Physics of Semiconductors

3.1 Introduction

Most of the modern electronic devices are made of semiconductors. Insulators practically do not conduct current, while metals are good conductor of electricity. Semiconductors are materials whose conductivity lies in between those of an insulator and a conductor. All semiconductors behave like a perfect insulator at absolute zero. In contrary to the metals semiconductors have negative temperature coefficient of resistance, i.e., they show a reduction in resistance with increase in temperature. In semiconductors current is carried by two types of carriers whereas in metals current is carried only by the free electrons. Silicon (Si) and Germanium (Ge) are the two most commonly used electronic device materials. However, as a semiconductor device material Si is superior to Ge. Nowadays electronic devices are being made almost entirely of Si. Apart from Ge and Si there are compounds like gallium arsenide (GaAs), indium phosphide (InP), indium arsenide (InAs) etc. which show semiconducting properties. These are called *compound semiconductors.*

3.2 Semiconductor-Crystal and the Concept of Hole: Covalent Bond Theory

Si and Ge are available in the form of crystalline solids. They have diamond lattice structures, i.e., each atom is surrounded by four equidistant nearest neighbours which lie at the corner of a tetrahedron. Both of them belong to the group IV of the periodic table and have four valence electrons. Each atom forms four covalent bonds with four nearest neighbouring atoms by sharing of valence electrons with opposite spin. Because of this formation of covalent bonds the valence electrons are not available for the conduction of electricity. So at 0 K no free carrier is available and the crystal behaves as perfect insulator. However at room temperature ($\sim$ 300 K) a few of the electrons acquire sufficient kinetic energy from thermal agitation and break their covalent bonds

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and conduction is made possible. The dislodged electrons can wander freely in a random fashion throughout the crystal. The minimum energy required to break such a covalent bond is about 0.72 eV for Ge and 1.1 eV for Si. When an electron escapes from covalent bond an electron-vacancy is created in the bond and such an incomplete bond is called a *hole*. The hole may be imagined to behave like a positively charged particle and can take part in the conduction of electricity. Under the action of an external electric field an electron from a nearby filled covalent bond, having almost the same energy as the hole, may come and fill the hole. This electron in turn leaves a new hole or vacancy behind. Thus the hole appears to move in a direction opposite to the direction of movement of the electron. Both of them contribute to the current in the same direction. So far as electrical conduction is concerned the hole behaves like a particle having charge equal and opposite to that an electron.

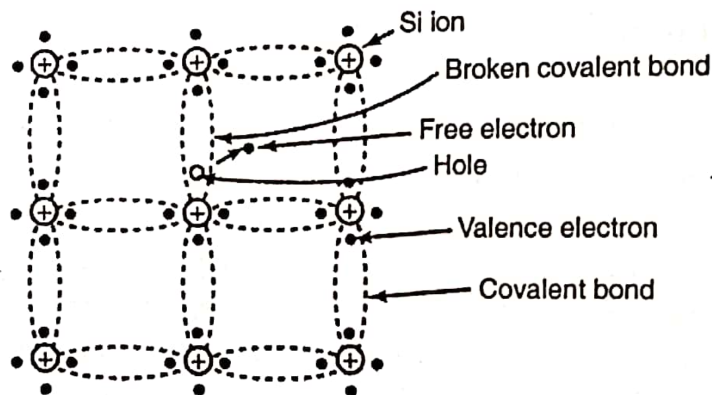

Fig. 3.2-1: Si crystal with a broken covalent bond illustrated symbolically in two dimensions

The generation of a free electron and a hole by thermal breakage of a covalent bond is commonly known as *'electron-hole pair' generation.* There is a process opposite to this generation known as *recombination.* A free electron moving randomly throughout the crystal may occasionally collide with a broken covalent bond and as a result it may combine with a hole. The free electron is converted into a bound electron. The electron-hole pair will no longer be available for the conduction of electricity. In thermal equilibrium the rate of generation of electron-hole pairs equals the rate recombination and we get a definite number of electron-hole pairs per unit volume of the solid.

In pure or *intrinsic semiconductor* the number of free electrons is equal to the number of holes. So free electron concentration n must be equal to the hole concentration p, i.e.,

$$n = p = n_i$$

where n_i is called the intrinsic concentration.

3.3 Impure or Extrinsic Semiconductors

The characteristics of semiconductor materials can be changed significantly by adding a small percentage of impurity atoms. This process of addition of impurities is termed *doping* and the resulting semiconductor is known as impure or *extrinsic semiconductor*. There are two types of extrinsic semiconductors: n-type and p-type.

