The region containing the uncompensated acceptor and donor ions is called depletion region. This is because there is a depletion of mobile charges (holes and free electrons) in the region. Moreover, since this region contains only the immobile ions which are electrically charged, therefore, this region is also called space-charge region.

4.19 SEMICONDUCTOR DIODE (*p-n* JUNCTION DIODE)

Any device which freely allows electric current in one direction but does not allow it in the opposite direction is called a diode. An ideal diode does not allow any current in the reverse direction.

A *p-n* junction acts as a diode. Infact, it may be regarded as an ideal diode because it allows very small current in the opposite direction. A *p-n* junction is generally referred to as "*p-n* junction diode."

A semiconductor diode [Fig. 4.22(*a*)] is basically a *p-n* junction with metallic contacts provided at the ends for the application of an external voltage. It is a two terminal device. A *p-n* junction diode is symbolically represented as shown in Fig. 4.22(*b*).

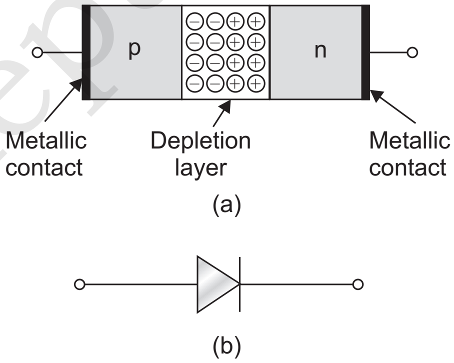


Fig. 4.22. (*a*) Semiconductor diode, (*b*) Symbol for *p-n* junction diode.

4.20 *p-n* JUNCTION DIODE UNDER FORWARD BIAS

When an external voltage V is applied across a semiconductor diode such that p-side is connected to the positive terminal of the battery and n-side to the negative terminal, it is said to be forward biased.

The applied voltage mostly drops across the depletion region and the voltage drop across the *p*-side and *n*-side of the junction is negligible. The direction of the applied voltage (V) is opposite to the built-in potential V_0. As a result, the depletion layer width decreases and the barrier height is reduced [Fig. 4.23]. The effective barrier height under forward bias is $(V_0 - V)$.

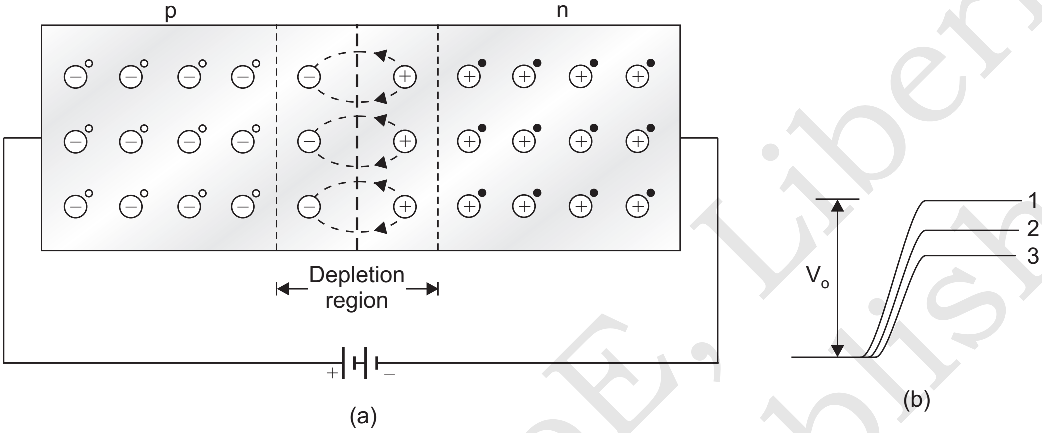


Fig. 4.23. (*a*) *p-n* junction diode under forward bias. (*b*) Barrier potential.

