Study Material

(Semiconductor Physics, BBS00015)

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Table of Contents

Contents

Semiconductors: Intrinsic and extrinsic semiconductors

Solid-state materials can broadly be divided into three classes – insulators, semiconductors and conductors. While through any conductor electric charges can flow easily, insulators do not conduct electricity at normal conditions. There is another group of materials, such as germanium and silicon, whose conductivity lies between conductors and insulators. At room temperature, these materials have conductivities considerably lower than that of the conductors, but much higher than that of insulators. These materials are known as semiconductors.

When the temperature of a conductor, such as copper, increases, its resistivity increases. However, the resistance of a semiconductor increases with the decrease in temperature and vice versa. Thus, semiconductors have a negative temperature coefficient.

The conducting properties of a semiconductor change to a large extent by adding a little amount of some specific materials called impurities. Semiconductors that do not contain any impurity atoms or defects are called **intrinsic** (or **pure**) **semiconductors.** On the other hand, those semiconductors that contain impurities are called **extrinsic** (or **doped**) **semiconductors.** Extrinsic semiconductors are further divided into N-type and P-type semiconductors, depending on the type of impurity added.
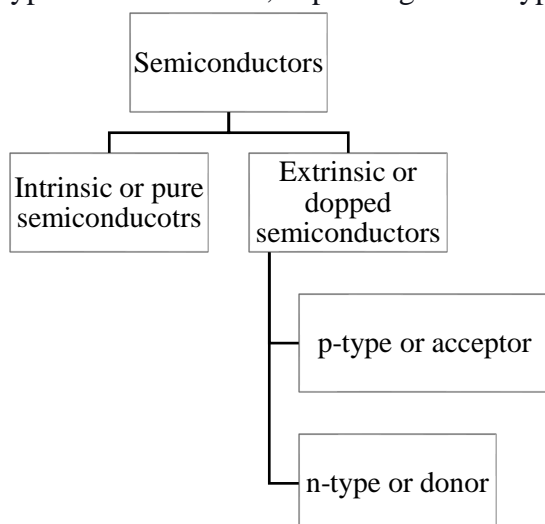
Intrinsic Semiconductors

An intrinsic semiconductor does not contain any impurity atoms or defects. Silicon (Si) and Germanium (Ge) are two common examples of intrinsic semiconductors. At absolute zero, all the valence electrons are
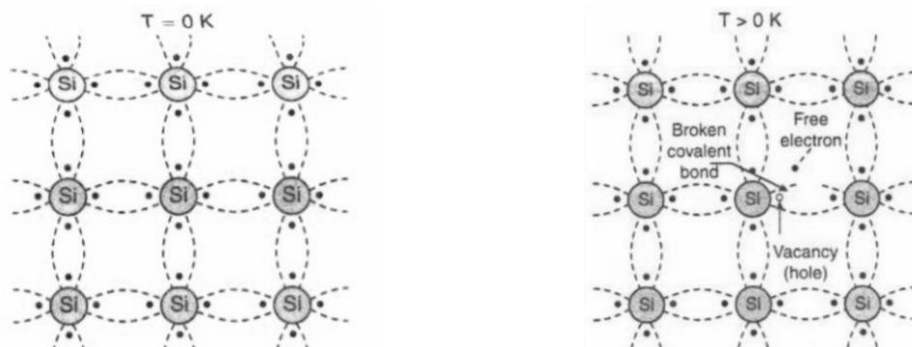

Fig. 1 Simplified representation of the crystalline structure of a semiconductor at (a) T = 0 K and at (b) $T > 0$ K.

tightly bound to the parent atoms. Therefore, no free electrons are available for electrical conduction. Thus, the semiconductor behaves as a perfect insulator at absolute zero temperature. Room temperature is sufficient to break a covalent bond and the electron becomes free to move in the crystal. In other words, at room temperature the thermal energy of the electrons at the valence band are enough to overcome the energy gap and reach the conduction band. Thus, free electrons are generated that can conduct electricity. When an electron becomes a free electron by breaking a bond a vacancy is created in the broken covalent bond. This vacancy or the absence of an electron is called a hole. Whenever a free electron is generated, a hole is simultaneously created. Therefore, concentration of free electrons and that of the holes are always equal in an intrinsic semiconductor.

The higher the temperature, the concentration of charge carriers becomes higher, since more charge carriers are available. The conductivity of an intrinsic semiconductor, therefore, increases with temperature. Hence the resistivity (inverse of conductivity) decreases as the temperature increases. Thus, the semiconductors have a negative temperature coefficient of resistance.