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n-type semiconductor

Suppose a pentavalent impurity like arsenic (As), antimony (Sb), phosphorous (P) etc. is added in small percentage (about 1 impurity atom per 10^6 semiconductor atoms) to pure Si at the time of crystal growing. The impurity atoms displace some of the Si atoms in the lattice. Four of the five valence electrons of the impurity atoms form four covalent bonds with four nearest neighbouring Si atoms. The fifth valence electron remains very loosely bound to the impurity atom. The energy required to detach this fifth electron from the impurity atom is of the order of 0.05 eV for Si and 0.01 eV for Ge. This is known as *'ionisation energy'* of the impurity atom. The low ionisation energy of impurity atoms as compared with that of hydrogen atom (~ 13.6 eV) can be accounted for by considering the fact that here the fifth electron moves in a dielectric medium (of dielectric constant K ~ 11 for Si) instead of vacuum (K ~ 1) as in the case of hydrogen. Moreover, here the electron mass is to be replaced by its effective value. Almost all the impurity atoms become ionised even at room temperature (300 K). Thus each of the impurity atoms added donates one free electron for conduction. In addition there are equal number of free electrons and holes due to thermal breakage of a few covalent bonds. The presence of large number of free electrons increases recombination rate and decreases the hole concentration below the intrinsic level. Thus here the number of free electrons far exceeds the number of holes. Here electrons are called *majority carrier* and holes are called *minority carrier*. The resulting semiconductor is known as donor type or n-type semiconductor.

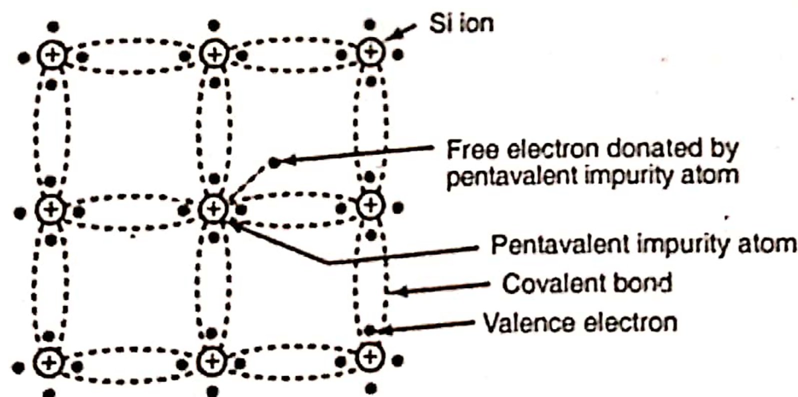

Fig. 3.3-1: Two dimensional symbolic crystal structure of Si doped with pentavalent impurity

p-type semiconductor

Suppose a trivalent impurity like boron, gallium, indium etc. is added in small percentage to Si at the time of crystal growing. The impurity atoms displace some of the Si atoms in the lattice. The three valence electrons of the impurity atom form three covalent bonds with three nearest neighbouring Si atoms and the impurity atom lacks by one electron to form the fourth covalent bond with its fourth neighbour. The vacancy that exists in the fourth bond constitutes a hole. So corresponding to each impurity atom added a hole is formed which can accept one electron. Moreover, there are equal number of holes and electrons formed due to thermal breakage of a few covalent bonds.

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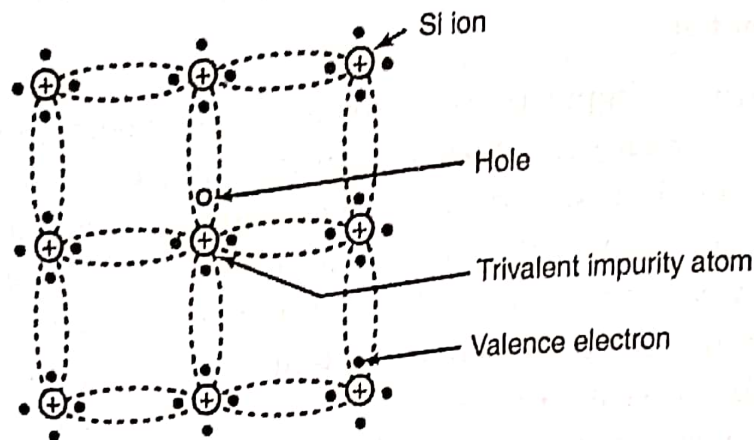

Fig. 3.3-2: Two dimensional symbolic crystal structure of Si doped with trivalent impurity

The presence of large number of holes increases recombination rate and decreases the electron concentration below the intrinsic level. Thus here the number of holes far exceeds the number of electrons. Here holes are called majority carrier and electrons are called minority carrier. The resulting semiconductor is known as acceptor type or *p*-type semiconductor.

3.4 Semiconductors in the light of Band Theory of Solid

Semiconductor devices and their electrical behaviour can be better understood in terms of energy band structure of solids. So it is important to know about the energy bands in semiconductors.