4.21 p-n JUNCTION DIODE UNDER REVERSE BIAS

When an external voltage (V) is applied across the diode such that n-side is positive and p-side is negative, it is said to be reverse biased. The applied voltage mostly drops across the depletion region. The direction of applied voltage is same as the direction of barrier potential. As a result, the barrier height increases and the depletion region widens due to the change in the electric field. The effective barrier height under reverse bias is $(V_0 + V)$, [Fig. 4.24 (*b*)]. This suppresses the flow of electrons from *n* → *p* and holes from *p* → *n*. Thus, diffusion current decreases enormously compared to the diode under forward bias.

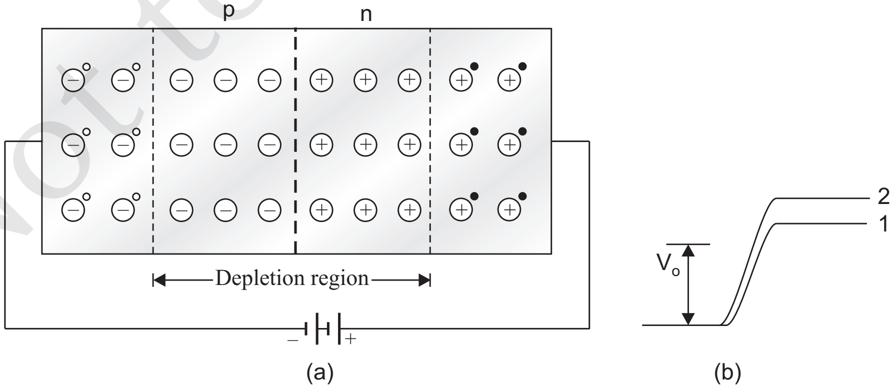


Fig. 4.24. (*a*) Diode under reverse bias. (*b*) Barrier potential under reverse bias.

The electric field direction of the junction is such that if electrons on *p*-side or holes on *n*-side in their random motion come close to the junction, they will be swept to its majority zone. This drift of carriers gives rise to current. The drift current is of the order of a few μA. This is quite low because it is due to the motion of carriers from their minority side to their majority side across the junction. The drift current is also there under forward bias but it is negligible (μA) when compared with current due to injected carriers which is usually in mA.

The diode reverse current is not very much dependent on the applied voltage. Even a small voltage is sufficient to sweep the minority carriers from one side of the junction to the other side of the junction. The current is not limited by the magnitude of the applied voltage but is limited due to the concentration of the minority carriers on either side of the junction.

The current under reverse bias is essentially voltage-independent upto a critical reverse bias voltage, known as breakdown voltage (V_{br}). When $V = V_{br}$, the diode reverse current increases sharply. Even a slight increase in the bias voltage causes large change in the current. If the reverse current is not limited by an external circuit below the rated value (specified by the manufacturer) the *p-n* junction will get destroyed. Once it exceeds the rated value, the diode gets destroyed due to overheating. This can happen even for the diode under forward bias, if the forward current exceeds the rated value.

Example 1: *The V-I characteristic of a silicon diode is shown in the Fig. 4.25. Calculate the resistance of the diode at (a) I_D = 15 mA and (b) V_D = – 10 V.*

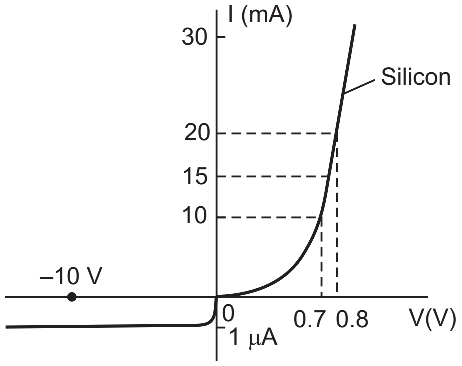


Fig. 4.25

Solution: Considering the diode characteristic as a straight line between I = 10 mA to I = 20 mA, we can calculate the resistance using Ohm's law.

