1.3. *p-n* Junction Imp

When a *p*-type semiconductor is brought in close contact to *n*-type semiconductor by suitable means, the arrangement of both the semiconductors is known as *p-n* junction. Thus, a single piece of a semiconductor material (either Si or Ge) whose one portion is doped with *n*-type impurity and the other portion is doped with *p*-type impurity behaves as *p-n* junction (Fig. 9). In fact, the boundary dividing the two halves of such a semiconductor is called a junction and the arrangement is known as ***p–n* junction diode.**

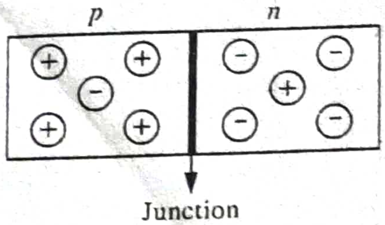


Fig. 9.

Formation of p-n Junction.

A small sphere of *trivalent impurity say indium* is pressed on a thin ***wafer*** of *n*-type germanium or silicon slab. The system is heated so that the indium fuses to the surface of germanium and produces *p*-type germanium just below the surce of contact (Fig. 10A). This *p*-type alongwith the *n*-type germanium wafer form a *p-n* junction (Fig. 10B). Both the upper and lower portions of the system have metallic contacts. Surface

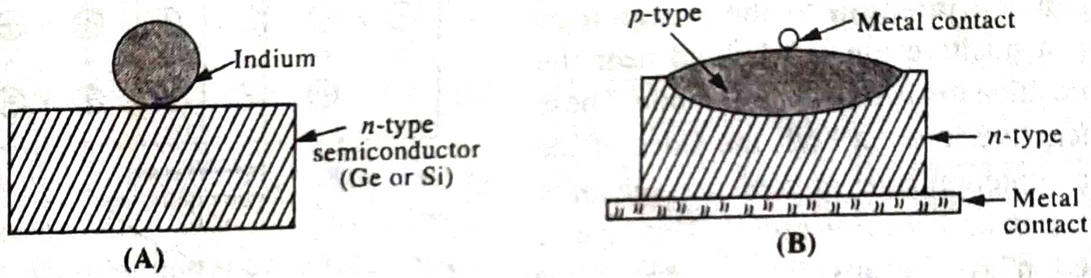


Fig. 10.

Similarly a *p-n* junction can be made by diffusion of a pentavalent impurity like phosphorous into a *p*-type semiconductor. In this process, *p*-type semiconductor is heated in phosphorus gas to result into diffused *n*-type layer on the semiconductor (Fig. 11).

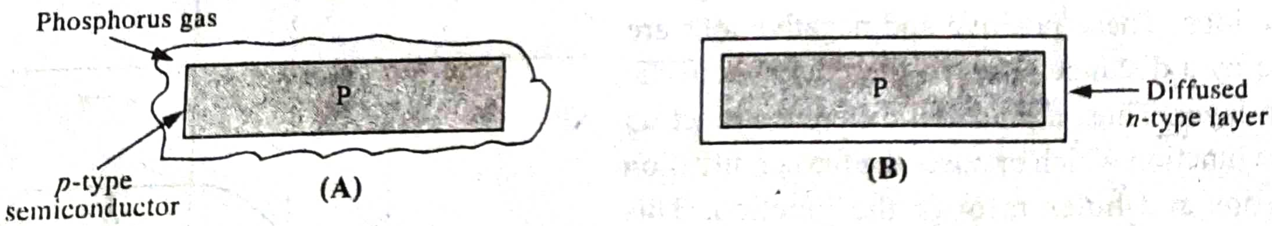


Fig. 11.

Formation of depletion Layer in a p-n junction

There is high concentration of holes in the *p*-region and high concentration of electrons in the *n*-region of *p-n* junction. The holes from *p*-region and electrons from *n*-region diffuse through the junction. The electrons which diffuse through the junction to *p*-region recombine with holes. As a result of this recombination, holes disappear and an excess negative charge appears in *p*-side of the junction.