An electron in an isolated atom can have only certain discrete energies. Let us now examine what happens to these discrete energy levels when isolated atoms are brought close together to form a crystalline solid. Suppose two identical atoms with single valence electrons are slowly brought close to each other until their electron shells begin to overlap. The electron-ion and electron-electron interactions start to take place, the atomic orbitals start overlapping. These interactions cause splitting of each individual energy level into two. It happens so because interacting electrons form a single system and according to Pauli's exclusion principle, cannot occupy the same state. An electron may now occupy any of the two levels–one a little higher ($E+\Delta E$) and the other a little lower ($E-\Delta E$) than that (E) of the individual isolated atom. In crystalline solids with large number of atoms ($\sim 10^{23}$/c.c.) closely packed together each discrete atomic level splits into as many energy levels as there are atoms in the solid. The number of energy levels are so enormous and so close together that they can be regarded as essentially continuous. This is known as *energy band*. The width of a band depends on the nature of crystal and proximity of packing. In a solid with N single-electron atoms there are N energy levels in each allowed energy band. Since the number of electrons in the solid is limited, only the lower energy bands will be filled. The outermost band which is completely filled up with due quota of electrons is called *valence band*. The allowed band just above the valence band is called *conduction band*. The energy gap between valence band and conduction band is called *forbidden energy* gap (E_g). Since all the

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energy states in the valence band are occupied conduction of electricity is possible only when electrons are available in the empty conduction band.

In case of insulators the band gap E_g is very large (typically $E_g > 3$ eV) and ordinary temperature or electric field cannot impart sufficient energy to the electrons in the valence band to cross the gap to reach the conduction band (Fig. 3.4-1). So conduction is practically zero. In conductors there exists a partly filled conduction band which may be formed due to overlapping of filled and empty bands or from partially filled atomic levels. As a result plenty of electrons are available here for conduction. There is a group of solids called *intrinsic semiconductors* in which the width of the forbidden energy gap is relatively small (~ 1 eV). Most common semiconductor Si has

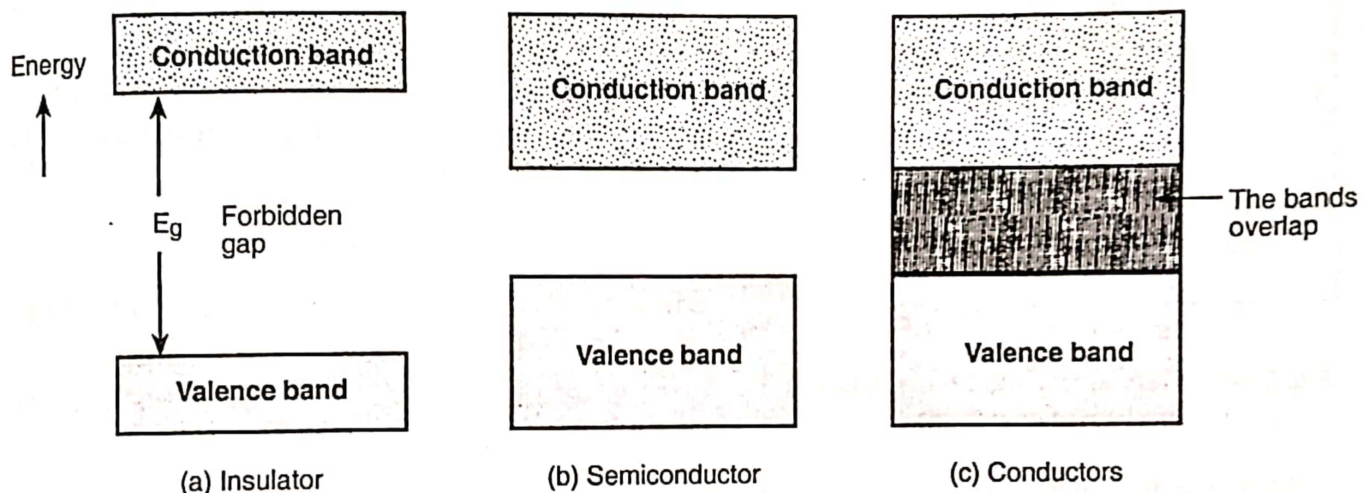

Fig. 3.4-1: Energy band structure in solids

a band gap $E_g = 1.12$ eV and Ge has band gap $E_g = 0.72$ eV at room temperature (300 K). Some of the electrons in the valence band may gain sufficient energy from thermal agitation to cross the forbidden gap and enter the unfilled conduction band. These electrons permit a small current flow when an electric field is applied. At 0 K electrons in valence band normally cannot gain enough energy to jump the forbidden energy gap and hence the semiconductors behave as insulators. As the temperature is increased more and more electrons jump to the conduction band and hence conductivity increases with temperature.

When an electron jumps from filled valence band to conduction band a state in the valence band becomes unoccupied. Such an unoccupied state of otherwise filled band is called a *hole*. It can also contribute to the current flow. In fact a hole can be considered as a quasiparticle with a charge equal and opposite to that of an electron.

As a result of an electron jump from filled valence band to the conduction band an electron in the conduction band and a hole in the valence band become available for the conduction of electricity. This is known as '*electron hole*' *pair generation*. There is a process opposite to this generation known as *recombination*. In this process of recombination an electron in the conduction band jumps into the valence band and combines with a hole there. Thus in this process an electron-hole pair is lost in the

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sense that it will no longer be available for the conduction of electricity. In the process of recombination some amount of energy, almost equal to the band gap Eg, is released. In some cases this released energy goes to heat the crystal and in some cases it is emitted in the form of electromagnetic radiation.