Extrinsic Semiconductors
A doped semiconductor is called an extrinsic semiconductor. Practically all the semiconductor devices are made of extrinsic semiconductors. The electrical conductivity of a semiconductor depends on its level of doping. The addition of impurity significantly increases the conductivity of a semiconductor. The added impurity is called dopant. The doping agents used are of two types, resulting in two types of extrinsic semiconductor, (a) N-type semiconductors and (b) P-type semiconductors.

N- type semiconductors

When a small amount of pentavalent impurity, for example, phosphorus (P), arsenic (As), or antimony (Sb) is added to a sample of intrinsic semiconductor (pure Si or Ge), an N-type semiconductor is formed. Silicon of Group IV has four valence electrons and phosphorus of Group V has five valence electrons. The fifth electron has no chance to form a covalent bond. It requires very little energy to free itself from the attractive force of its nucleus. This energy is only 0.01 eV in the case of germanium and 0.05 eV in the case of silicon. This energy is so small that at room temperature practically all such electrons become free. At room temperature, each impurity atom donates one electron to the conduction band. This type of impurity is called donor type. All the electrons that have been donated by the impurity atoms can take part in the conduction of electric current. The number of thermally generated electron-hole pairs is very small compared to the number of free electrons due to the impurity atoms. Therefore, the number of free electrons is much higher than the number of holes. Thus, in an N-type semiconductor electron are the majority charge carriers and holes are the minority charge carriers.
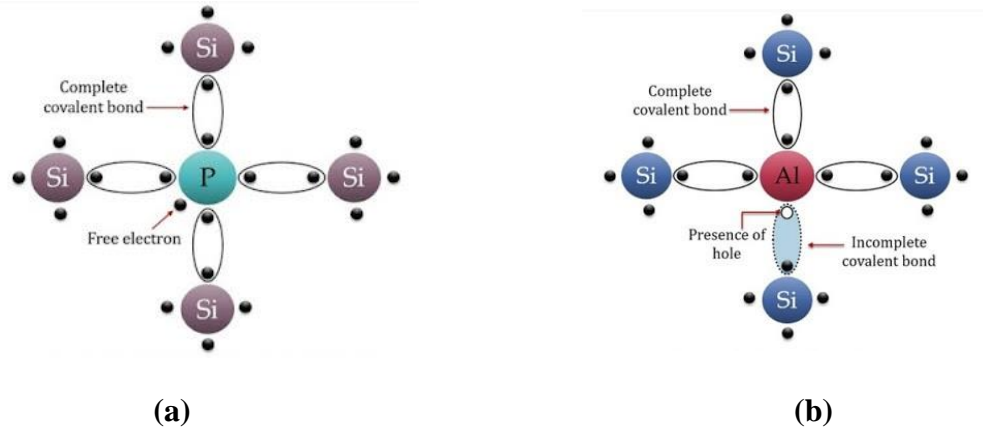
(a)   **(b)**

Fig. 2: Schematic diagram of electronic configuration in (a) an N-type semiconductor and (b) a P-type semiconductor

P-type semiconductors

When a small amount of trivalent impurity, e.g., boron (B), gallium (Ga) or indium (In) is added to a sample of intrinsic semiconductor (pure Si or Ge), a P-type semiconductor is formed. The trivalent boron atom has only three valence electrons. These electrons form covalent bonds with the three neighbouring silicon atoms. But the fourth neighbouring silicon atom remains unable to form a covalent bond with the boron atom since the fourth electron is not available in its valence orbit. Thus, there remains a deficiency of an electron or hole around the boron atom. An electron in an adjacent covalent bond, having very small additional energy, can jump to occupy the vacant position or recombine with the hole. This electron then completes the covalent bond around the boron atom. The additional energy required for this is of the order of 0.01 eV. During the jump of the electron from the adjacent covalent bond, a vacancy, or, hole is created in the adjacent bond from where the electron had jumped. Due to the filling of the incomplete bond around boron, it now becomes a negative ion by accepting one electron. This type of impurity is called acceptor type. Besides the excess holes created due to the addition of an acceptor-type impurity, there are also some holes generated by breaking covalent bonds. A P-type material thus has holes as the majority charge carriers and free electrons as the minority charge carriers.

Density of states in conduction and valence bands

The density of states gives the number of allowed states (electron states or hole states) per volume at a given energy. Let, E_c represents the minimum electron energy in the conduction band and E_v represents the maximum hole energy in the valence band. The density of states function in the conduction band, $D_c(E)$ and the density of states function in the valence band, $D_v(E)$ can be represented as follows,

$$D_c(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E - E_c)^{1/2} \qquad \text{for } E > E_c \qquad (1)$$

$$D_v(E) = \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_v - E)^{1/2} \qquad \text{for } E_v > E \qquad (2)$$

m_e^* and m_h^* represents effective masses of electrons and holes respectively, h is the Planck's constant. The density of states in the forbidden gap region is zero.

