UNIT 2

Semiconducting Materials

2.1 INTRODUCTION

Semiconductors are materials whose electrical conductivity lies between that of conductors and insulators. The conductivity of semiconductor is in the order of 10^4 to 10^{-4} mho m^{-1}. It is a special class of material, very small in size and sensitive to heat, light and electricity.

Semiconducting materials behave as insulators at low temperatures and as conductors at high temperatures. Semiconductors are of two types.

(i) Intrinsic (or) pure semiconductors, and

(ii) Extrinsic (or) doped semiconductors

We have seen that in metals addition of impurities as well as rise of temperature result in decrease in the electrical conductivity whereas in semiconductors the electrical conductivity increases. Germanium and Silicon are important elemental semiconductors used in the manufacturing of diodes and transistors. Gallium Arsenide (GaAs) and Indium Phosphide (InP) are the important compound semiconductors used in LED's and laser diodes.

Definition

The resistivity of a semiconductor is lesser than an insulator but more than that of a conductor. It is in the order of 10^{-4} to 0.5 ohm-metre.

A semiconductor has nearly empty conduction band and almost filled valence band with a very small energy gap ($\simeq 1$ eV).

2.2 PROPERTIES OF SEMICONDUCTOR

1. The resistivity of semiconductors lies between that of a conductor and an insulator (i.e.,) It varies from 10^{-4} to $0.5\ \Omega$-m.
2. At 0K, semiconductors behave as insulators.
3. In semiconductors, both electrons and holes are charge carriers.

$$\sigma = \sigma_e + \sigma_h$$

   where σ_e and σ_h is the conductivities due to electrons and holes. Both the charge carriers (electrons & holes) take part in the conduction process.
4. They have an empty conduction band and almost filled valence band at 0K.
5. Semiconductors have negative temperature coefficient of resistance

$$\left[\because \rho \propto \frac{1}{T} \text{ or } \sigma \propto T \right]$$

6. If impurities are added, it will increase the electrical conductivity of semiconductors.
7. If we increase the temperature of semiconductor, its electrical conductivity also increases.

2.3 ELEMENTAL AND COMPOUND SEMICONDUCTORS

Based on the composition of elements they are classified into two types. They are

(i) Elemental semiconductors and

(ii) Compound semiconductors

(i) Elemental semiconductors

The elemental semiconductor is made of single element. These semiconductors are from the group IV elements in the periodic table and have four valence electrons in their outermost shell. These are also named as indirect and bandgap semiconductors.

Here, electron from the conduction band recombines with the hole is the valence band via treps. In this process, the phonons are emitted and they heat the lattice.

Ex. Germanium and Silicon

(ii) Compound semiconductors

The compound semiconductors are made of two or more elements. These

compound semiconductors belongs to the third and fifth group elements and also belongs to the second and sixth group elements. These are also named as direct bandgap semiconductors since recombination of electrons and holes takes place directly leading to the emission of photons in the visible (or) Infrared range.

Since the life time of the charge carrier is so small, the current amplification is small. Hence, they are not suitable for making transistors and ICs and they are used for making LEDs and LASER diodes.

Ex. GaAs and GaP

2.4 DIFFERENCES BETWEEN ELEMENTAL AND COMPOUND SEMICONDUCTOR

S. No.	Elemental semiconductors	Compound semiconductors
1.	These are made from single element	These are made from compound (mixed) elements
2.	These are made from IV group elements of periodic table	These are made from III and V [or] II and VI group elements of periodic table.
3.	These are called as indirect band gap semiconductor (electron–hole recombination takes place through traps)	These are called as direct band gap semiconductor (electron –hole recombination takes place directly)
4.	Heat is produced during recombination	Photons are emitted during recombination
5.	Life time of charge carriers is more due to indirect recombination.	Life time of charge carriers is less due to direct recombination.
6.	Current amplification is more	Current amplification is less.
7.	These are used for making diodes, transistor, etc. **Example :** Ge, Si	These are used for making LED, laser diodes, etc. **Example :** GaA, GaP

2.5 TYPES OF SEMICONDUCTORS

Based on the purity of the semiconductors, they are classified into two types.

(i) Intrinsic semiconductor

(ii) Extrinsic semiconductor

2.6 INTRINSIC SEMICONDUCTOR

A semiconductor in an extremely pure form, without addition of impurities is known as an intrinsic semiconductor.

Ex. Germanium and Silicon

We know Germanium and Silicon are the fourth group elements of the periodic table. The Germanium has 32 electrons and Silicon has 14 electrons in their atomic structure.

Semiconductors like Germanium and Silicon have crystalline structure. Both the semiconductors are tetravalent i.e., each has four valence electrons in the outermost orbit. In the case of pure Germanium, out of 32 electrons, 28 electrons are tightly bound to the nucleus while the remaining 4 electrons revolve in the outermost orbit. These 4 electrons are known as valence electrons as shown in Fig. 2.1.

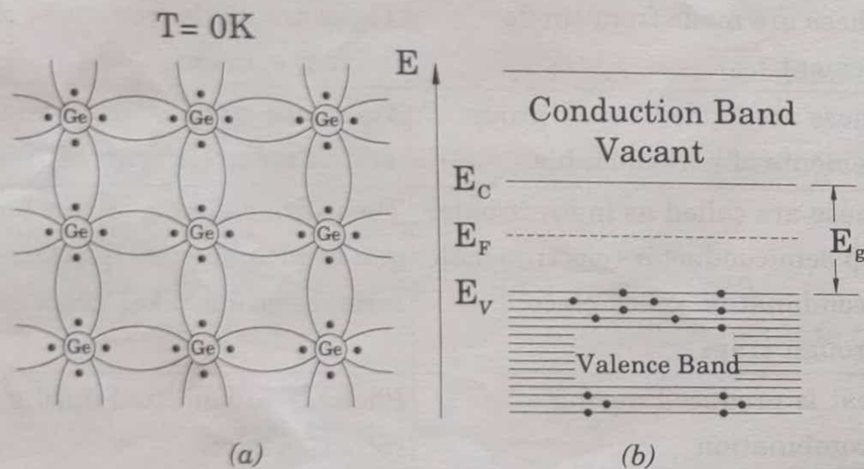


Fig.2.1 Germanium Crystal at 0K

In the case of Silicon, out of 14 electrons, 10 electrons are tightly bound to the nucleus while the remaining 4 electrons revolve in the outermost orbit.

Let us consider the case when the two atoms of Germanium are brought close to each other. Now the positive core of one atom interacts with one of the valence electrons of the other atom. Each core attracts the electron from the other atom and the two electrons are shared by two atoms. These two such electrons form an electron pair. When the attractive force is balanced by the repulsive force between two positive cores, a covalent bond is formed.

At 0K, no free electrons are available for conduction. Hence, this semi conductor behaves as an insulator.

To get free electrons, the covalent bonds must be broken. There are many ways of breaking the covalent bond and setting the electrons free. One such way is to increase the crystal temperature above 0K.