When holes diffuse through the junction, an excess positive charge appears in n-side of the junction (Fig. 12). The thin region around the junction containing immobile positive and negative charges is known as **depletion layer.**

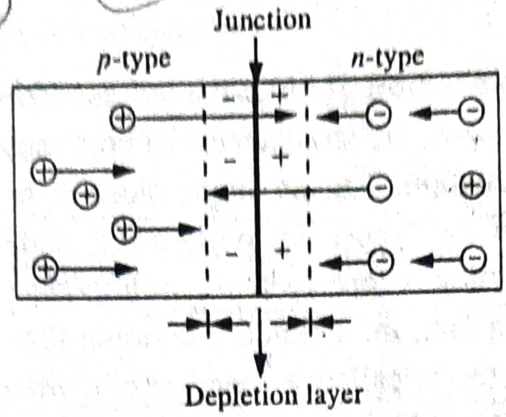


Fig. 12.

In fact, on the p side of a p-n junction, there are negative ions fixed in their positions in the crystal lattice surrounded by holes. When a hole diffuses through the junction to the n-region of semiconductor, a negative ion is left behind near the junction. This negative ion is fixed or immobile. Similarly, on the n side of the p-n junction, there are positive ions fixed in their respective positions in the crystal lattice surrounded by free electrons. When an electron diffuses through the junction to the p-region of semiconductor, a positive ion left behind near the junction. This positive ion is fixed or immobile. These positive and negative ions on both the sides of the junction form a depletion layer or *depletion region* or *space charge region* or *transition region.* This layer is known as depletion layer because it is depleted of free and mobile charge carriers. The thickness of depletion layer is about 10^{-3} mm or 10^{-6} m.

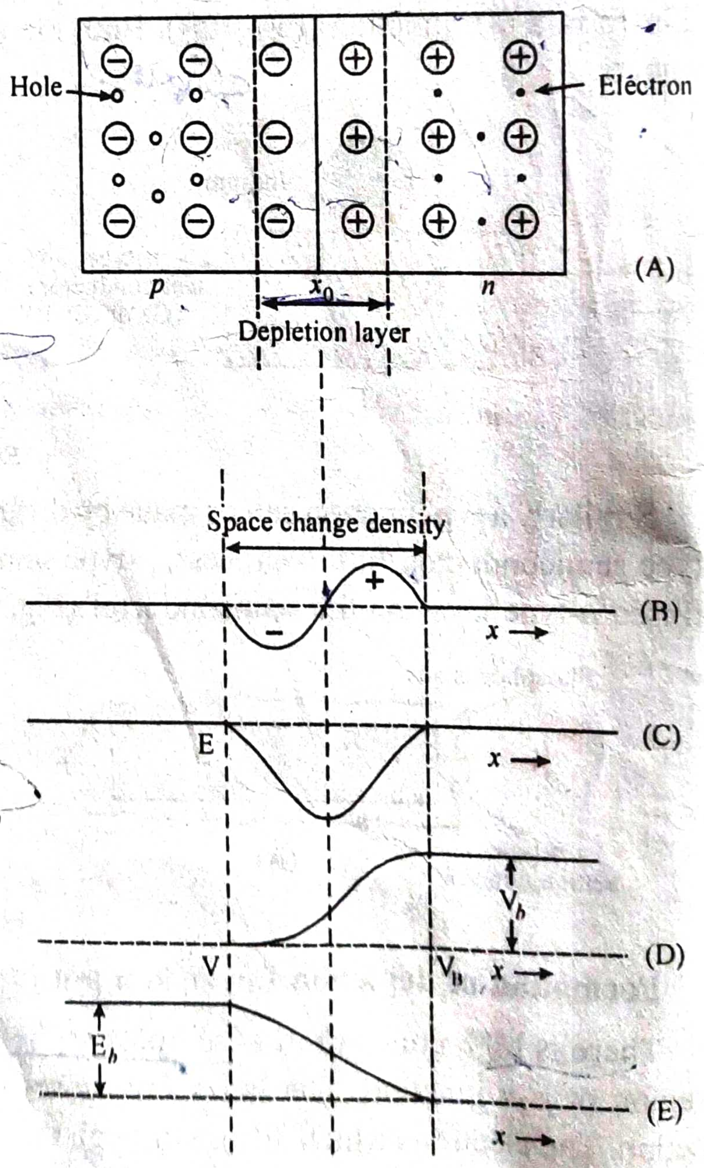


Fig. 13.