The generation and recombination of electron-hole pairs go on simultaneously. However, in thermal equilibrium the rate of generation and recombination of electron-hole pairs become equal and we get a definite number of electron-hole pairs per unit volume of the solid at a particular temperature. If the temperature of the semiconductor is increased a new equilibrium is reached with greater electron and hole concentrations. Note that for an intrinsic semiconductor electron concentration (n) equals the hole concentration (p), i.e.,

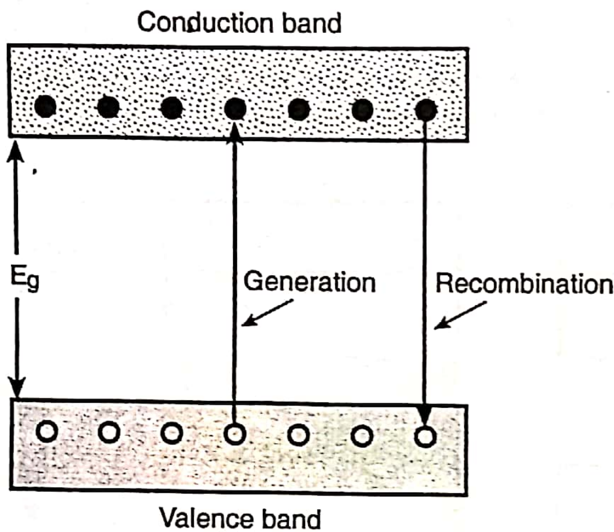

Fig. 3.4-2: Generation and recombination of electrons and holes

$$n = p = n_i$$

when n_i is called the intrinsic concentration. The value of n_i depends on the temperature of the semiconductor. It increases rapidly with increase in temperature.

The conductivity of intrinsic semiconductors is very small. Moreover, we have a little control over it. The characteristics of such semiconductors can be changed drastically by adding a small percentage of impurity atoms. The resulting semiconductor is known as *extrinsic* semiconductor. If a small amount of pentavalent impurity atoms like arsenic, antimony, phosphorus is added to intrinsic semiconductor additional impurity energy levels corresponding to the loosely bound valence electrons are formed near the top of the otherwise forbidden energy gap (Fig. 3.4-3). If the valence electron were completely free its energy would have lied somewhere in the conduction band. Since its binding energy is ~ 0.05 eV, it is not loose enough to conduct. It clearly suggests that donor impurity levels lie about 0.05 eV below the conduction band edge. These new

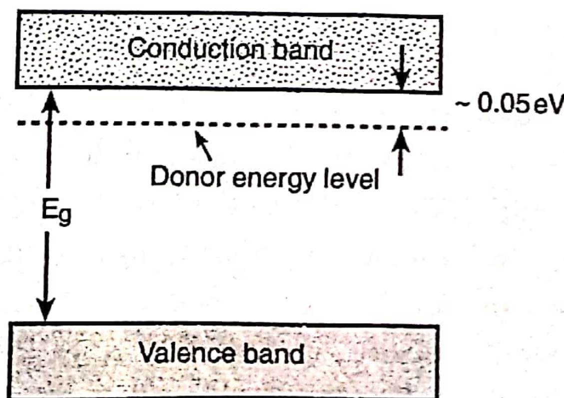

Fig. 3.4-3: Energy band diagram of an n-type semiconductor

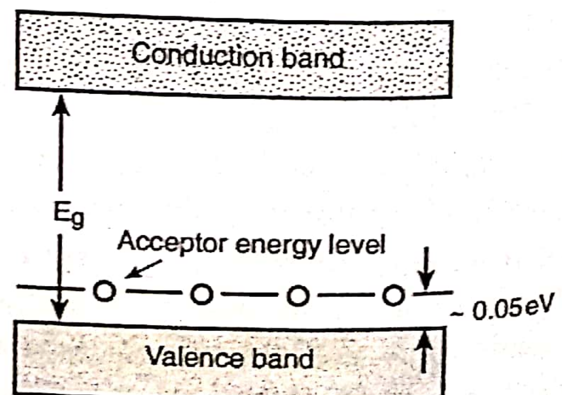

Fig. 3.4-4: Energy band diagram of a p-type semiconductor

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allowable levels are essentially discrete level because the impurity atoms are located far apart in the crystal and their interaction is small.

These impurity levels are filled at 0 K. The energy gap between impurity level and the bottom of the conduction band is only 0.05 eV for Si and 0.01 eV for Ge. So as the temperature is elevated to room temperature thermal excitation of practically all the electrons from impurity levels into the unfilled conduction band causes appreciable conductivity through drift of electrons alone. Also there are some electrons which jump from valence band to conduction band and create some holes in the valence band. Here electrons are majority and holes are minority carriers. The resulting semiconductor is called donor type or n-type semiconductor.

If a small percentage of trivalent impurities such as boron, gallium, indium etc. is added to intrinsic semiconductor additional discrete impurity energy levels are formed near the bottom of the otherwise forbidden energy gap (Fig. 3.4-4). The levels are normally unoccupied at 0 K. A very small amount of energy is required for an electron to leave the valence band and occupy the acceptor level. For this even at room temperature electrons are thermally excited from filled valence band into these unoccupied levels and leave behind holes which can drift in an electric field and cause appreciable conductivity. Apart from this a few of the electrons from the valence band jump to the conduction band and create a few more holes in valence band. Here holes are majority and electrons are minority carriers. The resulting semiconductor is called acceptor type or p-type semiconductor.