Due to thermal excitation, some of the electrons acquire sufficient energy to break the covalent bonds. The energy needed to break such a covalent bond is about 0.72eV for Germanium and 1.1eV for Silicon. Thus even at room temperature an electron of one atom or the other can get detached from it's bond by thermal agitation. The detached electrons now becomes free and can move throughout the crystal lattice in a random motion as shown in Fig.2.2

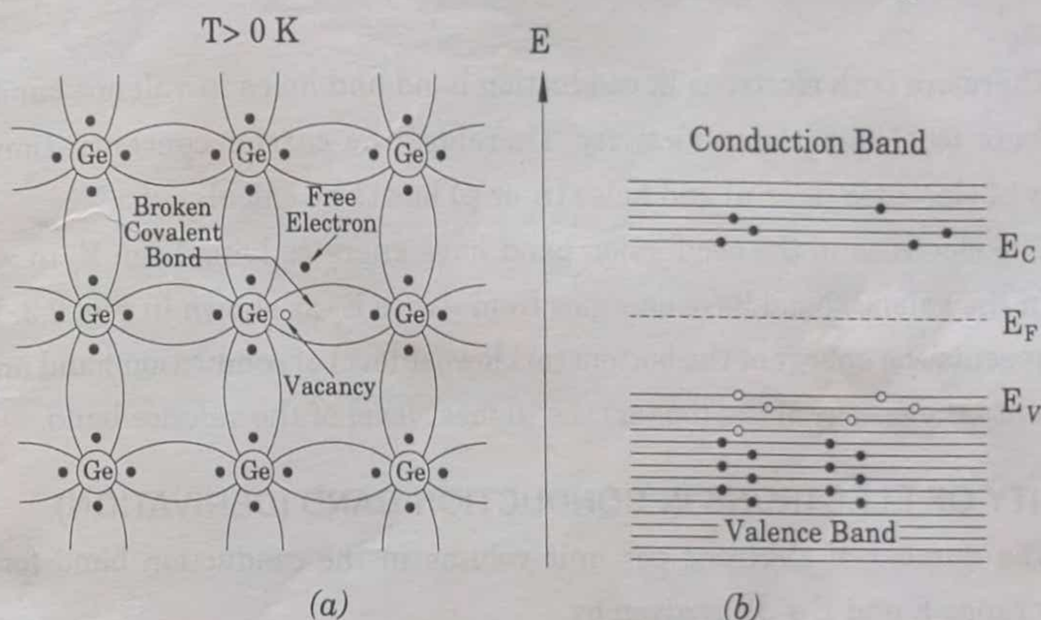


Fig.2.2 Germanium crystal at temperature above 0K

At any temperature, the number of free electrons in the conduction band are equal to the number of holes in the valence band.

When the electron escapes from the covalent bond, an empty space is left behind which is called a *hole*. Once a hole is created, an electron from the covalent bond of a nearby atom shifts to occupy this hole. In this way this process continues and the hole goes on shifting from one atom to another. The hole acts like a free positive charge and the hole moves towards the negative plate. *Therefore in a semiconductor both holes and electrons are charge carriers* and current transport is effectively taking place by holes and electrons.

2.7 CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTOR

The number of electrons in the conduction band per unit volume of the material is called electron concentration (n). Similarly the number of holes in

the valence band per unit volume (p) of the material is called hole concentration. In general, the number of charge carriers per unit volume of the material (i.e., intrinsic semiconductor) is known as *carrier concentration*.

At 0 K intrinsic semiconductor behaves as insulator. As the temperature of the semiconductor is increased, electrons from the valence band excited into the conduction band. These electrons in the conduction band behaves like a free electrons. Therefore, the mass of the electron is replaced by its effective mass m_e^*.

Likely, the holes created by these electrons in the valence band also behave like a free particle. Therefore, the mass of the hole is replaced by its effective mass m_h^*.

Therefore both electrons in conduction band and holes in valence band will contribute to electrical conductivity. Therefore the carrier concentration (or) density of electrons (n_e or n) and holes (n_h or p) has to be calculated.

The electrons in the conduction band have energies lying from E_c to ∞ and holes in the valence band have energies from – ∞ to E_v as shown in Fig. 2.3. Here E_c represents the energy of the bottom (or) lowest level of conduction band and E_v represents the energy of the top (or) the highest level of the valence band.

DENSITY OF ELECTRONS IN CONDUCTION BAND (DERIVATION)

The number of electrons per unit volume in the conduction band for the energy range E and E + dE is given by

$$dn = Z(E)\, F(E)\, dE \qquad ...(1)$$

where Z(E) dE – Density of states in the energy range E and E + dE

F(E) – Electron probability occupancy

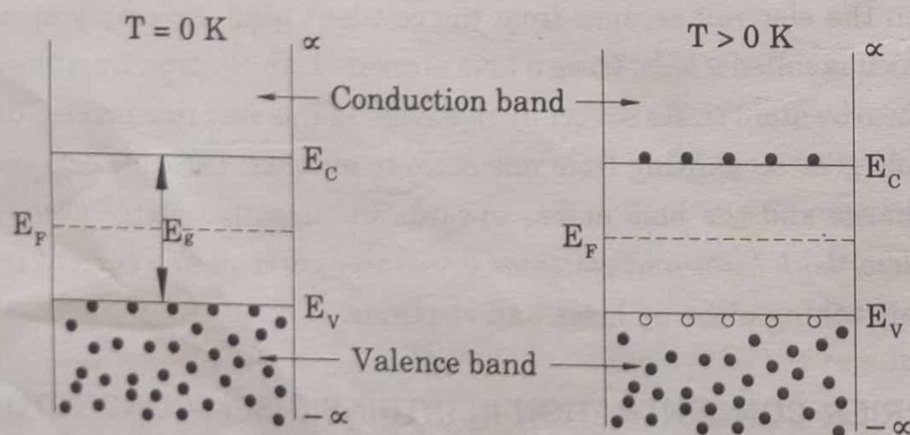


Fig. 2.3 Energy band diagram of an intrinsic semiconductor

The number of electrons in the conduction band for the entire region is calculated by integrating equation (1) between energy range E_C and $+\infty$.

dn = n.

$$\int dn = n = \int_{E_C}^{\infty} Z(E)\, F(E)\, dE \qquad ...(2)$$

E_C is the energy corresponding to the bottom most level of the conduction band and $+\infty$ is energy corresponding to the upper most level of the conduction band.

Density of states in the conduction band between the energy range E and E + dE is given by

$$Z(E)\, dE = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} E^{\frac{1}{2}}\, dE \qquad ...(3)$$

The bottom edge of the conduction band (E_C) denotes the potential energy of an electron at rest. Therefore, $(E - E_C)$ is the kinetic energy of the conduction electron at higher energy levels.

Thus in equation (3), E is replaced by $(E - E_C)$

$$Z(E)\, dE = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} (E - E_C)^{\frac{1}{2}}\, dE \qquad ...(4)$$

The probability of electron occupation is given by Fermi distribution function.

$$F(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}} \qquad ...(5)$$

Substituting the eqns (4) and (5) in (2), we get

$$n = \int_{E_C}^{+\infty} \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} (E - E_C)^{\frac{1}{2}} \times \frac{1}{1 + e^{\frac{E - E_F}{kT}}}\, dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} \int_{E_C}^{+\infty} \frac{(E - E_C)^{\frac{1}{2}}}{1 + e^{\frac{(E - E_F)}{kT}}}\, dE \qquad ...(6)$$

Since kT is very small ~ 0.03 eV and $(E - E_F)$ is greater than kT, $e^{\frac{E - E_F}{kT}}$ is very large compared to '1'. Hence, '1' from the denominator of the equation (6) is neglected. i.e., $1 + e^{\frac{E - E_F}{kT}} \approx e^{\frac{E - E_F}{kT}}$.

Now the equation (6) becomes

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} \int_{E_C}^{\infty} \frac{(E - E_C)^{\frac{1}{2}} dE}{e^{\frac{(E-E_F)}{kT}}}$$

(or)

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} \int_{E_C}^{+\infty} (E - E_C)^{\frac{1}{2}} e^{\frac{-(E-E_F)}{kT}} dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} \int_{E_C}^{+\infty} (E - E_C)^{\frac{1}{2}} e^{\frac{(E_F-E)}{kT}} dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{\frac{E_F}{kT}} \int_{E_C}^{\infty} (E - E_C)^{\frac{1}{2}} e^{\frac{-E}{kT}} dE \qquad ...(7)$$

To solve the integral in the eqn. (7), let us assume

$E - E_C = x$ | when $E = E_C$ | when $E = +\infty$

$E = E_C + x$ | $E - E_C = x$ | $+\infty - E_C = x$

$dE = dx$ | $\therefore x = 0$ | $\therefore x = +\infty$

Substituting the above values in equation (7), we have

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{\frac{E_F}{kT}} \int_{0}^{\infty} x^{\frac{1}{2}} e^{\frac{-(E_C+x)}{kT}} dx$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{\frac{(E_F-E_C)}{kT}} \int_{0}^{\infty} x^{\frac{1}{2}} e^{\frac{-x}{kT}} dx \qquad ...(8)$$

Using the gamma function, it can be shown that

$$\int_0^{\infty} x^{\frac{1}{2}} e^{\left(\frac{-x}{kT}\right)} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2} \qquad ...(9)$$

Substituting the eqn. (9) in the eqn. (8), we have

$$n = \frac{4\pi}{h^3}(2m_e^*)^{\frac{3}{2}} e^{\frac{(E_F-E_C)}{kT}} \left[\frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}\right]$$

$$n = \frac{2\pi}{h^3}(2m_e^*)^{\frac{3}{2}} (kT)^{\frac{3}{2}} \pi^{\frac{1}{2}} e^{\frac{(E_F-E_C)}{kT}}$$

or

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F-E_C)}{kT}} \qquad ...(10)$$

Equation (10) is the expression for concentration of electrons in the conduction band of an intrinsic semiconductor.