Junction Barrier *i.e.* Barrier Potential

The depletion layer contains positive and negative immobile ions. These positive and negative ions are separated by a distance equal to the thickness of the depletion layer. Thus, a potential difference is set up across the junction which opposes the further diffusion of electrons and holes through the junction. This potential difference is called **potential barrier** (V_b) (Fig. 13 A).

Thus, electric field ($\vec{E}$) appears across the junction. This electric field is also known as *barrier field* and it is directed from +ve ions to –ve ions in the

10.14. Unbiased *p-n* junction

When a *p*-type semiconductor is brought in close contact with an *n*-type semiconductor, the assembly formed is called the *p-n* junction. The portion of contact between the two types of semiconductors is called the junction. There are large number of free electrons in *n*-type semiconductor and a large number of holes in the *p*-type semiconductor. At the junction of two semiconductors, electrons diffuse into the *p* region from *n* region and are neutralized by an equal number of holes. Similarly, holes from the *p*-region enter into the *n* region through the junction where they are neutralized by an equal number of electrons. The diffusion of electrons from the *n* region into the *p* region through the junction leaves the donor atoms as positively charged ions. Also, the diffusion of holes from the *p* region into the *n* region leaves the acceptor atoms as negatively charged ions as shown in Figure 10.15*(a)*. These positively and negatively charged ions are called *unneutralized charges* or *uncovered charges.* As a result of the production of uncovered charges, *p* semiconductor develops a negative potential and *n* semiconductor develops a positive potential. It means that a potential difference arises between the *p* and *n* semiconductors which stops the further diffusion of electrons in the *p* region and holes into the *n* region. This potential difference is called the barrier potential or built in potential and is denoted by V_B. Its value is approximately 0·3 V for *pn* junction made of Ge and approximately 0·7 V for silicon. The electric field corresponding to this potential barrier is called the barrier field and it is directed from *n*-type semiconductor to the *p*-type semiconductor.

As yet only the diffusion of electrons across the junction has been discussed. Apart from diffusion, drift of electrons and holes also takes place across the junction. Under the effect of the barrier electric field, the minority charge carriers in *p*-semiconductor (*i.e.* electrons) are drifted towards the *n* region