Electron and hole concentration in intrinsic semiconductors

In intrinsic semiconductor the concentration of electron and hole must be the same since they are thermally generated in pairs. The electron concentration and hole concentration in the respective conduction band and valence band can be determined statistically by using the density of states function and Fermi Dirac distribution function. The Fermi Dirac distribution function can be written as follows,

$$f(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{k_B T}\right)} \qquad (3)$$

where E_F is the Fermi energy and k_B is Boltzmann constant.

In conduction band, the distribution of electrons is given by the density of states times the probability that a state is occupied by an electron.

At thermal equilibrium the concentration of electron per unit volume in the conduction band, n_0 is found by integrating this function over the entire conduction band energy.

$$n_0 = \int_{E_c}^{\infty} D_c(E) f(E) dE \qquad \text{………..} (4)$$

where $D_c(E)$ is the density of states of electron in conduction band and $f(E)$ is the Fermi-Dirac distribution function. The lower limit of the integration is taken as E_c, the minimum energy of conduction band and the upper limit of the integration is taken as infinity. Substituting the value from Eqn. (1) and Eqn. (3) in Eqn. (4) one can obtain the following expression.

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_e^*)^{3/2}(E-E_c)^{1/2}}{h^3} \frac{1}{1 + \exp\left[\frac{(E-E_F)}{k_B T}\right]} dE$$

$$\text{…………..} (5)$$

Assuming the Fermi energy E_F is within the forbidden gap region, for electrons in the conduction band, $E > E_c$. If $E_c - E_F \gg k_B T$, then $E - E_F \gg k_B T$ [Thermal energy $k_B T$ at room temperature ≈ 0.026 eV]

Therefore, we can write $1 + \exp\left[\frac{(E-E_F)}{k_B T}\right] \approx \exp\left[\frac{(E-E_F)}{k_B T}\right]$ and $f(E) = \frac{1}{1+\exp\left[\frac{(E-E_F)}{k_B T}\right]} \approx \exp\left[\frac{-(E-E_F)}{k_B T}\right]$

Applying the Boltzmann approximation to Eqn. (5), concentration of electrons at thermal equilibrium in conduction band is given by,

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_e^*)^{3/2}(E-E_c)^{1/2}}{h^3} \exp\left[\frac{-(E-E_F)}{k_B T}\right] dE$$

$$\text{….............} (6)$$

By solving the integration of Eqn. (6), electron concentration in conduction band at thermal equilibrium can be obtained as follows. [Details of the derivation is not required]

$$n_0 = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} \exp\left[\frac{-(E_c - E_F)}{k_B T}\right]$$

Therefore

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{k_B T}\right]$$

…………... (7)

where, $N_c = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}$ is the effective density of states in the conduction band.

Similarly, in valence band, the hole distribution is given by the density of allowed states times the probability that a state is not occupied by an electron.

At thermal equilibrium the hole concentration per unit volume in the valence band, $p_0(E)$ is found by integrating this function over the entire valence band energy.

$$p_0 = \int_{-\infty}^{E_v} D_v(E)[1 - f(E)]dE$$

………... (8)

where $D_v(E)$ is the density of states of holes in valence band and $f(E)$ is the Fermi-Dirac distribution function. The upper limit of the integration is taken as E_v , the maximum energy of valence band and the lower limit of the integration is taken as -∞ since $[1 - f(E)]$ decays with increasing energy, E to the downward direction from the top of the valence band. Substituting the value from Eqn. (2) and Eqn. (3) in Eqn. (8) one can obtain the following expression.

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_h^*)^{3/2}(E_v - E)^{1/2}}{h^3}\left[1 - \frac{1}{1 + \exp\left[\frac{(E - E_F)}{k_B T}\right]}\right]dE$$

…………... (9)

In the valence band, $E_v > E$. If $E_F - E_v \gg k_B T$ (thermal energy $k_B T$ at room temperature ≈ 0.026 eV).

Therefore, we can write $1 - f(E) = \frac{1}{1+\exp\left[\frac{(E_F-E)}{k_B T}\right]} \approx \exp\left[\frac{-(E_F-E)}{k_B T}\right]$

then applying the Boltzmann approximation to Eqn. (9), hole concentration at thermal equilibrium in the valence band is given by,

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_h^*)^{3/2}(E_v - E)^{1/2}}{h^3} \exp\left[\frac{-(E_F - E)}{k_B T}\right] dE$$

…............... (10)

By solving the integration of Eqn. (10), hole concentration in valence band at thermal equilibrium can be obtained as follows. [Details of the derivation is not required]

$$p_0 = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} \exp\left[\frac{-(E_F - E_v)}{k_B T}\right]$$

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{k_B T}\right]$$

………….. (11)

where, $N_v = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2}$ is the effective density of states in the valence band.