(*a*) From the curve, at I = 20 mA, V = 0.8 V, I = 10 mA, V = 0.7 V,

$r_{fb} = \Delta V/\Delta I = 0.1\ V/10\ mA = \mathbf{10\ \Omega}$

(*b*) From the curve at V = – 10 V, I = – 1 μA.

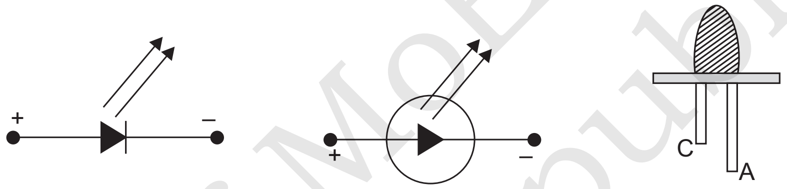
Therefore, $r_{rb} = 10\ V/1\ \mu A = \mathbf{1.0 \times 10^7}\ \Omega$

4.22 LIGHT-EMITTING DIODE (LED)

(i) Now-a-days, we can hardly avoid the brightly-coloured "electronic" numbers that glow at us from cash registers and gasoline pumps, microwave ovens and alarm clocks. In nearly all cases, this light is emitted from a *p-n* junction operating as a light-emitting diode (LED).

(ii) ***Light-emitting diode (LED)*** *is a heavily doped p-n junction diode which under forward bias emits visible light.* The light energy is produced by the recombination of electrons and holes at the junction.

Light-emitting diodes are generally made from semiconducting materials gallium arsenide or indium phosphide. Silicon or Germanium diodes emit radiation in the infrared region.



(a) (b) (c)

Fig. 4.26

Figs. 4.26(*a*) and (*b*) give the two symbols of the light emitting diode. The actual shape is shown in Fig. 4.26(*c*). The shorter, of its two leads, corresponds to its *n* (or cathode side) while the longer lead corresponds to its *p* (or anode side).

A circuit which uses light-emitting diode is shown in Fig. 4.27. The diode has been forward-biased. The brightness can be controlled by R_L.

If light-emitting diode is reverse-biased, then no light would be emitted at all. In-fact, the LED can be damaged on being reverse-biased.

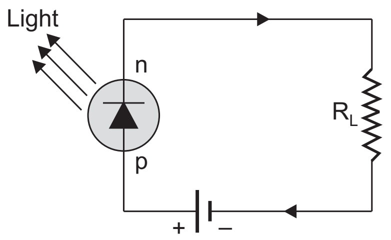


Fig. 4.27. Light-emitting diode.

4.23 PHOTODIODE

A *p-n* junction diode made of photosensitive semiconductor is called **photodiode.** A photodiode is a special purpose *p-n* junction diode fabricated with a transparent window to allow light to fall on the diode. Fig. 4.28 shows the symbolic representation of a photodiode.

In a semiconductor, the electrons jump from valence band to the conduction band by absorbing energy from some external source of energy. If the incident visible light is the external source of energy, then the semiconductor is said to be photosensitive. When visible light is incident on a photosensitive semiconductor, more electrons become available to participate in conduction. Thus, the conductivity of a photosensitive semiconductor increases when light is incident on it.

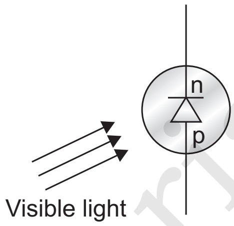


Fig. 4.28. Photodiode.

It is generally operated under reverse bias. It is easier to observe the change in the current with change in the light intensity, if a reverse bias is applied. Thus photodiode can be used as a photodetector to detect optical signals. When the photodiode is illuminated with light (photons).

Fig. 4.29 shows an experimental arrangement in which photodiode has been reverse-biased. The applied voltage is less than the breakdown voltage. When the intensity of light increases to a value, say E_0, the current becomes maximum. This maximum current is called saturation current.