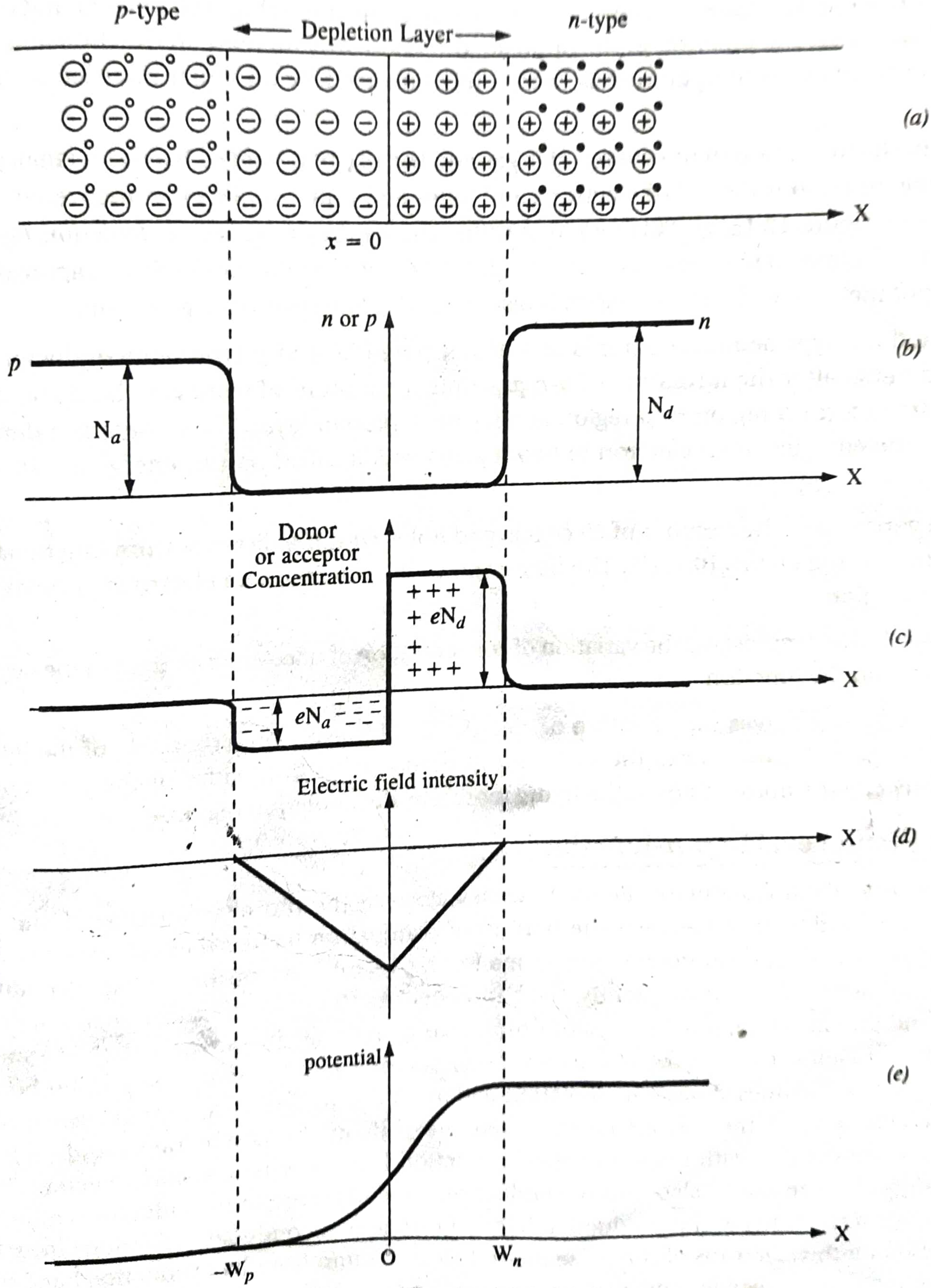


Figure 10.15.

and the minority carriers in n-semiconductor (*i.e.* holes) are drifted towards the p region. As a result of the drift of these electrons and holes, a drift current starts flowing across the p-n junction. The diffusion and drift of electrons and holes continues till the equilibrium between the drift current and diffusion current is reached. It may be noted that drift current and diffusion current flow across the junction in the opposite direction. Any increase in the diffusion current due to the increase in temperature is completely balanced by an equal increase in the drift current.

Due to the formation of uncovered charges and the rise of potential barrier, a small portion around the junction is devoid of electrons and holes and only contains the uncovered charges as shown in Figure 10.15*(a)*. This region is called the *depletion region* or *depletion layer.* The thickness of this region may be a fraction of a micron or more and the barrier field is approximately 10^7 volt per metre. The depletion region is also termed as the space charge region.

Since the n-type semiconductor is at a higher potential and p type semiconductor is at a lower potential after the formation of p-n junction, an amount of work is to be done to bring the electrons form n region to p region across the depletion layer. Thus, there is a difference between the energies of an electron in two regions and is called barrier energy E_B. Therefore, $E_B = eV_B$.

The variation of the number of electrons and holes with the distance from junction ($x = 0$) is as shown in the Figure 10.15(b). The figure shows that there are no electrons or holes in the depletion region.

Figure 10.15*(c)* represents the variation of concentration of uncovered charges in the depletion region around the junction.

Figure 10.15*(d)* gives the variation of electric filed intensity on either side of the junction whereas Figure 10.15*(e)* shows the variation of potential on both sides of the junction. The space between the dotted lines in the figure represent the depletion region.