DENSITY OF HOLES IN VALENCE BAND

The number of holes per unit volume in the valence band of a semiconductor can be found in a similar manner. As the presence of the hole can be regarded as the absence of an electron, the Fermi function of holes in the valence band is the inverse function equal to [1 – F(E)].

Let dp be the number of holes per unit volume in the valence band between the energy E and E tdE

$$dp = Z(E)\,(1 - F(E))\,dE \quad ...(1)$$

Where Z(E) dE – Density of states in the energy range E and E tdE

We know, F (E) represents the probability of filled state. As the maximum probability will be 1, the probability of unfilled states will be [1 – F (E)].

$$1 - F(E) = 1 - \frac{1}{1 + e^{\frac{(E-E_F)}{kT}}}$$

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

$$1 - F(E) = \frac{e^{\frac{(E-E_F)}{kT}}}{1 + e^{\frac{(E-E_F)}{kT}}} \quad ...(2)$$

Since E is very small when compared to E_F in the valence band, $(E - E_F)$ is a negative quantity. Therefore $e^{\frac{(E-E_F)}{kT}}$ is very small and it is neglected in the eqn.(3).

i.e.,

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

$$1 - F(E) = e^{\frac{(E-E_F)}{kT}} \quad ...(3)$$

Density of states in the valence band,

$$Z(E)\,dE = \frac{4\pi}{h^3}\left(2m_h^*\right)^{\frac{3}{2}} E^{\frac{1}{2}}\,dE \quad ...(4)$$

Here, m_h^* is the effective mass of the hole in the valence band.

E_v, top level in the valence band is the potential energy of a hole at rest.

Hence, $(E_v - E)$ is the kinetic energy of the hole at level below E_v. So the term E is replaced by $(E_v - E)$ in eqn. (4).

$$Z(E)\,dE = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_v - E)^{\frac{1}{2}}\,dE \quad ...(5)$$

Substituting the equations (3) and (5) in (1), we get

$$dp = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_v - E)^{\frac{1}{2}}\,e^{\frac{(E-E_F)}{kT}}\,dE \quad ...(6)$$

The number of holes in the valence band for the entire energy range is obtained by integrating the equation (6) between the limits $-\infty$ to E_v.

$$\int dp = p = \int_{-\infty}^{E_v}\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(E_v - E)^{\frac{1}{2}}\,e^{\frac{(E-E_F)}{kT}}\,dE$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}\,e^{\left(\frac{-E_F}{kT}\right)}\int_{-\infty}^{E_v}(E_v - E)^{\frac{1}{2}}\,e^{\left(\frac{E}{kT}\right)}\,dE \quad ...(7)$$

To solve the above integral in eqn. (7), let us assume,

	when	when
$E_v - E = x$	$E = -\infty$	$E = E_v$
$E = -x + E_v$	$E_v + \infty = x$	$x = E_v - E_v$
$\therefore dE = -dx$	$\therefore x = \infty$	$\therefore x = 0$

Substituting these values in equation (7), we have

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}\,e^{\left(\frac{-E_F}{kT}\right)}\int_{\infty}^{0}x^{\frac{1}{2}}\,e^{\frac{-x+E_v}{kT}}\,(-dx) \quad ...(8)$$

or $$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}\,e^{\frac{(E_v-E_F)}{kT}}\int_{0}^{\infty}x^{\frac{1}{2}}\,e^{\left(\frac{-x}{kT}\right)}\,dx \quad ...(9)$$

[–ve sign is omitted by interchanging the limits]

using the gamma function, it can be shown that

$$\int_0^{\infty}x^{\frac{1}{2}}\,e^{\left(\frac{-x}{kT}\right)}\,dx = \frac{(kT)^{\frac{3}{2}}\pi^{\frac{1}{2}}}{2} \quad ...(10)$$

substituting the eqn. (10) in the eqn. (9), we have

$$p = \frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}\,e^{\frac{(E_v-E_F)}{kT}}\left[\frac{(kT)^{\frac{3}{2}}\pi^{\frac{1}{2}}}{2}\right]$$

$$p = \frac{2\pi}{h^3}(2m_h^*)^{\frac{3}{2}}(kT)^{\frac{3}{2}}\pi^{\frac{1}{2}} e^{\frac{(E_v - E_F)}{kT}}$$

or

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_v - E_F)}{kT}} \quad ...(11)$$

The equation (11) is the expression for concentration of holes in the valence band of an intrinsic semiconductor.

INTRINSIC CARRIER CONCENTRATION

If the semiconductors is in the pure or intrinsic state, then the concentrations of holes and electrons must be equal.

Therefore $n = p = n_i$ where n_i is intrinsic carrier concentration,

$$np = n_i \times n_i = n_i^2 \quad ...(1)$$

Substituting the expressions for n and p in eqn. (1), we have

$$n_i^2 = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F - E_C)}{kT}} \times 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_v - E_F)}{kT}}$$

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{\frac{3}{2}} e^{\frac{(E_v - E_C)}{kT}}$$

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{\frac{3}{2}} e^{\frac{-E_g}{kT}} \quad ...(2)$$

where $(E_C - E_v = E_g)$ is the forbidden energy gap.

$$n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} e^{\frac{-E_g}{2kT}} \quad ...(3)$$

Therefore for intrinsic semiconductor even if impurity is added to increase n_e there will be decrease in n_h and hence the product $n_p\, n_h$ will remain constant. This is called *law of mass action*.

2.8 FERMI LEVEL AND ITS VARIATION WITH TEMPERATURE

For an intrinsic semiconductor, the density of the electrons is equal to the density of holes. i.e., $n = p$ ...(1)

Substituting the expressions of n and p in eqn. (1), we have

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F - E_C)}{kT}} = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_v - E_F)}{kT}}$$

Rearranging, we get

$$e^{\frac{(E_F - E_C)}{kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\frac{(E_v - E_F)}{kT}}$$

or

$$e^{\frac{2E_F}{kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\frac{(E_v + E_C)}{kT}}$$

Taking log on both sides, we get

$$\log_e e^{\frac{2E_F}{kT}} = \log_e \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} + \log_e e^{\frac{(E_v + E_C)}{kT}}$$

$$\frac{2E_F}{kT} = \frac{3}{2}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{(E_v + E_C)}{kT}$$

$$E_F = \frac{kT}{2}\left[\frac{3}{2}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{(E_v + E_C)}{kT}\right]$$

$$E_F = \frac{3kT}{4}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{kT}{2}\left[\frac{(E_v + E_C)}{kT}\right]$$

$$E_F = \frac{3kT}{4}\log_e \left(\frac{m_h^*}{m_e^*}\right) + \frac{(E_v + E_C)}{2} \quad ...(2)$$

If $m_h^* = m_e^*$, then $\log_e \left(\frac{m_h^*}{m_e^*}\right) = \log_e 1 = 0$

Hence, the equation (2) becomes

$$E_F = \frac{(E_v + E_C)}{2} \quad ...(3)$$

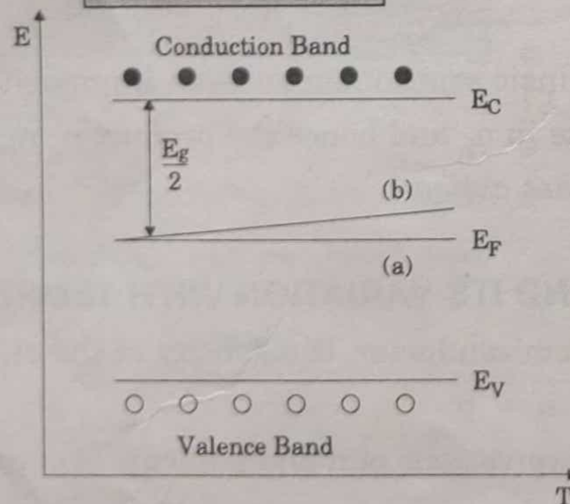


Fig. 2.4 Positions of Fermi level in an intrinsic semiconductor at various temperatures.