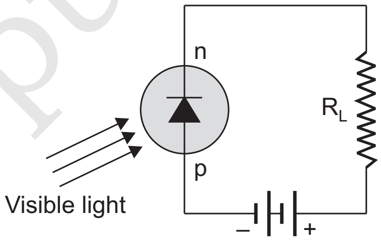


Fig. 4.29. Reverse-biasing of photodiode.

If the photodiode is forward biased as shown in Fig. 4.30, then a certain current exists in the circuit even when no visible light is made incident. This current is called **dark current.** It is represented by OA in the graph of Fig. 4.31.

When visible light of suitable energy is made incident on the photodiode, more electrons move from valence band to conduction band. Consequently, the current increases. The variation of current with intensity of incident light is shown graphically in Fig. 4.31. When the intensity becomes equal to E_0, the current attains its maximum value. It is called saturation current. It is represented by the straight portion BC in the graph of Fig. 4.31.

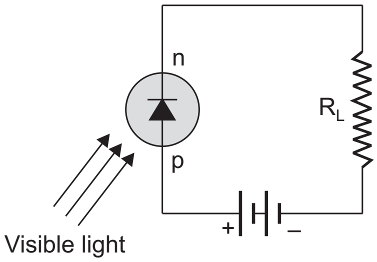


Fig. 4.30. Forward-biasing of photodiode.

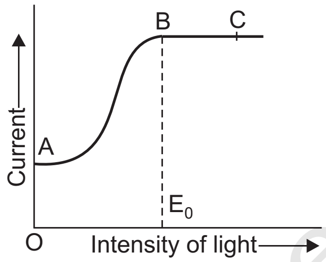


Fig. 4.31. Variation of current with intensity of incident light.

Typical I-V characteristics of a photodiode are shown in Fig. 4.32.

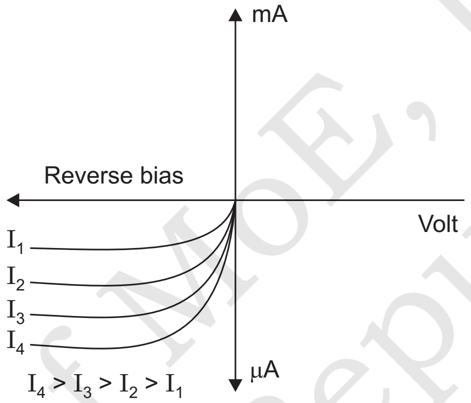


Fig. 4.32. I-V characteristics of a photodiode for different illumination intensities $I_4 > I_3 > I_2 > I_1$.

4.24 JUNCTION TRANSISTOR

By adding another junction to a *p-n* junction diode, we can obtain a device which can control the flow of majority charge carriers. This device is known as **transistor.** It is a combination of two words "transfer" and "resistor".

Transistor was first invented in 1948 by J. Bardeen and W.H. Brattain of Bell Telephone Laboratories, USA. The modern version of transistor was made by W. Shockley in 1951.

Transistor consists of two *p-n* junctions back-to-back. It is obtained by sandwiching either *p*-type or *n*-type semiconductor between a pair of opposite type of semiconductors. While the central slice is called the base, the left and the right crystals are called the emitter and the collector respectively.

All transistors are not alike. Broadly speaking, we have two different types of transistors, namely, *n-p-n* transistor and *p-n-p* transistor.

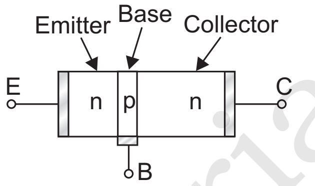


Fig. 4.33. *n-p-n* transistor.

(*i*) **n-p-n transistor** consists of a thin slice of *p*-type semiconductor sandwiched between two much thicker *n*-type semiconductors (Fig. 4.33).