10.15. Fermi Level in p-n-junction

In a p-type semiconductor, Fermi level lies close to the top of valence band and in an n-type semiconductor, it lies near the bottom of conduction band. When a contact between the p-type and n-type semiconductor is made, the Fermi level of the two semiconductors attains the same value. Consequently, the band edges in the p-type semiconductor are raised above and that in n-type semiconductor drop down to make an alignment with the Fermi level as shown in Figure 10.16 in the energy level diagram of a p-n junction. The portion between the dotted vertical lines shows the depletion region. In this region, an abrupt change in energy takes place. If V_B is the barrier height, then the shift in the conduction band of p-type semiconductor is eV_B with respect to the conduction band of n-type semiconductor. Clearly, the energy of the minority electrons in conduction band of p-type semiconductor is more than the energy of electrons in the conduction band of n-type semiconductor. Therefore, there is no restriction on the electrons of p-type semiconductor to jump from its conduction band to the conduction band of n-type semiconductor by crossing the depletion region.

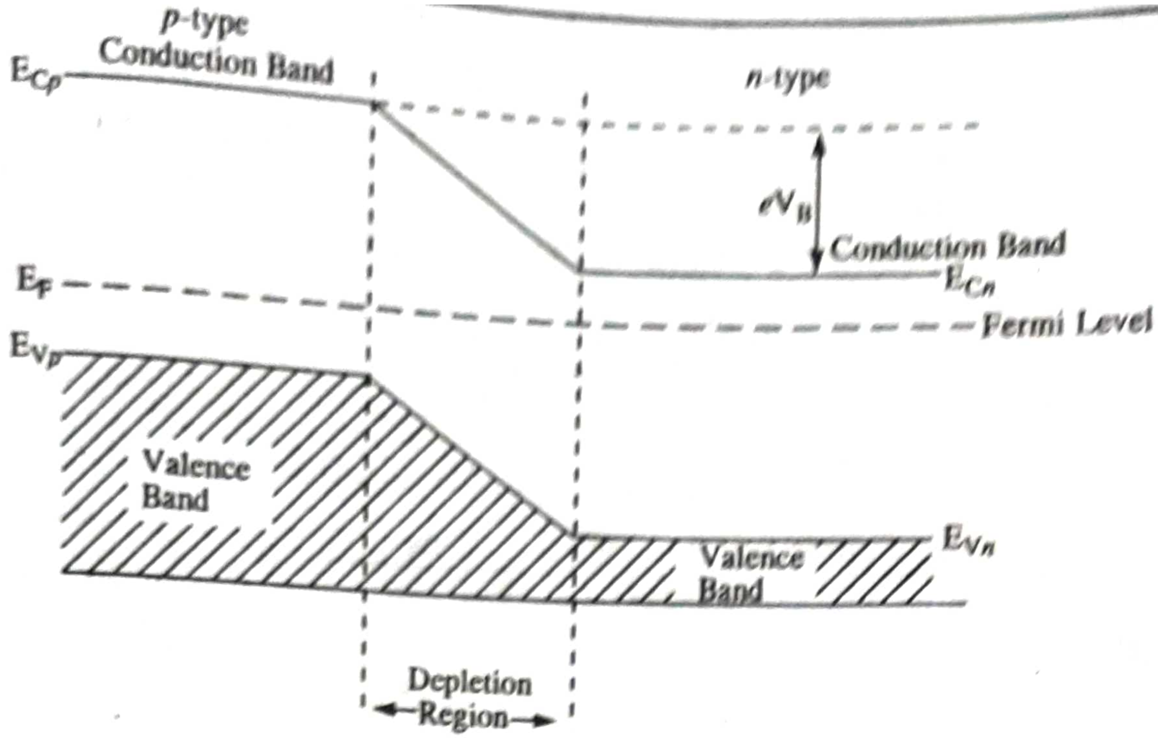


Figure 10.16.