In intrinsic semiconductor the Fermi energy level E_F can be replaced by E_{Fi}.

Law of mass action

In an intrinsic semiconductor the number of free electrons in the conduction band is equal to the number of holes in valence band. In intrinsic semiconductor at a particular temperature T the electron and hole concentration can be represented as n_i and p_i respectively. Therefore, $n_0 = p_0 = n_i = p_i$. Here we can use the parameter n_i as the carrier concentration of intrinsic semiconductor that refers to either the intrinsic electron or hole concentration. The Fermi energy level in intrinsic semiconductor can be written as E_{Fi}.

In thermal equilibrium at a given temperature the product of electron and hole concentration is always a constant and is equal to the square of the intrinsic carrier concentration.

Therefore, $n_0 p_0 = n_i^2$, where n_0 and p_0 represents the electron and hole concentration at thermal equilibrium.

Now by using Eqn. (7) and (11) we can write,

$n_0 p_0 = n_i^2 = N_c \exp\left[\frac{-(E_c - E_{Fi})}{k_B T}\right] N_v \exp\left[\frac{-(E_{Fi} - E_v)}{k_B T}\right]$ (Considering E_{Fi} as Fermi energy level of intrinsic semiconductor.)

Therefore, $n_i = (N_c N_v)^{1/2} \exp\left[-\frac{(E_c - E_v)}{2k_B T}\right] = (N_c N_v)^{1/2} \exp\left[-\frac{E_g}{2k_B T}\right]$, where $E_c - E_v = E_g$ is the bandgap of the semiconductor. At constant temperature n_i is constant and independent of Fermi energy.

By using $N_c = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}$ and $N_v = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2}$, the intrinsic carrier concentration, n_i can be written as follows,

$$n_i = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2} (m_e^* m_h^*)^{\frac{3}{4}} \exp\left[-\frac{E_g}{2k_B T}\right]$$

…………… (12)

Eqn. (12) can be written as $n_i = CT^{\frac{3}{2}} \exp\left(-\frac{E_g}{2k_BT}\right).$ ……….. (13)

Where, $C = 2\left(\frac{2\pi k_B}{h^2}\right)^{3/2}(m_e^* m_h^*)^{\frac{3}{4}}$

Location of Fermi Energy level of an intrinsic semiconductor

In an intrinsic semiconductor,

$$n_0 = p_0 = n_i(T)$$

$\therefore \quad N_c \exp\left[\frac{-(E_c - E_{Fi})}{k_BT}\right] = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{k_BT}\right]$

$\Rightarrow \quad 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}\exp\left[\frac{-(E_c - E_{Fi})}{k_BT}\right] = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2}\exp\left[\frac{-(E_{Fi} - E_v)}{k_BT}\right]$

$\Rightarrow \quad \exp\left[\frac{2E_{Fi} - (E_c + E_v)}{k_BT}\right] = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}}$

$\Rightarrow \quad \frac{2E_{Fi} - (E_c + E_v)}{k_BT} = \ln\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}}$

$\Rightarrow \quad E_{Fi} = \frac{E_c + E_v}{2} + \frac{3}{4}k_BT \ln\left(\frac{m_h^*}{m_e^*}\right)$ ………………………………… (14)

Now assuming the electron and hole effective masses to be the same, i.e., if $m_e^* = m_h^*$ then, $E_{Fi} = \frac{1}{2}(E_c + E_v)$.

Therefore, the Fermi energy level of an intrinsic semiconductor should be located at the middle of the bandgap. Though in reality m_h^* is slightly greater than m_e^*, for this reason the Fermi level is not exactly located at the middle of the gap but slightly above towards the conduction band edge.

Electrical conductivity of an intrinsic semiconductor

The electrical conductivity of an intrinsic semiconductor is given as,

$\sigma_i = \sigma_e + \sigma_h = n_i\mu_e|e| + p_i\mu_h|e|$ ………………….. (14)

$\therefore \sigma_i = n_i e\,(\mu_e + \mu_h)$ as $n_i = p_i$

where, n_i and p_i are electron and hole concentration and μ_e and μ_h are their respective mobilities.