The thin slice of *p*-type semiconductor is called the base. The left hand block of *n*-type semiconductor is called the emitter. The right hand block of *n*-type semiconductor is called the collector.

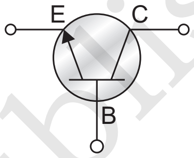


Fig. 4.34. Symbol of *n-p-n* transistor.

The symbol of *n-p-n* transistor is shown in Fig. 4.34. The direction of the arrow represents the direction of flow of current. It may be noted that it is opposite to the direction of motion of electrons.

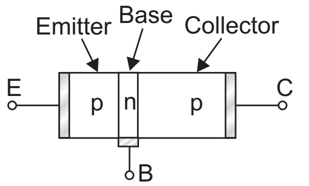


Fig. 4.35. *p-n-p* transistor.

(*ii*) **p-n-p transistor** consists of a thin slice of a few microns (10^{-6} m) of *n*-type semiconductor sandwiched between two much thicker *p*-type semiconductors [Fig. 4.35].

The thin slice of *n*-type semiconductor is called the base. The left hand block of *p*-type semiconductor is called the emitter. The right hand block of *p*-type semiconductor is called the collector.

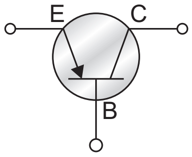


Fig. 4.36. Symbol of *p-n-p* transistor.

The symbol of *p-n-p* transistor is shown in Fig. 4.36. The direction of the arrow represents the direction of current. It is the same as the direction of motion of holes. In *p-n-p* transistor, the charge carriers are mainly holes.

4.25 THREE BLOCKS OF A TRANSISTOR

The three blocks of a transistor are not equal. Further, for getting correct transistor action, the doping levels in the different blocks are kept different as explained below.

(i) Emitter. This is the left hand block of the transistor. It is of moderate size and heavily doped semiconductor. This supplies a large number of majority carriers for the current flow through the transistor.

(ii) Base. This is the central block. It is very thin and lightly doped.

(iii) Collector. This collects a major portion of the majority carriers supplied by the emitter. The collector side is moderately doped and larger in size as compared to emitter.

Understanding of Cathode Ray Tube - CRT

Wrorking Principle

When two metal plates are connected to a high voltage source, the negatively charged plate called the cathode emits an invisible ray. The cathode ray is drawn to the positively charged plate, called the anode, where it passes through a hole and continues traveling to the other end of the tube. When the ray strikes the specially coated surface, the cathode ray produces a strong fluorescence or bright light. When an electric field is applied across the cathode ray tube, the cathode ray is attracted by the plate bearing positive charges. Therefore a cathode ray must consist of negatively charged particles. A moving charged body behaves like a tiny magnet, and it can interact with an external magnetic field. The electrons are deflected by the magnetic field. When the external magnetic field is reversed, the beam of electrons is deflected in the opposite direction.

In a cathode ray tube, the cathode is a heated filament and it placed in a vacuum. The ray is a stream of electrons that naturally pour off a heated cathode into the vacuum. Electrons are negative. The anode is positive, so it attracts the electrons pouring off the cathode. In a TV's cathode ray tube, the stream of electrons is focused by a focusing anode into a tight beam and then accelerated by an accelerating anode. This tight, high-speed beam of electrons flies through the vacuum in the tube and hits the flat screen at the other end of the tube. This screen is coated with phosphor, which glows when struck by the beam.

Opperation of CRT

Cathode Ray Tube (CRT) is a computer display screen, used to display the output in a standard composite video signal. The working of CRT depends on the movement of an electron beam which moves back and forth across the back of the screen. The source of the electron beam is the electron gun; the gun is located in the narrow, cylindrical neck at the extreme rear of a CRT which produces a stream of electrons through a thermionic emission. Usually, a CRT has a fluorescent screen to display the output signal. A simple CRT is shown in Fig. 4.37 below.