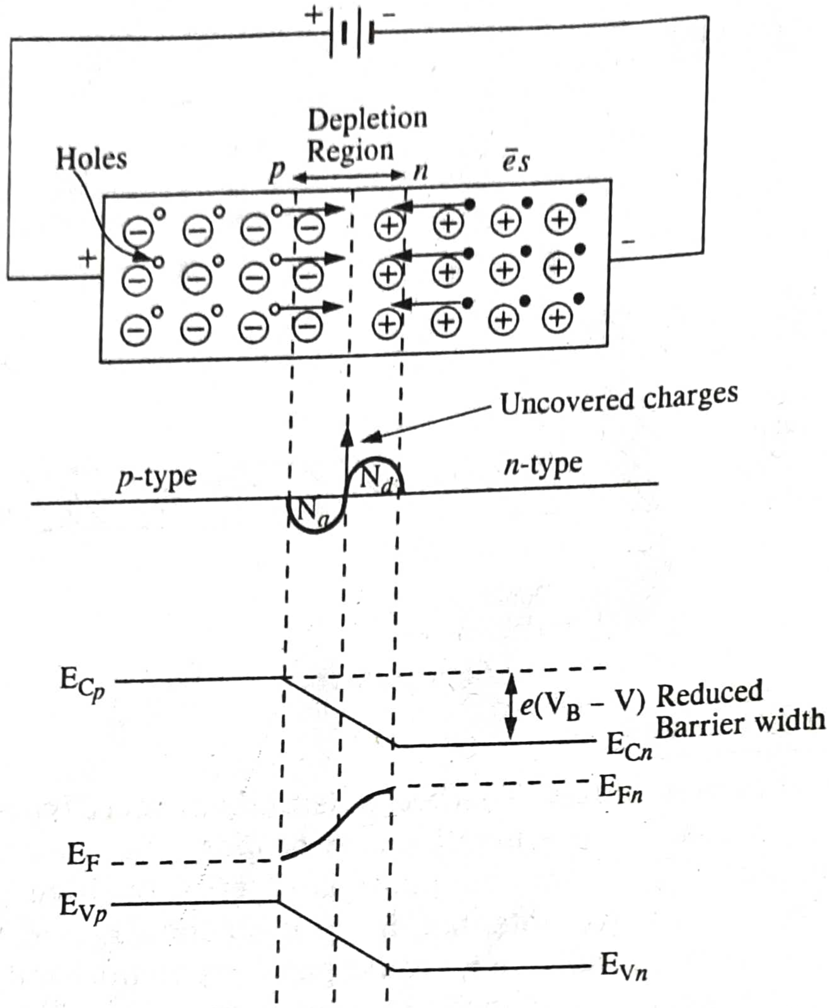
10.16. Biased *p-n* Junction

A p-n junction is said to be biased, if a direct potential difference is applied across the n and p regions of the p-n junction. The p-n junction may be biased in two ways : Forward bias and Reverse bias. When the *p*-type semiconductor is given a positive potential and *n*-type semiconductor is given a negative potential, the *p-n* junction is said to be forward biased. However, when the *n*-type semiconductor is given a positive potential and *p*-type semiconductor is given a negative potential, the *p-n* junction is said to be reverse biased. We shall study the behaviour of *p-n* junction in both the cases.

(a) **Forward Bias.** When the forward bias is applied, majority electrons in the *n*-type semiconductor and majority holes in the *p*-type semiconductor are repelled towards the junction as shown in Figure 10.16*a*. As a result of it, the effective potential barrier is reduced. If the forward voltage V is applied, then the barrier width becomes $V_B - V$ (assuming that $V < V_B$), where V_B is the potential barrier width. Also, the magnitude of the barrier energy is reduced to $e(V_B - V)$. This reduces the width of depletion region as well as the width of uncovered charges. It is as shown in the Figure 10.16*(b)*.

If the forward bias is increased beyond the barrier potential, the electrons penetrate into the *p* region and holes penetrate into the *n* region and combine with each other to neutralize. As soon as an electron-hole pair combines, a new electron emerges in the *n*-type semiconductor and a new hole in *p*-type semiconductor. Thus a current is established across the junction.

The forward bias reduces the resistance of the *p-n* junction. When the forward voltage is increased, the resistance is almost reduced to zero and the current is increased. Minority carriers current also flows opposite to the forward current but it does not affect the forward current because the current due to minority carriers is a function of temperature only.



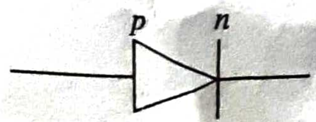
[E_{Cp} = Energy of bottom of conduction band in p semiconductor, E_{Vp} is energy of top of valence band in p semiconductor, E_{Fp} is the energy of Fermi level in p semiconductor and E_{Cn}, E_{Vn}, E_{Fn} are corresponding terms in n-type semiconductor]

Figure 10.16.