Now, the mobility can be written as $\mu \propto T^{-\frac{3}{2}}$

Therefore, $\mu_e \propto T^{-\frac{3}{2}}$ and $\mu_h \propto T^{-\frac{3}{2}}$

$\therefore \mu_e = \alpha\, T^{-\frac{3}{2}}$ and $\mu_h = \beta\, T^{-\frac{3}{2}}$ (where α, β are proportionality constant)

$\therefore \sigma_i = n_i e\,(\alpha + \beta)T^{-\frac{3}{2}}$ ………………….(15)

By using Eqn. (13) in Eqn. (15),

$$\sigma_i = B \exp\left(-\frac{E_g}{2k_BT}\right), B = \text{constant}$$

$$\therefore \rho = A \exp\left(\frac{E_g}{2k_BT}\right), \text{where } A = \frac{1}{B} = \text{constant and } \sigma_i = \frac{1}{\rho}, \rho \text{ is the resistivity of semiconductor.}$$

Therefore, $\ln\rho = \ln A + \frac{E_g}{2k_BT}$ ………………(16)

Thus, the slope of $\ln\rho$ vs $\frac{1}{T}$ curve provides the bandgap energy value E_g.

Location of Fermi Energy level of an extrinsic semiconductor

In an extrinsic semiconductor at thermal equilibrium, for every free electron there must be a thermally generated hole or positively charged donor ion and similarly for every hole there must be either a thermally generated free electron or negatively charged acceptor ion. Thus, the entire semiconducting crystal is electrically neutral.

In an extrinsic semiconductor,

The general equations for electron and hole concentration can be represented as follows,

$$n = CT^{\frac{3}{2}} \exp\left[\left(\frac{-(E_c-E_f)}{k_BT}\right)\right] \qquad\qquad \text{…………… (i)}$$

$$\text{and} \quad p = CT^{\frac{3}{2}} \exp\left[\left(\frac{-(E_f-E_v)}{k_BT}\right)\right] \qquad\qquad \text{…………… (ii)}$$

C is the constant term [where we consider C is equal to $2\left(\frac{2\pi k_B m_e^*}{h^2}\right)^{\frac{3}{2}}$ for electron and $2\left(\frac{2\pi k_B m_h^*}{h^2}\right)^{\frac{3}{2}}$ for hole],

E_f signifies the Fermi level of extrinsic semiconductor.

For N type material;

$n > p$

$$\therefore CT^{\frac{3}{2}} \exp\left[\frac{-(E_c-E_f)}{k_BT}\right] > CT^{\frac{3}{2}} \exp\left[\frac{-(E_f-E_v)}{k_BT}\right]$$

$$\Rightarrow -(E_c - E_f) > -(E_f - E_v)$$

$$\Rightarrow (E_c - E_f) < (E_f - E_v)$$

It shows that the Fermi level shifts upward, closer to the conduction band in N-type semiconductor. Similarly, the Fermi level shifts downward, closer to the valence band in P-type semiconductor.
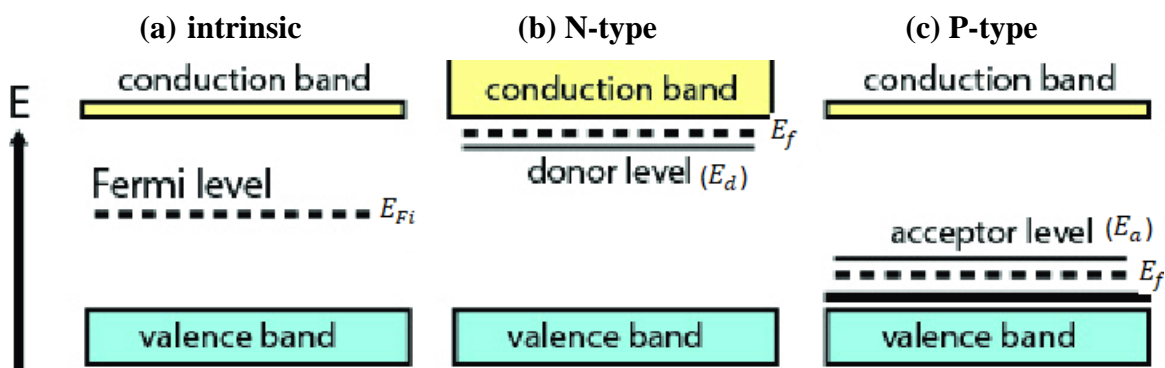

Fig. 2 Fermi energy level in an intrinsic and extrinsic semiconductor

Variation of Fermi Level with temperature and impurity concentration

For an N-type semiconductor, when the temperature is raised, the number of electron-hole pairs due to thermal excitation from the valence band to conduction band will increase. As the donor atoms are already ionized, the number of electrons coming from the donor level will remain constant. At very high temperature, the concentration of thermally generated free electrons from the valence band will be much larger than the concentration of free electrons contributed by the donors. At this situation, the hole and the electron concentrations will be nearly equal and the semiconductor will behave like an intrinsic one.