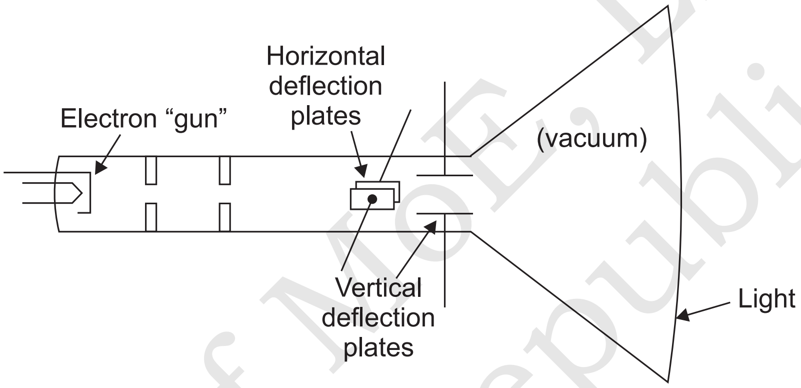


Fig. 4.37. Cathode Ray Tube

The operation of a CRT monitor is very simple. A cathode-ray tube consists of one or more electron guns, possibly internal electrostatic deflection plates, and a phosphor target. CRT has three electron beams one for each (Red, Greern, and Blue) is clearly shown in Fig. 4.37. The electron beam produces a tiny, bright visible spot when it strikes the phosphor-coated screen. In every monitor device, the entire front area of the tube is scanned repetitively and systematically in a fixed pattern called a raster. An image (raster) is displayed by scanning the electron beam across the screen. Thus CRT produces the three colour images which are primary colours.

The main parts of the cathode ray tube are cathode, control grid, deflecting plates and screen.

(*i*) **Cathode**. The heater keeps the cathode at a higher temperature and electrons flow from the heated cathode towards the surface of the cathode. The accelerating anode has a small hole at its center and is maintained at a high potential, which is of positive polarity. The order of this voltage is 1 to 20 kV, relative to the cathode. This potential difference creates an electric field directed from right to left in the region between the accelerating anode and the cathode. Electrons pass through the hole in the anode travel with constant horizontal velocity from the anode to the fluorescent screen, The electrons strike the screen area and it glows brightly.

(*ii*) **The Control Grid.** The control grid regulates the brightness of the spot on the screen. By controlling the number of electrons by the anode and hence the focusing anode ensures that electrons leaving the cathode in slightly different directions are focused down to a narrow beam and all arrive at the same spot on the screen.

(*iii*) **Deflecting Plates.** Two pairs of deflecting plates allow the beam of electrons. An electric field between the first pair of plates deflects the electrons horizontally, and an electric field between the second pair deflects them vertically. The electrons travel in a straight line from the hole in the accelerating anode to the centre of the screen when no deflecting fields are present, where they produce a bright spot.

REVIEW EXERICSE

A. MULTIPLE CHOICE QUESTIONS (MCQs)

1. In a circuit containing a capacitor, an inductor and a resistor in series, V_C , V_L and V_R represent the potential differences across those components and I represents the current through them. Which of the following statements is true ?

1. V_C and I are 180° out of phase.
2. V_R and I are 90° out of phase.
3. V_L and V_C are 180° out of phase.

(*a*) if 1, 2, 3 are correct (*b*) if 1, 2 are correct
(*c*) if 2, 3 are correct (*d*) if 1 only
(*e*) if 3 only.

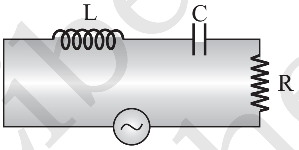
2. An alternating current of 1.5 mA rms and angular frequency $\omega = 100$ rad s^{-1} flows through a 10 kΩ resistor and a 0.50 μF capacitor in series. The rms potential difference across the capacitor is

(*a*) 4.8 V (*b*) 15 V (*c*) 30 V (*d*) 34 V
(*e*) 190 V.