(a) At T = 0K, Fermi level is in the middle of the forbidden band.

(b) As the temperature rises, it shifts upward since $m_h^* > m_e^*$.

Thus, Fermi level is located half way between the top of the valence band and bottom of the conduction band as shown in Fig.2.4. Its position is independent of temperature

In reality $m_h^* > m_e^*$; thus, Fermi level is just above the middle of energy gap and it rises slightly with increasing temperature.

Density of electrons and holes interms of E_g

In terms of energy gap (E_g) where $E_g = E_c - E_v$ we can get the expression of n_e and n_h by substituting the value of E_F in terms of E_c and E_v.

Substituting eqn. (2) in (10) we get

$$n_e = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \exp\left[\frac{\frac{E_c + E_v}{2} + \frac{3}{4} kT \log_e\left(\frac{m_h^*}{m_e^*}\right) - E_c}{kT}\right]$$

$$= 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^*)^{3/2} \exp\left[\frac{2E_c + 2E_v + 3kT \log_e\left(\frac{m_h^*}{m_e^*}\right) - 4E_c}{4kT}\right]$$

$$= 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^*)^{3/2} \exp\left[\frac{2(E_v - E_c)}{4kT} + \frac{3}{4} \log_e\left(\frac{m_h^*}{m_e^*}\right)\right]$$

Since $E_g = E_c - E_v$, we can write

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

$$= 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^*)^{3/2} \frac{(m_h^*)^{3/4}}{(m_e^*)^{3/4}} e^{-E_g/2kT}$$

$$= 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^*)^{3/4} (m_h^*)^{3/4} e^{-E_g/2kT}$$

$$n_e = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2kT} \quad \text{... (1)}$$

Similarly by substituting eqn. (2) in (11) we get

$$n_h = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_h^* . m_e^*)^{3/4} e^{-E_g/2kT} \quad \text{... (2)}$$

Thus, it is found that $n_e = n_h = n_i$ where n_i is the intrinsic carrier concentration.

2.9 MOBILITY AND ELECTRICAL CONDUCTIVITY OF INTRINSIC SEMICONDUCTORS

Since there are two types of carriers in the intrinsic semiconductor, then the electric conductivity is the sum of the conductivities σ_n due to free electrons and σ_h due to holes.

$$\therefore \quad \sigma_i = \sigma_n + \sigma_h$$

$$\sigma_i = (ne\mu_e + pe\mu_h) \quad \ldots (1)$$

where μ_e and μ_h are the mobility of electron and hole respectively.

Mobility is the velocity acquired by the electron or hole under unit potential gradient. In the case of intrinsic semiconductor

$$\sigma_i = n_i e (\mu_e + \mu_h) \qquad \text{since } n = p = n_i$$

$$\sigma_i = (\mu_e + \mu_h) 2e \left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{(-E_g/2kT)} \text{ (from eqn. 3)} \quad \ldots (2)$$

Thus the *electrical conductivity* depends upon the negative exponential of the forbidden energy gap between the valence and conduction band and on the mobilities of both holes and electrons.

The mobilities in a pure semiconductor are determined by the interaction of electrons with lattice waves or phonons. μ_e and μ_h are almost independent of temperature so that we can express the temperature dependent as

$$\sigma = A(T)^{3/2} e^{-(E_g/2kT)}$$

where $A = 2e\left(\frac{2\pi k}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} (\mu_e + \mu_a)$ is a constant for the given semiconductor and is independent of temperature.

At room temperature (300 K) the variation of $(T)^{3/2}$ with temperature is very small comparing the variation of $e^{-(E_g/2kT)}$ with temperature. We may assume that $(T)^{3/2}$ is almost constant for small changes in temperature. Therefore the electrical conductivity in the intrinsic semiconductor can be written as

$$\sigma_i = Ae^{-E_g/2kT}$$

where A is a constant. Taking logarithms on both sides

$$\boxed{\log \sigma_i = \log A - \frac{E_g}{2kT}}$$

A typical graph drawn between $\frac{1}{T}$ and log σ_i is shown in Fig. 2.5. From the graph we know that conductivity increases with temperature.

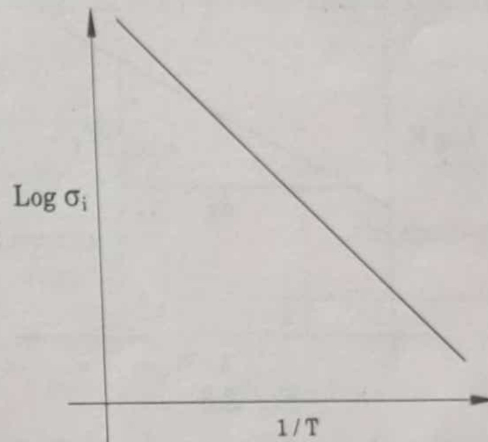


Fig. 2.5

2.10 DETERMINATION OF BAND GAP (OR) ENERGY GAP IN INTRINSIC SEMICONDUCTOR

We know that for an intrinsic semiconductor

$$\sigma_i = Ae^{-E_g/2kT}$$

∴ The resistivity of the intrinsic semiconductor,

$$\rho_i = \frac{1}{A} e^{(E_g/2kT)}$$

Since resistivity is resistance per unit area per unit length $\left(\text{since } \rho = \frac{R_i a}{L}\right)$

$$\frac{R_i a}{L} = \frac{1}{A} e^{(E_g/2kT)}$$

where R_i is the resistance, 'a' the area of cross section and L is the length of intrinsic semiconductor.

Since, 'a' and 'L' are constants,

$$R_i = Ce^{(E_g/2kT)} \qquad \text{where } C = \frac{L}{aA}$$

Take log on both sides,

$$\text{Log } R_i = \log C + \left(\frac{E_g}{2kT}\right)$$

The above equation gives us a method of determining the energy gap of an intrinsic material. If we find the resistance of the intrinsic semiconductor using post office box or Carey Foster's bridge at various temperatures, we can plot a graph between 1/T and log R_i. Then the slope of that curve will give the value of E_g / 2kT. (Fig. 2.6)

From the curve $\frac{dy}{dx} = \frac{E_g}{2k}$

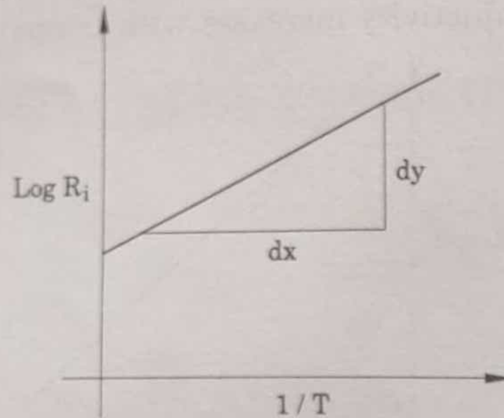


Fig. 2.6

Therefore by finding the slope of line we can calculate the energy band gap E_g with the following expression.

$$E_g = 2k\frac{dy}{dx} \text{ Joules}$$

2.11 EXTRINSIC SEMICONDUCTOR

A Semiconducting material in which the charge carriers originate from impurity atoms added to the material is called impurity semiconductor (or) extrinsic semiconductor.