Similarly, at a very high temperature a P-type semiconductor will behave like an intrinsic semiconductor. The general result is that as the temperature of extrinsic semiconductor increases, the semiconductor becomes intrinsic one.

At very low temperature, some of the free carriers move into the impurity level and neutralize the charged impurity atoms.

Considering N-type semiconductor,

(i)   At $T = 0$ K, the Fermi level lies exactly half way between the donor level and bottom of the conduction band. So, $E_f = \frac{E_c + E_d}{2}$.

(ii)   As T increases, Fermi level falls below the donor level and it approaches to the centre of the forbidden gap, which makes the material an intrinsic semiconductor.

For N-type semiconductor, the formula of Fermi level will be (not valid for $T = 0$ K and T tends to infinity)

$$E_f = E_c + k_B T \ln \frac{N_d}{N_c} = E_c - k_B T \ln \left(\frac{N_c}{N_d} \right)$$

where, N_d = Concentration of donor atoms and $N_c = 2 \left(\frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}$.

Effect of doping concentration:

For a given T, the Fermi level shifts upward as concentration increases.

The density of electron is given by,

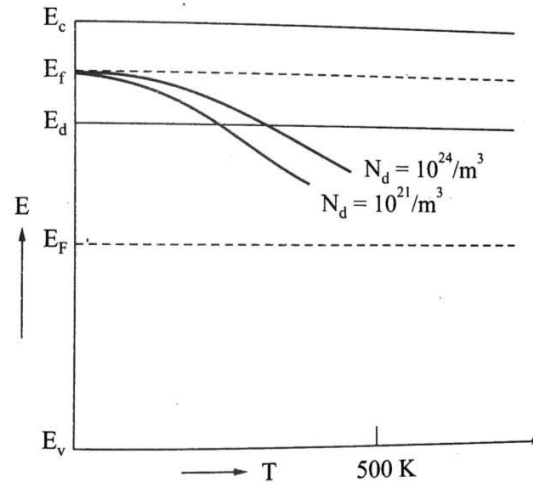$$n = (N_c N_d)^{\frac{1}{2}} \exp \left[-\frac{E_c - E_d}{2 k_B T} \right]$$

Fig. 3: The variation of Fermi level with temperature for different concentrations

For P-type semiconductor,

(i)   At $T = 0$ K, the Fermi level lies exactly halfway between the acceptor level and top of the valence band. So, $E_f = \frac{E_a + E_v}{2}$.

(ii)   As T increases, Fermi level moves upward, crosses the acceptor level and approaches the centre of the forbidden energy gap, which make the substance an intrinsic semiconductor.

The formula for Fermi level of P-type semiconductor (not valid for $T = 0$ K and T tends to infinity):

$$E_f = E_v + k_B T \ln \frac{N_v}{N_a}$$

where, N_a = Concentration of acceptor atoms.

$N_v = 2 \left(\frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2}$

Effect of doping concentration:

For a given T, the Fermi level shifts downward as concentration increases.

The density of holes is given by,

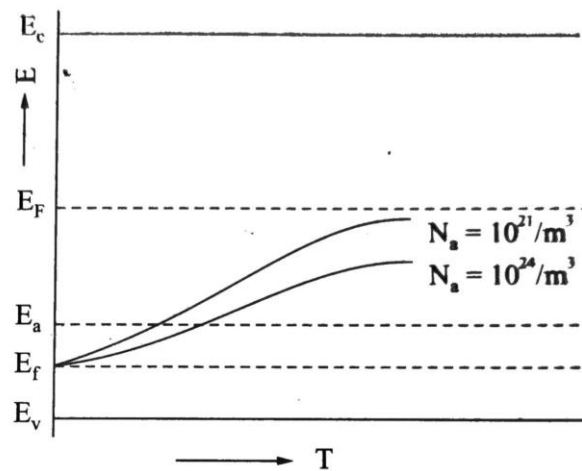$$p = (N_a N_v)^{\frac{1}{2}} \exp \left(-\frac{E_a - E_v}{2k_B T} \right).$$

Fig. 4: The variation of Fermi level with temperature for different concentration

Carrier Generation and Recombination

In thermal equilibrium the relationship, $pn = n_i^2$ is valid. If excess carriers are introduced to a semiconductor so that $pn > n_i^2$, the system reaches to a non-equilibrium situation. The process of introducing excess carriers is called carrier injection.

Whenever the thermal-equilibrium condition is disturbed $(i.e., pn \neq n_i^2)$ there are processes to restore the system to equilibrium where $pn = n_i^2$ is maintained. In the case of injection of excess carriers, the mechanism that restores equilibrium is known as recombination of the injected minority carriers with the majority carriers.