Direct and indirect band-gap semiconductors

On the basis of the energy band structures, semiconductors can be classified as *direct* and *indirect band-gap types*. In a direct band gap semiconductor (such as GaAs, InP) the minimum of conduction band and the maximum of valence band are at the same point in wavevector ($\vec{k}$) space (Fig. 3.4-5). Here an electron may jump from the minimum of conduction band to the valence band maximum without change in $\vec{k}$ (or equivalently momentum). Thus momentum is automatically conserved and there is direct recombination of electrons and holes and the excess energy is emitted in the form of photons. The minimum frequency (ν) of the emitted photon is given by $E_g = h\nu$ or $\nu = E_g/h$ where h is Planck's constant.

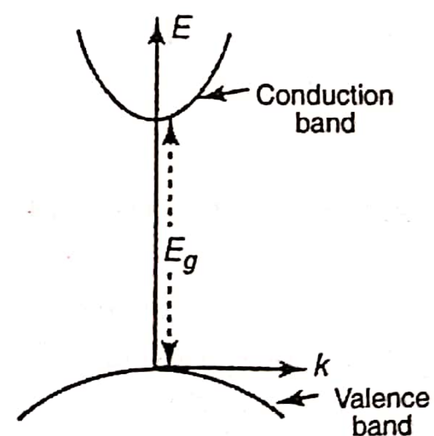

Fig. 3.4-5: Energy-wavevector diagram of a direct gap semiconductor

This type of semiconductors is suitable for laser and light emitting diodes.

In indirect gap semiconductors (such as Ge, Si) the valence band maximum and the conduction band minimum do not occur at the same point in $\vec{k}$-space

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(Fig. 3.4-6). So the transition of an electron from the conduction band minimum to the valence band maximum involves change in energy as well as momentum. As a result there is no direct recombination of electrons and holes. Here recombination takes place via traps or recombination centres which contribute defect states in the band gap. Such a location acts effectively as a third body which helps to satisfy the requirement of momentum conservation. As a result the energy liberated generally goes to heat the crystal. This type of semiconductor is used for the construction of diodes and transistors. They are not suitable for optoelectronic devices.

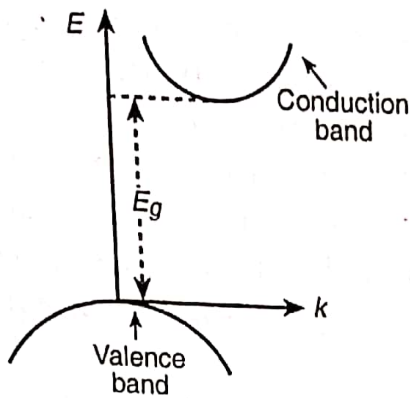

Fig. 3.4-6: Energy-wavevector diagram of an indirect gap semiconductor

Degenerate and non-degenerate semiconductors

For a semiconductor with low impurity concentrations (about 1 impurity atom per 10^{10} or more semiconductor atoms) the number of electrons in the conduction band and of holes in the valence band is usually much less than the number of quantum states in these bands. Here the impurity states are discrete levels and the carriers obey classical distribution law. This type of semiconductor is called *non-degenerate* semiconductor.

When the impurity concentrations become very high (e.g., one impurity atom present for less than 10^6 semiconductor atoms) the impurity levels develop into energy band, the number of carriers approach or become greater than the number of quantum states. In this case classical distribution laws become inapplicable. Such semiconductors are called *degenerate semiconductors*. Here carrier concentration is essentially independent of temperature and conduction is much like that of a poor metal. For highly doped materials the band gaps become smaller. Degenerate semiconductors are used for the manufacture of tunnel diodes.

3.5 Electrons and Holes in Semiconductors

Electrical conduction in semiconductors consists of movement of electrons in the nearly empty conduction band and of holes in a nearly full valence band under the influence of electric field. The motion of electrons and holes in a periodic crystal field under the action of external applied field is governed by quantum mechanics and not by the classical Newtonian mechanics. However, it is possible to treat the electron and hole as imaginary classical particles with some effective masses m_e^* and m_h^* respectively. The effective mass is usually different from the rest mass of free electron. Its value depends on the shape of the energy band in k-space. It may be positive or negative, many times larger or smaller in magnitude than electron's rest mass. It is not a scalar quantity but, in general, a tensor of rank two. For this effective mass is defined for a given

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band and near a given extremum. The negative effective mass brings the notion of a hole. The advantage of introducing the concept of effective mass is that we may treat electrons and holes as though they were free and use classical Newtonian mechanics to determine their motion through the crystal in the applied field.

Carrier concentration in intrinsic semiconductor

In order to calculate the conductivity of a semiconductor we are to know the density of electrons in conduction band and the density of holes in the valence band. We assume the temperature and the carrier densities to be small so that the electron gas in conduction band and the hole gas in valence band are non-degenerate.

