3.5 CURRENT FLOW IN SEMICONDUCTORS

In the absence of an externally applied electric field, the current carriers (i.e., electrons and holes) in a semiconductor move in a random fashion on account of their thermal energy (Fig. 3.14*a*). The frequent changes in the direction of motion of the carriers arise from their scattering by the thermal vibrations of the lattice atoms and by the Coulomb fields of the ionized impurity atoms. When an external electric field is applied, a drift velocity is superimposed on the random thermal velocity of the carriers (Fig. 3.14*b*). In the steady state, the rate at which the carriers gain energy and momentum from the field equals that at which they lose energy and momentum through scattering. Under this condition, the drift velocity attains a steady value, giving a steady electric current.

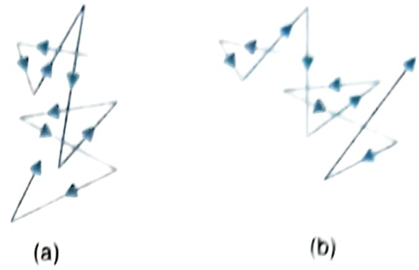

Fig. 3.14 (a) Random thermal motion (b) drift plus random motion of a current carrier.

(*a*) *n*-Type Semiconductors

In an *n*-type material, the electrons are the majority carriers. We neglect here, for simplicity, the contribution of the holes which are the minority carriers to the electric current. Let a battery be connected to a pair of electrodes fitted at the ends of a bar of an *n*-type semiconductor (Fig. 3.15). The resulting electric field in the semiconductor bar will cause a steady drift of the free electrons inside the bar towards the positive electrode. On reaching the positive electrode the electrons disappear and the immobile positive donor ions close to the negative electrode become unneutralized. Consequently, these positive ions attract electrons from the negative electrode. In this way, a continuous flow of electrons from one terminal to the other of the battery through the semiconductor bar takes place.

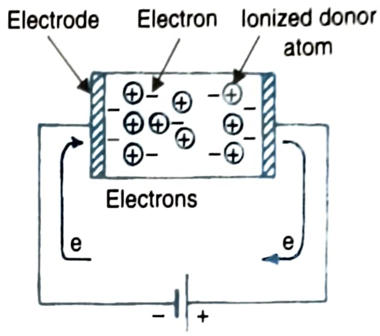

Fig. 3.15 Current flow in an *n*-type material.

(*b*) *p*-Type Semiconductors

Here, the holes are the majority carriers. We neglect the contribution of the electrons to the current. Let a *p*-type semiconductor bar be inserted between a pair of electrodes which are connected to the two terminals of a battery (Fig. 3.16). The electric field produced in the semiconductor bar will cause a constant drift of the holes towards the negative electrode. As the holes reach the negative electrode, they recombine with the electrons emerging from the negative electrode and thus collapse. The process leaves immobile negatively charged acceptor atoms in the vicinity of the positive electrode unneutralized. The positive electrode attracts the extra electrons of these acceptor atoms. Consequently, these electrons leave the acceptor atoms, come to the positive electrode and are lost there. The acceptor atoms then collect electrons from the adjacent covalent bonds, thereby creating holes. The holes disappearing at the negative electrode are thus replenished by the new holes produced near the positive electrode. Notice

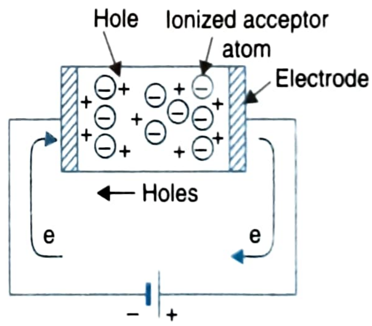

Fig. 3.16 Current flow in a *p*-type material.

For an n-type semiconductor, $n >> p$, so that the relevant conductivity is

$$\sigma_{n\text{ type}} = ne\mu_n \tag{3.11}$$

For a p-type semiconductor, $p >> n$ and the product $p\mu_p$ is greater that $n\mu_n$ for heavily doped materials. In this case we have

$$\sigma_{p\text{ type}} = pe\mu_p \tag{3.12}$$

Carrier Mobility

If an electric field F is applied to a semiconductor, the rate at which a current carrier gains momentum from the field is eF, by Newton's second law of motion. Here e is the charge of the carrier. The rate at which the carrier loses momentum through scattering is usually given by $m^* v/\tau$, where m^* is the effective mass of the carrier and v is its drift velocity. The quantity τ has the dimension of time and is referred to as the *momentum relaxation time*. It has the significance that when the field is removed, the momentum reduces to 1/exp (1) of its initial value in time τ. In the steady state, the rate of gain of momentum from the electric field equals the rate of loss of momentum through scattering, *i.e.*

$$eF = \frac{m^* v}{\tau}.$$

The mobility is thus expresssed by

$$\mu = \frac{v}{F} = \frac{e\tau}{m^*} \tag{3.13}$$

Usually, τ is a function of the carrier energy and the mobility is correctly written in the form

$$\mu = \frac{e < \tau >}{m^*}. \tag{3.14}$$

where $< \tau >$ represents an average value of τ involving all the carriers. In SI, e is in coulomb, τ is in second, and m^* is in kg, whence μ comes out in $m^2/(V.s)$.