Carrier generation in semiconductor

We can introduce excess carriers by thermal and/or optical excitation and additionally through bombardment by high energy particle. Most of the semiconductor devices are operated by the creation of charge carriers in excess of the thermal equilibrium values. At finite temperature $(T > 0 \text{ K})$ excitation of electrons from valence band to the conduction band (fig. 4(a)) in a semiconductor results in generation of electron-hole pair shown by the dotted line in fig. 4(b). the process of generation leads to the build-up of free carriers to give rise to a carrier concentration exceeding the equilibrium carrier concentration.
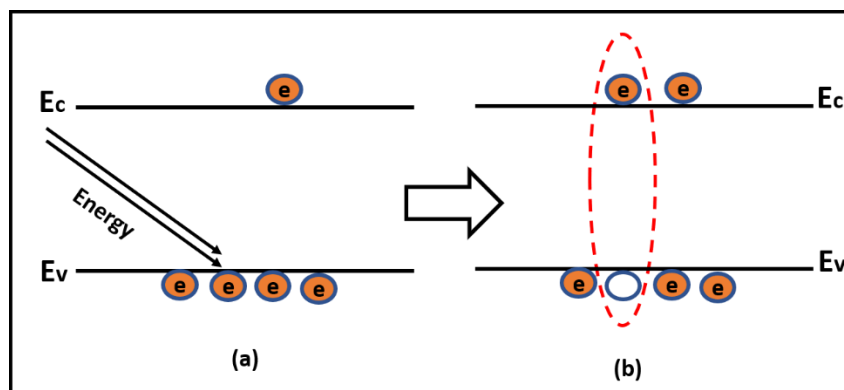

Fig. 5 : Generation of electron-hole pair in a semiconductor

Recombination

When an electron makes a transition downward from the conduction band to the valence band, an electron-hole pair is annihilated. This process is called recombination.

Depending on the nature of the recombination process, the energy released from the recombination process can be emitted as a photon or dissipated as heat to the lattice. When a photon is emitted, the process is called radiative recombination; otherwise, it is called nonradiative recombination. Recombination phenomena can be classified as direct and indirect processes. Direct recombination, also called band-to-band recombination, usually dominates in direct-bandgap semiconductors (shown in fig 5(a)), such as gallium arsenide, whereas indirect recombination via bandgap recombination dominates in indirect-bandgap semiconductors (fig 5(b)), such as silicon.
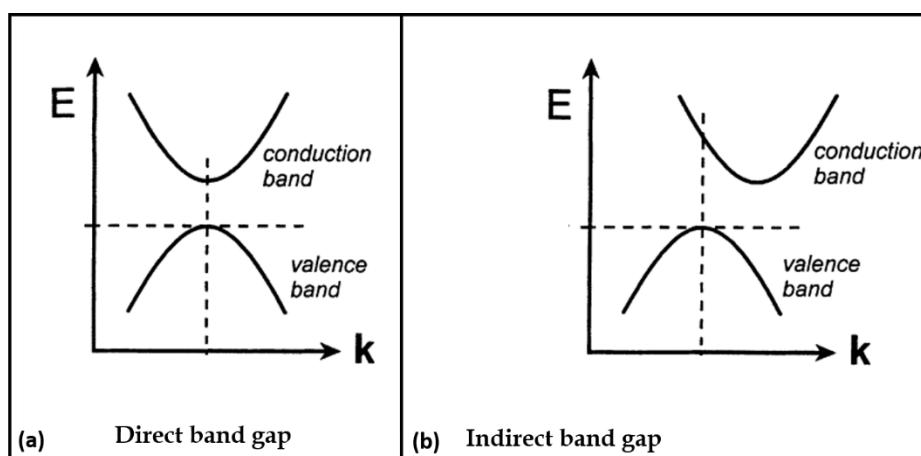

Fig. 6: (a) Direct and (b) Indirect bandgap of semiconductor

In this process electrons from conduction band drop down to valence band by releasing the excess energy in the form of light photons (radiative recombination) or by transferring energy to another free electron (Auger recombination) as shown in in Fig. 6 (a) and (b) respectively. This process is important for most III-V compound semiconductors having direct energy gap.
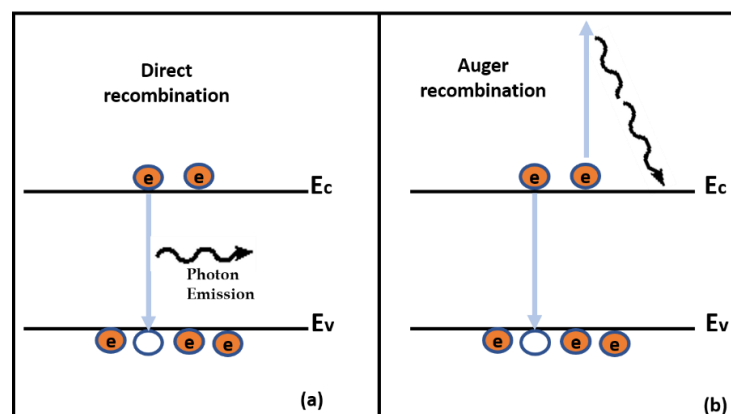