Then the* *density of states* in the conduction band is given by

$$g(E) = C(E - E_c)^{\frac{1}{2}} \tag{3.5-1}$$

in which $C = 4\pi\left(\frac{2m_e^*}{h^2}\right)^{\frac{3}{2}}$; m_e^* is the effective mass of electron, E_c is the energy corresponding to the bottom of *conduction band*. The probability that a state with energy E is occupied is given by the† *Fermi-Dirac* distribution function,

$$f(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}} \tag{3.5-2}$$

where E_F is the Fermi energy.

Therefore, the number of electrons in the energy range E to $E+dE$ per unit volume in the conduction band is equal to

$$dn = f(E)g(E)dE$$

Hence density of electrons in the conduction band is

$$n = \int_{E_c}^{\infty} f(E)g(E)dE \tag{3.5-3}$$

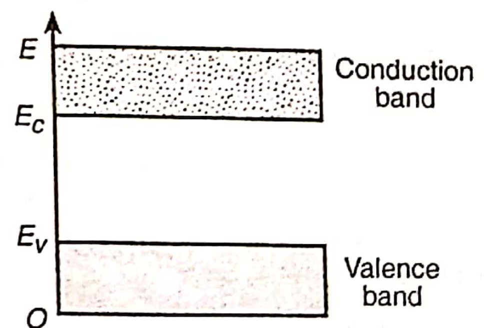

Fig. 3.5-1: Energy band diagram of an intrinsic semiconductor

where the upper limit is taken ∞ instead of the energy of the top of the conduction band. This is allowed because the distribution function $f(E)$ will be appreciable only around E_c and practically zero for $E \gg E_c$. At low temperature and for $E \geq E_c$, $E - E_F \gg kT$ and Eq. (3.5-2) reduces to

$$f(E) = e^{-\frac{(E - E_F)}{kT}}$$

$$\therefore \quad n = C\int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} \cdot e^{-\frac{(E - E_F)}{kT}} \cdot dE$$

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Putting $\dfrac{E - E_c}{kT} = x$,

$$n = C \cdot e^{\frac{-(E_c-E_F)}{kT}} \cdot \int_0^{\infty} (kT)^{\frac{3}{2}}\, x^{\frac{1}{2}}\, e^{-x} dx$$

$$= C \cdot e^{\frac{-(E_c-E_F)}{kT}} \cdot (kT)^{\frac{3}{2}} \cdot \frac{\sqrt{\pi}}{2}$$

$$= 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \cdot e^{\frac{-(E_c-E_F)}{kT}} = N_c \cdot e^{\frac{-(E_c-E_F)}{kT}} \quad (3.5\text{-}4)$$

where $N_c = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}$ has the dimensions of a concentration.

Now to find the density of holes in the valence band we note that the density of states is given by

$$g(E) = C(E_v - E)^{\frac{1}{2}}$$

where $C = 4\pi\left(\frac{2m_h^*}{h^2}\right)^{\frac{3}{2}}$; m_h^* is the effective mass of hole; E_v is the energy corresponding to the top of the valence band. Since a hole signifies an unoccupied state, the Fermi function for a hole is $1 - f(E)$ which represents the probability of not occupying the energy state E by an electron. At low temperature for $E \leq E_V$, $E_F - E \gg kT$ and we can write

$$1 - f(E) \approx e^{\frac{-(E_F-E)}{kT}}$$

Hence the hole density in the valence band will be

$$p = \int_{-\infty}^{E_v} C(E_v - E)^{\frac{1}{2}} \cdot e^{\frac{-(E_F-E)}{kT}} dE$$

Putting $\dfrac{E_v - E}{kT} = x$,

$$p = C \cdot e^{\frac{E_v-E_F}{kT}} \cdot \int_0^{\infty} (kT)^{\frac{3}{2}}\, x^{\frac{1}{2}}\, e^{-x} dx$$

$$= C \cdot e^{\frac{E_v-E_F}{kT}} (kT)^{\frac{3}{2}} \cdot \frac{\sqrt{\pi}}{2}$$

$$= 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \cdot e^{\frac{E_v-E_F}{kT}} = N_v \cdot e^{\frac{E_v-E_F}{kT}} \quad (3.5\text{-}5)$$

where $N_v = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}$ has the dimensions of a concentration.

Eqs. (3.5-4) and (3.5-5) are applicable to both intrinsic and extrinsic semiconductors. For intrinsic semiconductor $n = p$. Therefore from Eqs. (3.5-4) and (3.5-5) we get

$$E_F = \frac{E_c + E_v}{2} + \frac{kT}{2} \ln \frac{N_v}{N_c} = \frac{E_c + E_v}{2} + \frac{3kT}{4} \ln\left(\frac{m_h^*}{m_e^*}\right) \quad (3.5\text{-}6)$$

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If we assume $m_h^* = m_e^*$ then the *Fermi level of an intrinsic semiconductor lies exactly at the middle of the forbidden energy gap.* In general $m_h^* > m_e^*$ and Fermi level is raised slightly with temperature.