Based on the type of impurity added they are classified into two types. They are,

(i) n-type semiconductor (ii) p-type semiconductor

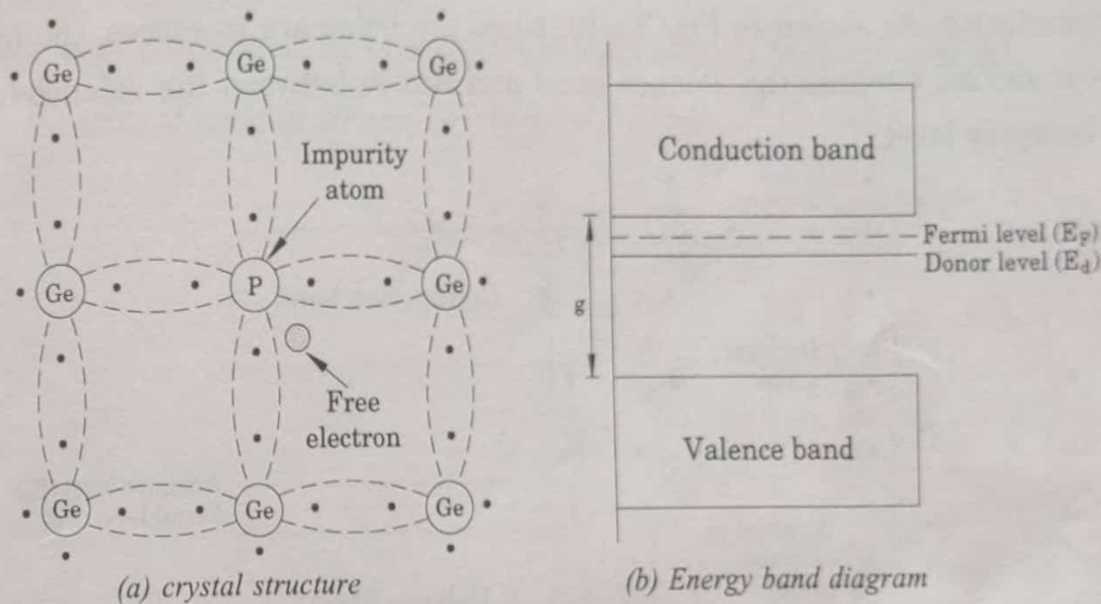
(i) n-type semiconductor

n-type semiconductor is obtained when a pentavalent impurity atom (5 electrons in valence band) like Phosphorus, Arsenic, Antimony, etc., is doped with an intrinsic semiconductor.

As shown in Fig. 2.7(a) the four electrons of the Phosphorous atom form covalent bonds with the valence electrons of the Ge atoms. The fifth electron of the Phosphorous atom is not covalently bonded but is loosely bound to the Phosphorous atom. By increasing the thermal energy or by applying electric field, this electron can easily be excited from the valence band to the conduction band and is available for electrical conduction.

Every Phosphorous atom added to the semiconductor contributes one conduction electron without creating a positive hole. Hence Phosphorous is called a donor atom, since it donates free electrons. The material as a whole has excess of electrons which are the majority current carriers and they form *donor energy*

level (E_d) which lies close to the conduction band. Since the majority current carriers are negatively charged particles, this type of semiconductor is called an *n-type semiconductor.* Fig. 2.7(b) gives the band diagram of the n-type semiconductor.



(a) crystal structure (b) Energy band diagram

Fig. 2.7 n-type semiconductor

It is seen that the Fermi level is shifted towards the conduction band and lies in between the conduction band and donor level, indicative of the presence of excess of electrons.

(ii) p-type semiconductor

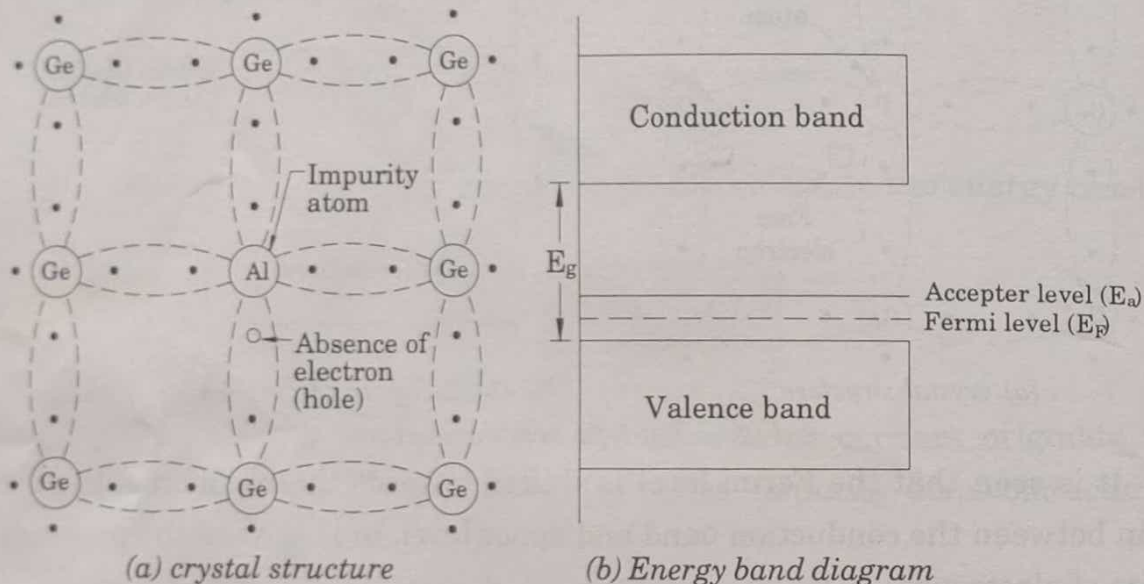
p-type semiconductor is obtained when a trivalent impurity atom (3 electrons in valence band) like Aluminium, Boron, Gallium, etc., is doped with an intrinsic semiconductor.

As shown in Fig. 2.8(a) the three valence electrons of the Aluminum atom form covalent bonds with the valence electrons of Ge atom. One more electron is needed for bonding which is not available. This deficiency of one electron becomes a hole.

For every Aluminum atom added, a hole is introduced in the semiconductor. The holes which are in excess in a p-type semiconductor are treated as positively charged particles. They take part in electrical conduction and the majority carriers in the p-type semiconductor.

Due to thermal excitation, a hole in one location may be occupied by an electron from the neighbouring atom in which case the hole is shifted to a new location. This process goes on as a result of which the hole moves about in random. Thus the holes are free to conduct electricity.

The impurity atoms which contribute holes to the semiconductor are called acceptor impurities and they form *acceptor level* (E_a) which lies close to the valence band. Since the current carriers are positively charged holes, this type of semiconductor is called *p-type*. Fig.2.8(b) gives the band diagram of a p-type semiconductor. As shown in Fig. 2.8(b), since the holes are in excess, the fermi level is shifted towards the valence band and lies in between the valence band and acceptor level.



(a) crystal structure *(b) Energy band diagram*

Fig. 2.8 p-type semiconductor

2.12 CARRIER CONCENTRATION IN n - TYPE SEMICONDUCTOR [Derivation]

The energy band diagram of a n - type semiconductor is shown in Fig. 2.9. In the n - type semiconductor, the donor level is just below the conduction band. N_d denotes donor concentration, i.e., the number of donor atoms per unit volume of the material and E_d represents the energy of the donor level.

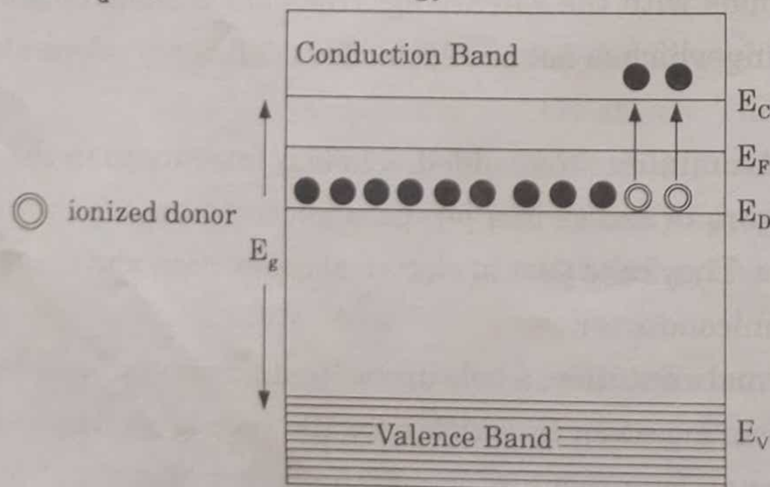


Fig. 2.9 Energy band diagram of a n-type semiconductor

Density of electrons per unit volume in the conduction band is given by

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F - E_C)}{kT}} \quad ...(1)$$

where E_F – Energy of the Fermi level;

E_C – Energy corresponding to the bottom most level of conduction band.