Fig. 7 : (a) Direct and (b) Auger recombination

Carrier drift

Let's consider an n-type semiconductor with uniform donor concentration in thermal equilibrium. The conduction electrons in the semiconductor conduction band are essentially free particles, since they are not associated with any particular lattice or donor site. The influence of crystal lattices is incorporated in the effective mass of conduction electrons, which differs somewhat from the mass of free electrons. Under thermal equilibrium, the average thermal energy of a conduction electron can be obtained from the theorem for equipartition of energy, $\frac{1}{2}k_B T$ units of energy per degree of freedom, where k_B is Boltzmann constant and T is the absolute temperature.

When a small electric field $\vec{E}$ is applied to the semiconductor sample, each electron will experience a force $(-q\vec{E})$ from the field and will be accelerated along the field (in the opposite direction to the field) during the time between collisions. Therefore, an additional velocity component will be superimposed upon the thermal motion of electrons. This additional component is called the drift velocity. Consequently, there is a net displacement of the electron in the direction opposite to the applied field.

We can obtain the drift velocity $\vec{v}_d$ by equating the momentum (force × time) applied to an electron during the free flight between collisions to the momentum gained by the electron in the same period. The momentum applied to an electron is given by $(-q\vec{E}\tau_c)$, and the momentum gained is $m_e^* \vec{v}_d$ .We have

$$qE\tau_c = m_e^* v_d \qquad (17)$$

From this equation it is clear that the electron drift velocity is proportional to the applied electric field i.e, $v_d \propto E$. Then obviously,

$$v_d = \mu E \qquad (18)$$

The proportionality factor μ is called mobility of a carrier where $\mu \left(= \frac{q\tau_c}{m_e^*}\right)$ depends on the mean free time and the effective mass. Mobility is an important parameter for carrier transport because it describes how strongly the motion of an electron is influenced by an applied electric field. Another point to note that mobility is directly connected to another important material parameter conductivity (σ) as

$$\sigma = ne\mu \qquad (19)$$

where n is the electron density.

The current density due to drift electrons only

$$j = \sigma E = ne\mu E \qquad (20)$$

Total current density of the semiconductor due to drift of both electrons and holes

$$j = ne\mu_e E + pe\mu_h E \qquad (21)$$

where μ_e and μ_h are mobility of electrons and holes respectively. From this equation total conductivity due to both types of carriers can be written as

$$\sigma = ne\mu_e + pe\mu_h \qquad (22)$$

Consequently, resistivity (ρ) can be written as

$$\rho = \frac{1}{ne\mu_e + pe\mu_h} \tag{23}$$

Diffusion of carriers

Apart from drift of carriers in an electric field, another transport phenomenon occurs in a semiconductor in the absence of electric field when there is a concentration gradient of mobile carriers due to which the carriers move from higher concentration region to lower one. This phenomenon is called diffusion which is random disordered motion of electrons. Like drift motion, in diffusion also, carriers experience collisions with various scattering centers.

Let, diffusion and consequent change of concentration occurs along x-direction. Then the current density due to electrons and holes will be according to equations (12) and (13) respectively.

$$j_n = qD_n \frac{dn}{dx} \tag{24}$$

$$j_p = qD_p \frac{dp}{dx} \tag{25}$$

where D_n and D_p are diffusion coefficient of electrons and holes respectively. Diffusion coefficient can be obtained from Einstein's relation as,

$$\frac{D}{\mu} = \frac{K_B T}{e} \tag{26}$$

Diffusion is a random, irregular and disorderly motion where the ratio $\frac{D}{\mu}$ signifies the ratio of disordered to ordered motion.

Current due to both drift and diffusion

Current densities due to drift and diffusion are as follows.

$$J^e_{drift} = ne\mu_e E \tag{27}$$

$$J^e_{diffusion} = eD_n \frac{dn}{dx} \tag{28}$$

Total electron current density due to diffusion and drift

$$J_e = ne\mu_e E + eD_n \frac{dn}{dx} \tag{29}$$

Similarly, total hole current density due to diffusion and drift

$$J_h = pe\mu_h E - eD_p \frac{dp}{dx} \tag{30}$$

where,

$$J^h_{drift} = pe\mu_h E \tag{31}$$

$$J^h_{diffusion} = -eD_p \frac{dp}{dx}.$$