One can now calculate intrinsic carrier concentration $n = p = n_i$ (say) by substituting Eq. (3.5-6) in Eq. (3.5-4) or (3.5-5). Thus we get intrinsic density of electrons or holes as

$$n_i = \sqrt{N_c N_v} \cdot e^{\frac{-E_g}{2kT}} = 2\left(\frac{2\pi kT}{h^2}\right)^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} \cdot e^{\frac{-E_g}{2kT}} \qquad (3.5\text{-}7)$$

where $E_g = E_c - E_v$ represents the band gap.

Experiments show that for most semiconductors the band gap decreases linearly with temperature. So we can write

$$E_g = E_{go} - \beta T$$

where E_{go} is the band gap at 0 K and β is a constant for a particular semiconductor.

Using this relationship Eq. (3.5-7) may be written in the following form :

$$n_i = AT^{3/2} e^{-E_{go}/2kT}$$

where $A = 2\left(\frac{2\pi k}{h^2}\right)^{\frac{3}{2}} \cdot (m_e^* m_h^*)^{\frac{3}{4}} \cdot e^{\frac{\beta}{2k}}$

Obviously intrinsic carrier concentration is highly dependent on temperature.

Carrier concentration in extrinsic semiconductor

Eqs. (3.5-4) and (3.5-5) are applicable to both intrinsic and extrinsic semiconductors. The product of free electron and hole concentrations, under thermal equilibrium, can be obtained from these equations as,

$$np = n_i^2 \qquad (3.5\text{-}8)$$

where n_i is the intrinsic carrier concentration as given by the Eq. (3.5-7).

The relationship (3.5-8) is called the *mass action law.* It states that the product of free electron and hole concentrations is constant independent of the amount of donor or acceptor impurities at a particular temperature. Addition of n-type impurities increases the number of free electrons over the intrinsic carrier concentration but decreases the number of holes due to increased recombination of holes with excess electrons. Similarly the addition of p-type impurities increases the number of holes and decreases the number of free electrons.

Assuming that all the donor and acceptor impurity atoms are ionised we can write from the *charge neutrality condition* (i.e. the semiconductor as a whole electrically neutral) or the *total negative charge must be equal to the total positive charge,*

$$n + N_a = p + N_d \qquad (3.5\text{-}9)$$

where N_a and N_d are respectively, the concentrations of acceptor and donor impurity atoms.

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For an n-type semiconductor $n \gg p$.

Therefore,

$$n \approx N_d - N_a \tag{3.5-10}$$

The concentration of holes in n-type material is then obtained from Eq. (3.5-8) as

$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_d - N_a} \tag{3.5-11}$$

For a p-type semiconductor $p \gg n$

Therefore, from Eq. (3.5-9)

$$p \approx N_a - N_d \tag{3.5-12}$$

and from Eq. (3.5-8), the concentration of electrons in p-type material is

$$n = \frac{n_i^2}{p} = \frac{n_i^2}{N_a - N_d} \tag{3.5-13}$$

If two types of impurities are added in equal amounts i.e., $N_a = N_d$ then from Eq. (3.5-9) $n = p$. This indicates that the resulting semiconductor becomes intrinsic. Such a semiconductor is called *compensated semiconductor*. However, it differs from pure semiconductor in respect of carrier mobilities. Since lattice imperfections are more numerous in compensated semiconductors, the carriers will have lesser mobilities. If acceptor impurities are added to n-type semiconductor, n-type changes to p-type as soon as N_a exceeds N_d.

An extrinsic semiconductor when heated to high temperatures behaves like an intrinsic semiconductor. When the temperature of an n-type semiconductor is increased, the number of thermally generated electron-hole pairs increases whereas the number of electrons donated by the donor-impurity atoms remains same as these atoms are already ionised. Thus with the rise in temperature extrinsic semiconductor will start moving towards intrinsic behaviour. At very high temperatures the number of thermally generated electrons may become much greater than that donated by the donor atoms. Then the electron concentration becomes almost equal to the hole concentration and the semiconductor behaves like an intrinsic semiconductor. Similar argument also applies to p-type semiconductor.

Fermi level in semiconductors

Electrical characteristics of a semiconductor depends on the carrier concentrations. Eqs. (3.5-4) and (3.5-5) which give the free electron and hole concentrations respectively, are applicable to both intrinsic and extrinsic semiconductors. An examination of these two equations shows that the Fermi energy E_F is the only quantity which can change with impurities. So it is important to know how E_F depends on the impurity concentrations. We have seen that *for an intrinsic semiconductor E_F lies exactly at the middle of the forbidden energy gap* (Fig. 3.5-2(a)). As the Fermi level position indicates

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the probability of occupancy of a level the above result indicates equal concentration for free electrons in conduction band and holes in valence band.