Density of ionised donors $= N_d[1 - F(E_d)]$

$$= N_d\left[1 - \frac{1}{1 + e^{\frac{(E_d - E_F)}{kT}}}\right]$$

$$= N_d\left[\frac{1 + e^{\frac{(E_d - E_F)}{kT}} - 1}{1 + e^{\frac{(E_d - E_F)}{kT}}}\right]$$

$$= \frac{N_d\, e^{\frac{(E_d - E_F)}{kT}}}{1 + e^{\frac{(E_d - E_F)}{kT}}} = \frac{N_d}{\frac{1 + e^{\frac{(E_d - E_F)}{kT}}}{e^{\frac{(E_d - E_F)}{kT}}}}$$

$$= \frac{N_d}{\frac{1}{e^{\frac{(E_d - E_F)}{kT}}} + 1}$$

$$= \frac{N_d}{e^{\frac{-(E_d - E_F)}{kT}} + 1}$$

$$\text{Density of ionised donors} = \frac{N_d}{1 + e^{\frac{(E_F - E_d)}{kT}}} \quad ...(2)$$

At equilibrium, the density of electrons in the conduction band is equal to the density of ionised donors.

∴ Equating (1) and (2), we have

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F - E_C)}{kT}} = \frac{N_d}{1 + e^{\frac{(E_F - E_d)}{kT}}} \quad ...(3)$$

E_F lies more than a few kT above donor levels, $e^{\frac{(E_F - E_d)}{kT}}$ is very large when compared to 1. Hence '1' from the denominator of R.H.S. of equation (3) is neglected.

Hence, the equation (3) becomes

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F - E_C)}{kT}} = \frac{N_d}{e^{\frac{(E_F - E_d)}{kT}}}$$

or
$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_F - E_C)}{kT}} = N_d\, e^{\frac{(E_d - E_F)}{kT}} \quad ...(4)$$

Taking log on both sides, we get

$$\log_e\left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}\right] + \log_e e^{\frac{(E_F - E_C)}{kT}} = \log_e N_d\, e^{\frac{E_d - E_F}{kT}}$$

$$\log_e\left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}\right] + \frac{E_F - E_C}{kT} = \log_e N_d + \frac{E_d - E_F}{kT} \quad ...(5)$$

Rearranging, we have

$$\frac{E_F - E_C - E_d + E_F}{kT} = \log_e N_d - \log\left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}\right]$$

$$\frac{2E_F - E_d - E_C}{kT} = \log_e\left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}}\right]$$

or
$$2E_F = E_d + E_C + kT\log_e\left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}}\right]$$

$$E_F = \frac{E_d + E_C}{2} + \frac{kT}{2}\log_e\left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}}\right] \quad ...(6)$$

Substituting the expression of E_F from (6) in (1), we get

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{\frac{E_d + E_C}{2} + \frac{kT}{2}\log_e\left\{\frac{N_d}{2\left\{\frac{2\pi m_e^* kT}{h^2}\right\}^{\frac{3}{2}}}\right\} - E_C}{kT}\right] \quad ...(7)$$

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_C + E_d - 2E_C}{2kT} + \frac{1}{2}\log_e\left\{\frac{N_d}{2\left\{\frac{2\pi m_e^* kT}{h^2}\right\}^{\frac{3}{2}}}\right\}\right]$$

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_d - E_C}{2kT} + \log_e\left\{\frac{(N_d)^{\frac{1}{2}}}{\left[2\left\{\frac{2\pi m_e^* kT}{h^2}\right\}^{\frac{3}{2}}\right]^{\frac{1}{2}}}\right\}\right]$$

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \frac{\left(\frac{N_d}{2}\right)^{\frac{1}{2}}}{\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{4}}} e^{\frac{(E_d - E_C)}{2kT}} \quad ...(8)$$

Rearranging the expression (8), we get

$$n = 2^{\frac{1}{2}} N_d^{\frac{1}{2}} \left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_d - E_C)}{2kT}} \quad ...(9)$$

$$\boxed{n = (2N_d)^{\frac{1}{2}} \left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{4}} e^{\frac{-\Delta E}{2kT}}} \quad ...(10)$$

where $\Delta E = E_C - E_d$ is the ionisation energy of the donor. i.e., ΔE denotes the amount of energy required to transfer an electron from the donor energy level E_d to the conduction band E_C.

Results

(i) The density of electrons in the conduction band is proportional to the square root of the donor concentration. The equation (10) is vaild only at low temperatures.

(ii) But at high temperature, we must take the intrinsic carrier concentration along with this.

(iii) At very high temperatures, intrinsic carrier concentration over takes electrons due to donor concentration. That is, at very high temperatures, n-type semiconductor behaves like an intrinsic semiconductor and donor concentration becomes insignificant.

2.13 VARIATION OF FERMI LEVEL WITH TEMPERATURE AND CONCENTRATION OF DONOR ATOMS

The increase in temperature increases the fermi level as given by equation (4). Further increase in temperature ionise more and more donor atoms. For a particular temperature all the donor atoms are ionised. If the temperature increased beyond this electron hole pairs will be produced due to breaking of covalent bonds and the material tends to behave in intrinsic manner. Thus, the fermi level gradually moves towards the intrinsic fermi level E_i as shown in Fig. 2.10.

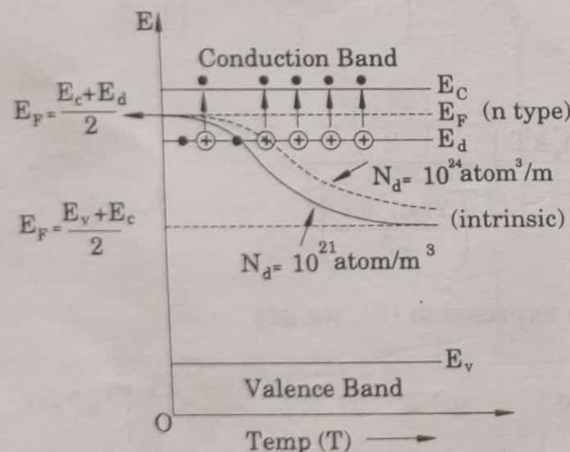


Fig. 2.10 Variation of Fermi level with temperature

It is seen from the figure that, lowering of fermi with temperature is *slow* in the case of *higher donor concentration* than the lower donor concentration. The highly doped semiconductor will behave in intrinsic manner only after all the donor atoms are ionised. The behaviour of fermi level for two different donor concentrations is given in Fig. 2.10.

2.14 CONCENTRATION OF HOLES IN THE VALENCE BAND OF p - TYPE SEMICONDUCTOR [Derivation]

In p - type semiconductor, acceptor energy level is just above the valence band (Fig. 2.11). E_a represents the energy of the acceptor level and N_a denotes the number of acceptor atoms per unit volume.