3. An LCR series circuit with R = 100 Ω is connected to a 200 V, 50 Hz ac source. When only the capacitance is removed, the current lags the voltage by 60°. When only the inductance is removed, the current leads the voltage by 60°. The current in the circuit is

(*a*) 2 A (*b*) 1 A (*c*) $\frac{\sqrt{3}}{2}$ A (*d*) $\frac{2}{\sqrt{3}}$ A.

4. Given LCR circuit has $L = 5$ H, $C = 80$ μF, $R = 40$ Ω and variable frequency source of 200 V. What is the source frequency which drives the circuit at resonance ?



(*a*) 25 Hz (*b*) $\frac{25}{\pi}$ Hz (*c*) 50 Hz (*d*) $\frac{50}{\pi}$ Hz.

5. The instantaneous values of current and voltage in an ac circuit are given by

$I = 6 \sin\left(100\,\pi t + \frac{\pi}{4}\right)$, $V = 5 \sin\left(100\,\pi t - \frac{\pi}{4}\right)$. Then

(*a*) current leads the voltage by 45°.

(*b*) voltage leads the current by 90°.

(*c*) current leads the voltage by 90°.

(*d*) voltage leads the current by 45°.

6. A resistor and a capacitor are connected in series with an ac source. If the potential drop across the capacitor is 5 V and that across resistor is 12 V, the applied voltage is

(*a*) 13 V (*b*) 17 V (*c*) 5 V (*d*) 12 V.

7. A capacitor and a coil in series are connected to a 6 volt ac source. By varying the frequency of the source, maximum current of 600 mA is observed. If the same coil is now connected to a cell of emf 6 volt and internal resistance of 2 ohm, the current through it will be

(*a*) 0.5 A (*b*) 0.6 A (*c*) 1.0 A (*d*) 2.0 A.

8. In a series LCR circuit $R = 200$ Ω and the voltage and the frequency of the main supply is 220 V and 50 Hz respectively. On taking out the capacitance from the circuit, the current lags behind the voltage by 30°. On taking out the inductor from the circuit, the current leads the voltage by 30°. The power dissipated in the LCR circuit is

(*a*) 242 W (*b*) 305 W (*c*) 210 W (*d*) Zero W.

9. A 50 volt ac is applied across an RC (series) network. The rms voltage across the resistance is 40 volt. Then the potential difference across the capacitance would be

(*a*) 10 V (*b*) 20 V (*c*) 30 V (*d*) 40 V.

10. A *n-p-n* transistor having ac current gain of 50 is to be used to make an amplifier of power gain of 300. What will be the voltage gain of the amplifier ?

(*a*) 8.5 (*b*) 6 (*c*) 4 (*d*) 3.

11. In a semiconducting material, $\left(\frac{1}{5}\right)^{\text{th}}$ of the total current is carried by the holes and the remaining is carried by the electrons. The drift speed of electrons is twice that of holes at this temperature. The ratio between the number densities of electrons and holes is

(*a*) $\frac{21}{6}$ (*b*) 5 (*c*) $\frac{3}{8}$ (*d*) 2.

12. In a common emitter amplifier, the input signal is applied across

(*a*) anywhere (*b*) emitter-collector

(*c*) collector-base (*d*) base-emitter.

13. A common emitter amplifier has a voltage gain of 50, an input impedance of 100 W and an output impedance of 200 W. The power gain of the amplifier is

(*a*) 500 (*b*) 1000 (*c*) 1250 (*d*) 50.

14. The device that can act as a complete electronic circuit is

(*a*) junction diode (*b*) integrated circuit

(*c*) junction transistor (*d*) Zener diode.

15. Which one of the following bonds produces a solid that reflects light in the visible region and whose electrical conductivity decreases with temperature and has high melting point ?

(*a*) metallic bonding (*b*) Van der Waal's bonding

(*c*) ionic bonding (*d*) covalent bonding.