Reverse Bias. When a reverse voltage is applied, majority electrons in *n*-type semiconductor and majority holes in *p*-type semiconductor are pulled apart from the junction, as shown in Figure 10.17(*a*). Therefore, the width of the depletion region and the width of uncovered charges is increased. If V is the reverse voltage, then the barrier height becomes $V_B + V$ and the barrier energy becomes $e(V_B + V)$. As a result of it, the current is reduced almost to zero. The junction offers a large resistance in this case.

Since there are minority electrons in the *p*-type semiconductor and minority holes in *n*-type semiconductor, there is a flow of very small current in the reverse direction. The generation rate of minority carriers depends upon temperature. Therefore, for the fixed temperature conditions, the generation rate of minority carriers and hence the current remain constant (*i.e.* independent of reverse voltage). This is the reason that the reverse current is also called the reverse saturation current. However, if a large reverse potential difference is applied, the crystal structure breakdown may occur, giving rise to a sudden increase in the reverse current.

Representation of a *p-n* junction diode. A *p-n* junction diode is represented by the following symbol :



The p region is termed as anode and the n region is termed as cathode.

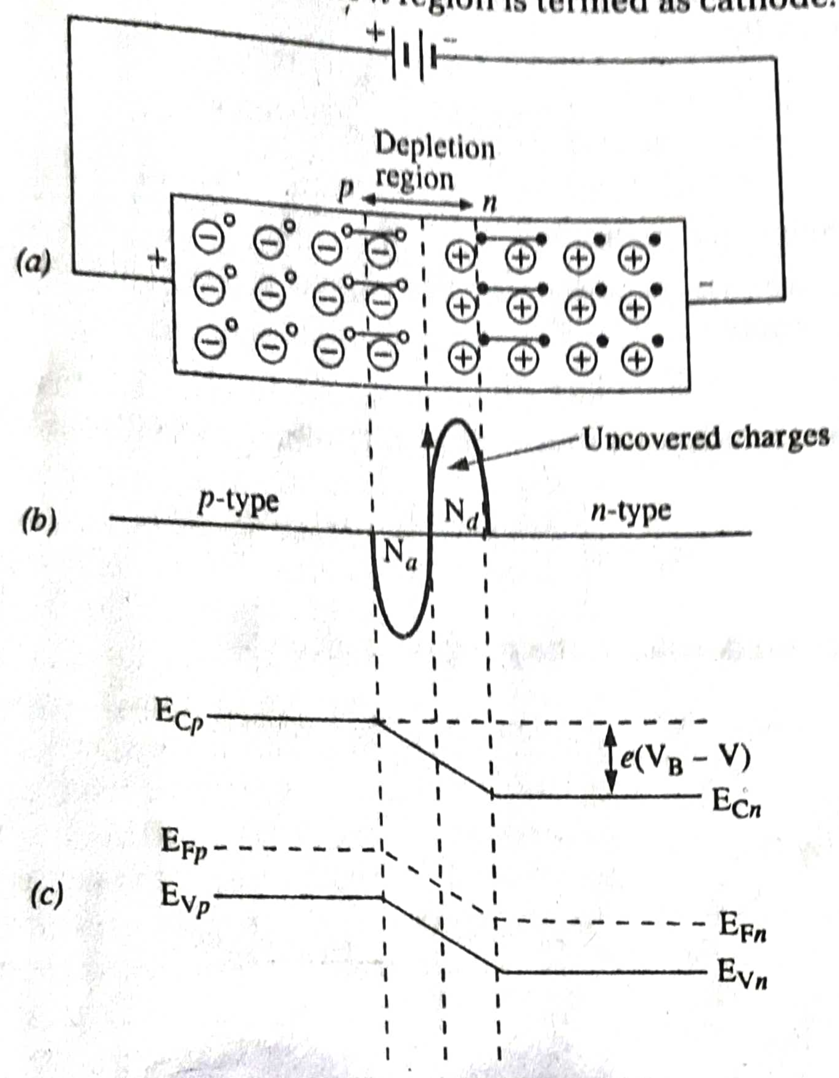


Figure 10.17.