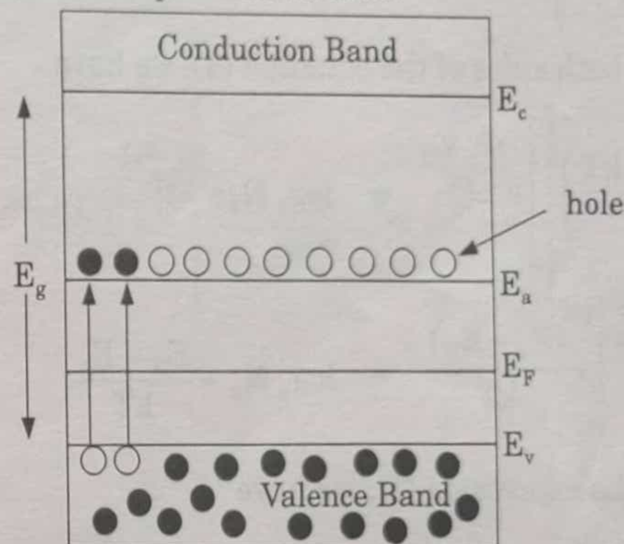


Fig. 2.11 Energy band diagram for p-type semiconductor

Density of holes per unit volume in the valence band is given by

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_v - E_F)}{kT}} \quad ...(1)$$

where E_F – Fermi energy level

E_v – Energy corresponding to the top level of valence band.

Density of ionised donors $= N_a F(E_a)$

$$= \frac{N_a}{1 + e^{\frac{(E_a - E_F)}{kT}}} \quad ...(2)$$

Where $$F(E_a) = \frac{N_a}{1 + e^{\frac{(E_a - E_F)}{kT}}}$$

Since $E_a - E_F$ is very large when compared to kT, $e^{\frac{(E_a - E_F)}{kT}}$ is a large quantity and thus '1' from the denominator of R.H.S. of the equation (2) is neglected.

Now, the eqn. (2) is modified as,

$$N_a F(E_a) = \frac{N_a}{e^{\frac{(E_a - E_F)}{kT}}}$$

Density of ionised acceptors $= N_a e^{\frac{(E_F - E_a)}{kT}}$ ...(3)

At equilibrium,

Density of holes in valence band = Density of ionised acceptors

$$2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} e^{\frac{(E_v - E_F)}{kT}} = N_a e^{\frac{(E_F - E_a)}{kT}} \qquad ...(4)$$

Taking log on both sides of the equation (4), we have

$$\log_e \left[2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}\right] e^{\frac{(E_v - E_F)}{kT}} = \log_e N_a e^{\frac{(E_F - E_a)}{kT}}$$

$$\log_e \left[2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}\right] + \frac{(E_v - E_F)}{kT} = \log_e N_a + \frac{E_F - E_a}{kT} \qquad ...(5)$$

Rearranging the expression (5), we have

$$\frac{E_F - E_a - E_v + E_F}{kT} = -\log_e N_a + \log_e \left[2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}\right]$$

or
$$\frac{2E_F - (E_a + E_v)}{kT} = -\log_e \left[\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}}\right]$$

or
$$2E_F = (E_a + E_v) - kT \log_e \left[\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}}\right] \qquad ...(6)$$

$$E_F = \frac{E_a + E_v}{2} - \frac{kT}{2} \log_e \left[\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}}\right] \qquad ...(7)$$

Substituting the expression of E_F from (7) in (1), we get

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_v - \frac{E_v - E_a}{2} + \frac{kT}{2}\log_e\left\{\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}}\right\}}{kT}\right]$$

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{2E_v - E_v - E_a}{2kT} + \frac{1}{2}\log_e\left\{\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}}\right\}\right] \quad ...(8)$$

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \frac{\left(\frac{N_a}{2}\right)^{\frac{1}{2}}}{\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{4}}} e^{\frac{(E_v - E_a)}{2kT}}$$

$$p = (2N_a)^{\frac{1}{2}}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{4}} e^{\frac{(E_v - E_a)}{2kT}} \quad ...(9)$$

$$\boxed{p = (2N_a)^{\frac{1}{2}}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{4}} e^{\frac{-\Delta E}{2kT}}} \quad ...(10)$$

where $\Delta E = E_a - E_v$

Results

(i) Density of holes in the valence band is proportional to the square root of acceptor concentration.

(ii) At high temperature, we must take the intrinsic carrier concentration along with this.

(iii) At very high temperatures, intrinsic carrier concentration over takes holes due to acceptor concentration. i.e., At very high temperature, p-type semiconductor behaves like an intrinsic semiconductor and acceptor concentration becomes insignificant.

2.15 VARIATION OF FERMI LEVEL WITH TEMPERATURE AND CONCENTRATION OF ACCEPTOR ATOMS

The increase of temperature decreases the Fermi level slightly. As the

temperature increases more and more acceptor atoms are ionised. For a particular temperature all the acceptor atoms are ionised. Further increase in temperature results in generation of electron hole pairs due to breaking of covalent bonds and the materials behave in intrinsic manner. The movement of Fermi level towards intrinsic Fermi level with temperature is shown in Fig. 2.12.

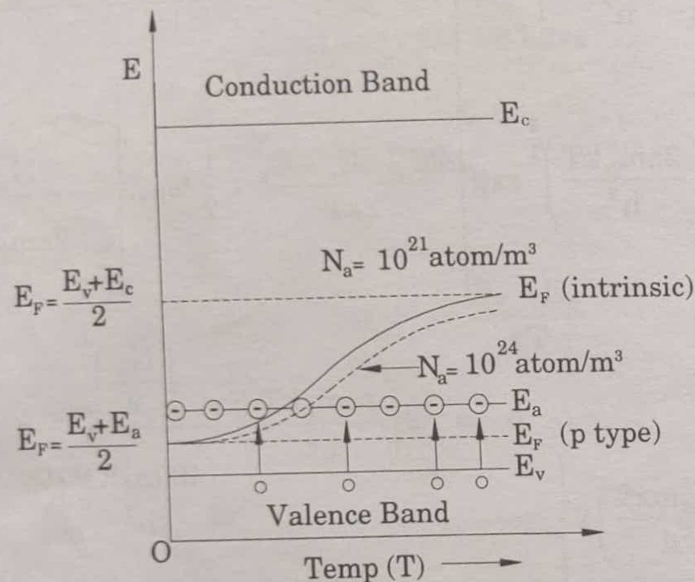


Fig. 2.12 Variation of Fermi level with temperature

The behaviour of P-type semiconductor with higher acceptor concentration is compared with a lower one in Fig. 2.12. *The Fermi level of the highly doped semiconductor is also low.* This is because the highly doped semiconductor will behave in intrinsic manner only after all the acceptor atoms are ionised.

2.16 VARIATION OF CARRIER CONCENTRATION WITH TEMPERATURE

The variation of carrier concentration with temperature for a n-type semi conductor is shown in Fig. 2.13.

At 0K both the conduction band and valence band are free from any charge carriers and hence conductivity is zero.

Now, when the temperature is slowly increased, the donor atoms get ionised and hence, the electron concentration in conduction band increases. Since this range occurs due to impurity atoms ionisation this region is called *impurity range.*

When the temperature is further increased, say at about room temperature, all the donor atoms are ionised and so, the concentrations of electrons in the conduction band remains constant over a certain range of temperature. This range is called the *exhaustion range.*

As the temperature is increased further, and if the thermal energy is sufficiently high, the covalent bonds get broken and thus electron-hole pairs are generated. As a result, electrons from the valence band starts moving towards the conduction band the thereby increasing the electron concentration in the conduction band considerably. Thus, with continuous increase of temperature, more and more electrons from the valence band reach the conduction band and completely outnumber donor electrons. The Fermi level moves down gradually until it reaches the middle of the forbidden gap. The material becomes intrinsic and this range is called *intrinsic range.*

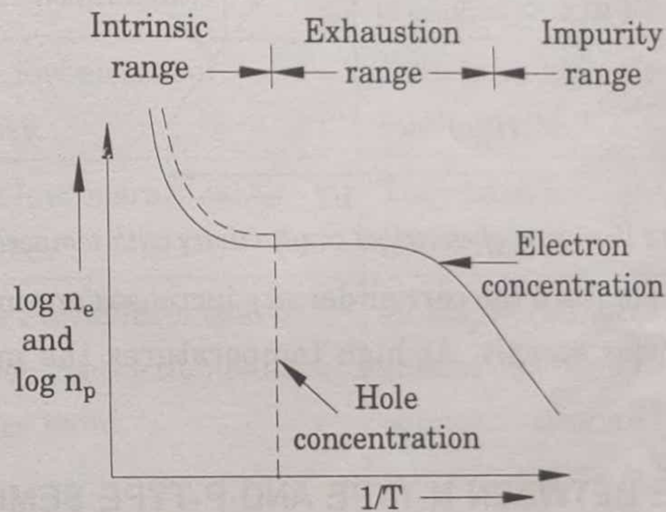


Fig. 2.13 Variation of carrier concentration with temperature

Hole concentration

The dotted curve indicates the hole concentration. In the intrinsic range both the hole and electron concentration curves overlap since they become equal in number. The exhaustion range is observable only for smaller concentration of N_d. If N_d is large, the low temperature impurity region extends towards intrinsic region.