3.6 HALL EFFECT

If a piece of current-carrying conductor (metal or semiconductor) is placed in a transverse magnetic field, an electric field appears inside the conductor in a direction perpendicular to both the current and the magnetic field. This phenomenon is referred to as the *Hall effect* and the electric field that is created is known as the *Hall field*.

We consider a rectangular specimen of the material carrying a current I in the positive x-direction. Let a magnetic field of induction B be applied along the positive z-direction (Fig. 3.18). A magnetic force will act on the current carriers in the negative y-direction. Consequently the carriers are deflected towards the bottom surface of the specimen and will accumulate there. If the semiconductor is n-type so that the current carriers are electrons, the collection of these electrons on the bottom surface makes it negatively charged relative to the top surface. As a result, an electric field, called the Hall field, appears along the negative y-direction. The force on the current-carrying electrons owing to the Hall field opposes the magnetic force. When the two forces cancel each other, no further accumulation of electrons occurs on the bottom surface. An equilibrium is then established and the Hall field acquires a steady value.

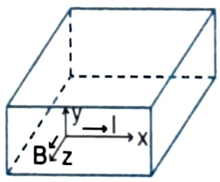

Fig. 3.18 Illustration of the Hall effect.

If the semiconductor is p-type so that the current is carried by holes, the accumulation of the holes on the bottom surface makes this surface positively charged with respect to the top surface.

The Hall field is now developed along the positive y-direction. The force on the holes due to the Hall field is opposite to the magnetic force. In equilibrium, these two forces balance and no further collection of holes is possible. The Hall field then becomes steady.

The average magnetic force on a current carrier is Bev, where e is the charge of a carrier and v is its drift velocity in the x-direction. If F_H is the Hall field developed in the y-direction, the force on a current carrier exerted by this field is eF_H. In equilibrium, the two forces balance so that

$$e F_H = B ev \tag{3.15}$$

If n_0 is the carrier concentration, the current density in the x-direction is

$$J = n_0 ev \tag{3.16}$$

Equations (3.15) and (3.16) give

$$F_H = \frac{J B}{n_0 e} \tag{3.17}$$

The quantity $F_H/(JB)$ represents the Hall field per unit current density per unit magnetic field and is known as the *Hall coefficient*, R_H. Thus

$$R_H = \frac{F_H}{J B} = \frac{1}{n_0 e}, \tag{3.18}$$

using Eq. (3.17). A rigorous analysis shows that

$$R_H = \frac{r}{n_0 e}, \tag{3.19}$$

where r is a constant not much different from unity. Thus the error resulting from using Eq. (3.18) for R_H is not large.

When the current is carried by electrons, the carrier charge is negative so that

$$R_H = -\frac{1}{n e}, \tag{3.20}$$

where n is the electron concentration.

If, on the other hand, the current carriers are holes, the carrier charge is positive. Therefore

$$R_H = \frac{1}{p e}, \tag{3.21}$$

where p is the hole concentration. The *sign* of the Hall coefficient is thus *opposite* for n- and p-type materials.

When both the electrons and the holes contribute to the current, the Hall coefficient can be determined as follows. Since the charges of the electrons and the holes are opposite and they are deflected in the same direction by the magnetic field, the net deflection current density in the y-direction is $(e p v_{yp} - e n v_{yn})$, where v_{yp} and v_{yn} denote respectively the y-components of the hole and the electron velocities arising from the deflection by the magnetic field. In equilibrium, this current density is balanced by the current density σF_H produced by the Hall field, σ being the conductivity. In other words,

$$\sigma F_H = e p v_{yp} - e n v_{yn} \tag{3.22}$$

Let v_{xp} and v_{xn} be respectively the drift velocities of the holes and the electrons along the x-direction. The magnetic force on a hole is Bev_{xp} and this produces the velocity v_{yp}. In equilibrium, the magnetic force is balanced by the rate of loss of the y-component of the hole momentum caused by scattering. Thus

$$Bev_{xp} = \frac{m_p v_{yp}}{\tau_p} \tag{3.23}$$