In an n-type extrinsic semiconductor with all the donor atoms ionised many of the of the energy states at the bottom of the conduction band are filled by the electrons and a fewer holes exist in the valence band. So it is expected that *E_F must move closer to the conduction band for an n-type semiconductor* (Fig. 3.5-2(b)). To find the exact position of the Fermi level in an n-type semiconductor with $N_a = 0$, we note that $n \gg p$ and hence $n \approx N_d$. Now using Eq. (3.5-4) we get

$$N_d = N_c e^{-(E_c - E_F)/kT} \tag{3.5-14}$$

Therefore,

$$E_F = E_c - kT \ln \frac{N_c}{N_d} \tag{3.5-15}$$

This equation shows that with the increase in doping concentration N_d the Fermi level moves closer to the conduction band.

A similar argument for p-type semiconductor with so many holes in the valence band and a fewer electrons in the conduction band indicates that E_F must move closer to the valence band (Fig. 3.5-2(c)). The exact position of the Fermi level in a p-type semiconductor with $N_d = 0$ and $p \approx N_a$ can be obtained, as before, from Eq. (3.3-5). Thus we have

$$N_a = N_v e^{-(E_F - E_v)/kT} \tag{3.5-16}$$

and

$$E_F = E_v + kT \ln \frac{N_v}{N_a} \tag{3.5-17}$$

Obviously, with increase in N_a, E_F moves closer to the valence band.

If the doping concentrations are very high then for an n-type semiconductor with $N_d > N_c$ the Fermi level moves into the conduction band and for a p-type semiconductor with $N_a > N_v$ the Fermi level moves into the valence band (Fig. 3.5-3). Such semiconductors are called *degenerate semiconductors.* On the other hand, semiconductors with relatively low doping level having the Fermi level within the forbidden energy gap are called *nondegenerate semiconductors.*

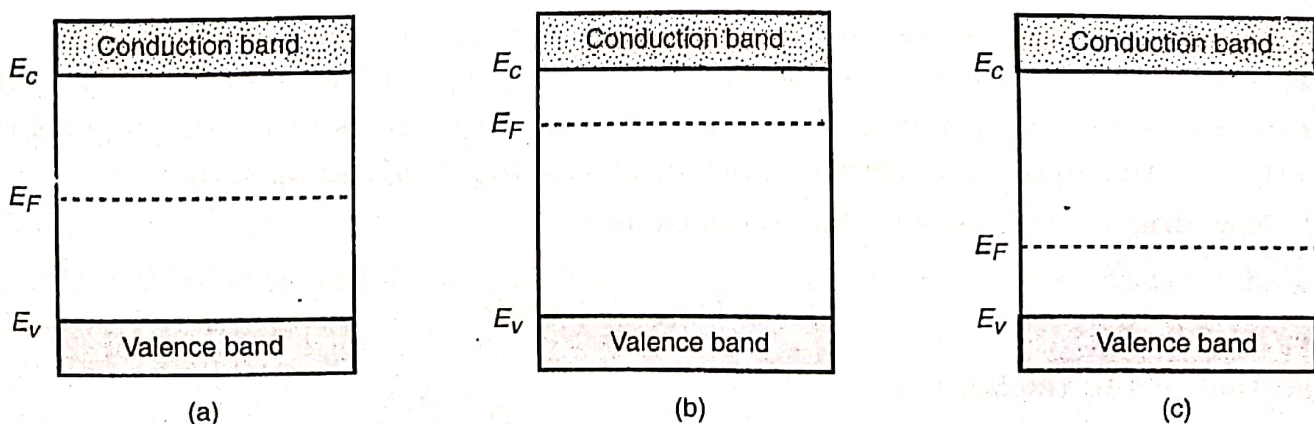

Fig. 3.5-2: Position of Fermi level in (a) an intrinsic semiconductor (b) an n-type semiconductor and (c) a p-type semiconductor

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For a compensated semiconductor i.e., with $N_a = N_d$ we note that addition of the Eqs. (3.5-15) and (3.5-17) and then division by 2 give Eq. (3.5-6) which indicates its intrinsic behaviour.

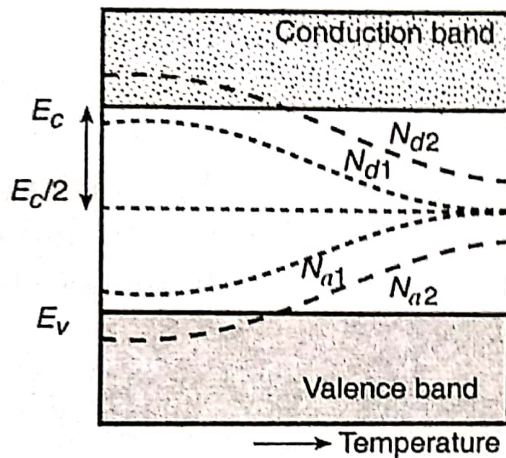

Fig. 3.5-3: Variation of Fermi level position with temperature and doping level ($N_{d2} > N_{d1}$; $N_{a2} > N_{a1}$)

For a given concentration if the temperature of an extrinsic semiconductor is increased it may become essentially intrinsic at high temperatures. We have already discussed it. So we may argue that as the temperature of n-type or p-type material increases, the Fermi level moves towards the centre of the forbidden energy gap i.e., towards intrinsic Fermi level position (Fig. 3.5-3).

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