B. FILL IN THE BLANKS

1. A light bulb is rated 100 W for a 220 V supply. The resistance of the bulb and the peak voltage of the source respectively are ....

2. The Q-factor of an LCR circuit in series is largest when ....

3. An LCR series ac circuit is at resonance with 10 V each across L, C and R. If the resistance is halved, the respective voltage across L, C and R are ....
4. An alternating supply of 220 volt is applied across a circuit with resistance 22 ohm and impedance of 44 ohm. The power dissipated in the circuit is ....
5. A fully charged capacitor C with initial charge q_0 is connected to a coil of self-inductance L at $t = 0$. The time at which the energy is stored equally between the electric and the magnetic fields is ....
6. When a *p-n* junction is forward biased, the flow of current across the junction is mainly due to ....
7. When a semiconductor is doped with a *p*-type impurity, each impurity atom will ....
8. In *p*-type semiconductor, increase in dopant concentration will ....
9. The collector supply voltage is 6 V and the voltage drop across a resistor of 600 Ω in the collector circuit is 0.6 V, in a transistor connected in common emitter mode. If the current gain is 20, the base current is ....
10. When the voltage across a *p-n* junction diode is increased from 0.65 V to 0.70 V, the change in the diode current is 5 mA. The dynamic resistance of the diode is ....

C. VERY SHORT ANSWER TYPE QUESTIONS

1. What is a logic gate?
2. Write down the truth table of NOR gate and also draw its logic symbol.
3. What is an integrated circuit?
4. Write the truth table of NAND gate.
5. Give the logic symbol of NOR gate.

D. SHORT ANSWER TYPE QUESTIONS

1. How many NAND gates are required to get an AND gate ?
2. How many NAND gates are required to make one NOT gate ?
3. How many NAND gates are required to get an OR gate ?
4. The output of a two-input NAND gate is fed as input to a NOT gate. Write down the truth table for the final output of the combination.
5. What will be the values of inputs *A* and *B* for the Boolean equation $(\overline{A + B}) . (\overline{A . B}) = 1$?

E. LONG ANSWER TYPE QUESTIONS

1. 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 volt, calculate the output ac signal.

2. A *p-n* photodiode is fabricated from a semiconductor with band gap of 2.8 eV. Can it detect a wavelength of 6000 nm?

3. The number of silicon atoms per m^3 is 5×10^{28}. This is doped simultaneously with 5×10^{22} atoms per m^3 of Arsenic and 5×10^{20} per m^3 atoms of Indium. Calculate the number of electrons and holes. Given that $n_i = 1.5 \times 10^{16}\ m^{-3}$. Is the material *n*-type or *p*-type ?

4. In an intrinsic semiconductor, the energy gap E_g is 1.2 eV. Its hole mobility is very much smaller than electron mobility and independent of temperature. What is the ratio between conductivity at 600 K and that at 300 K ? Assume that the temperature dependence of intrinsic carrier concentration n_i is given by

$$n_i = n_0 \exp\left(\frac{-E_g}{2k_BT}\right)$$

where n_0 is a constant.

5. In a *p-n* junction diode, the current I can be expressed as $I = I_0 \left[\exp\left(\frac{eV}{k_BT}\right) - 1\right]$ where I_0 is called the reverse saturation current, V is the voltage across the diode and is positive for forward bias and negative for reverse bias, and I is the current through the diode, k_B is the Botzmann constant (8.6×10^{-5} eV/K) and T is the absolute temperature. If for a given diode $I_0 = 5 \times 10^{-12}$ A and $T = 300$ K, then

(a) what will be the forward current at a forward voltage of 0.6 V ?

(b) what will be the increase in the current if the voltage across the diode is increased to 0.7 V ?

(c) what is the dynamic resistance ?

(d) what will be the current if reverse bias voltage changes from 1 V to 2 V ?