Note : The variation of carrier concentration with temperature for a p-type semiconductor can also be explained in the similar manner.

Conductivity of extrinsic semiconductor

The variation of conductivity with increase of temperature of an extrinsic semiconductor is shown in Fig. 2.14.

At low temperature, near absolute zero, only few of the impurity atoms get ionised and hence the conductivity low.

As the temperature is increased further, more and more of the impurity atoms get ionised and so conductivity σ increases. But, this increase in log σ is gradual due to large impurity scattering and the availability of small amount of carriers.

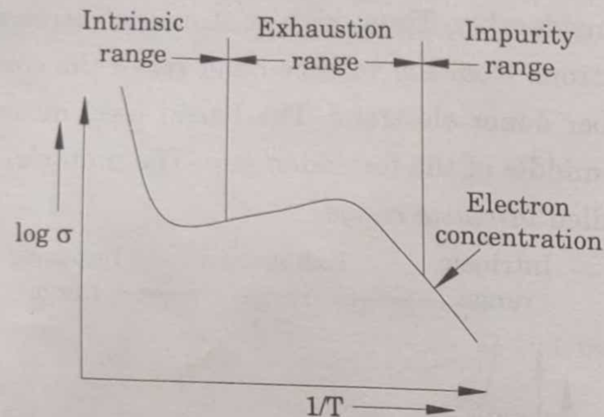


Fig. 2.14 Variation of electrical conductivity with temperature

At higher temperature the carrier density increases enormously and so the conductivity increases steeply. At high temperatures the material becomes practically intrinsic.

2.17 DIFFERENCE BETWEEN N-TYPE AND P-TYPE SEMICONDUCTOR

S.No.	n-type semiconductor	p-type semiconductor
1.	n-type semiconductor is obtained by doping an intrinsic semiconductor with pentavalent impurity.	p-type semiconductor is obtained by doping an intrinsic semiconductor with a trivalent impurity.
2.	Here electrons are majority carriers and holes are minority carriers.	Here holes are majority carriers and electrons are minority carriers.
3.	It has donar energy levels very close to conduction band.	It has acceptor energy levels very close to valence band.
4.	When temperature is increased, these semiconductors can easily donate an electron from donor energy level to the conduction band	When temperature is increased, these semiconductors can easily accept an electron from valence band to acceptor energy level.

2.18 DIFFERENCE BETWEEN INTRINSIC AND EXTRINSIC SEMICONDUCTOR.

S.No.	Intrinsic semiconductors	Extrinsic semiconductors
1.	Semiconductor in a pure form is called intrinsic semiconductor.	Semiconductor which are doped with impurity is called extrinsic semiconductor.
2.	Here the charge carriers are produced only due to thermal agitation.	Here the charge carriers are produced due to impurities and may also be produced due to thermal agitation.
3.	They have low electrical conductivity.	They have high electrical conductivity.
4.	They have low operating temperature.	They have high operating temperature.
5.	At 0K, the Fermi level exactly lies between conduction band and valence band. **Examples :** Si, Ge, etc.	At 0K, Fermi level lies closer to conduction band in 'n' type semiconductor and lies near valence band in 'p' type semiconductor. **Examples :** Si and Ge doped with Al, In, P, As etc.

2.19 HALL EFFECT

Measurement of conductivity will not determine whether the conduction is due to electron or holes and therefore will not distinguish between p-type and n-type semiconductor.

Therefore Hall effect is used to distinguish between the two types of carriers and their carrier densities and is used to determine the mobility of charge carriers.

Hall Effect

When conductor (metal or semiconductor) carrying a current is placed in a transverse magnetic field, an electric field is produced inside the conductor in a direction normal to both the current and the magnetic field. This phenomenon is known as *"Hall effect"* and the generated voltage is called *"Hall voltage"*.

Hall Effect in n - type Semiconductor

Let us consider an n-type material to which the current is allowed to pass

SOLVED PROBLEMS

PROBLEM : 1

Calculate the intrinsic carrier concentration in germanium at 300 K. Given that $m_e^* = 1.09\ m_0$, $m_h^* = 0.31\ m_0$ and $E_g = 0.68$ eV.

Given :

$T = 300$ K, $k = 1.38 \times 10^{-23}$ Jk^{-1}, $h = 6.626 \times 10^{-34}$ Js,

$m_0 = 9.11 \times 10^{-31}$ Kg, $E_g = 0.68$ eV $= 0.68 \times 1.6 \times 10^{-19}$ J,

$m_e^* = 1.09\ m_0 = 9.929 \times 10^{-31}$ Kg, $m_p^* = 0.31\ m_0 = 2.824 \times 10^{-31}$ Kg, $n_i = ?$

Solution :

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

$$n_i = 2\left[\frac{2\times 3.14\times 1.38\times 10^{-23}\times 300}{\left(6.626\times 10^{-34}\right)^2}\right]^{3/2}\left(9.929\times 2.824\times 10^{-62}\right)^{3/4}\times e^{-\left[\frac{0.68\times 1.6\times 10^{-19}}{2\times 1.38\times 10^{-23}\times 300}\right]}$$

$$= 2\left[\frac{2.599\times 10^{-20}}{6.626\times 6.626\times 10^{-68}}\right]^{3/2}\times\left(3.853 \times 10^{-46}\right)\times\frac{1}{e^{13.14}}$$

$$= 2\left[5.9197\times 10^{46}\right]^{3/2}\times 3.853 \times 10^{-46}\times\frac{1}{508896.53}$$

$$n_i = 2.18 \times 10^{19}/m^3.$$

PROBLEM : 2

Mobiities of electrons and holes in a sample of intrinsic germanium at 300 K are 0.32 $m^2V^{-1}s^{-1}$ and 0.15 $m^2V^{-1}s^{-1}$ respectively. If the conductivity of the specimen is $2\Omega^{-1}\ m^{-1}$, compute the carrier concentration.

Given :

$\sigma_i = 2.0\ \Omega^{-1}\ m^{-1}$, $\mu_e = 0.32\ m^2\ V^{-1}\ s^{-1}$, $\mu_h = 0.15\ m^2\ V^{-1}\ s^{-1}$,
$e = 1.602 \times 10^{-19}$ C, $n_i = ?$

Solution :

$$\sigma_i = n_i e\left(\mu_e + \mu_h\right)$$

$$n_i = \frac{\sigma_i}{e\left(\mu_e + \mu_h\right)}$$

$$= \frac{2.0}{1.602 \times 10^{-19} \times (0.32 + 0.15)}$$

$$n_i = 2.656 \times 10^{19}/m^3$$

PROBLEM : 3

The following data are given for intrinsic germanium at 300 K $n_i = 2.4 \times 10^{19}/m^3$, $\mu_e = 0.39\ m^2\ V^{-1}\ s^{-1}$, $\mu_h = 0.19\ m^2V^{-1}s^{-1}$. Calculate the conductivity of the sample.

Given :

$\mu_e = 0.39\ m^2\ V^{-1}\ s^{-1}$, $\mu_h = 0.19\ m^2\ V^{-1}\ s^{-1}$, $e = 1.602 \times 10^{-19}\ C$, $\sigma_i = ?$

Solution :

$$\sigma_i = n_i e (\mu_e + \mu_h)$$

$$= 2.4 \times 10^{19} \times 1.602 \times 10^{-19} (0.39 + 0.19)$$

$$\sigma_i = 2.22\ \Omega^{-1}m^{-1}$$

PROBLEM : 4

The Hall coefficient of certain silicon specimen was found to be $-7.35 \times 10^{-5}\ m^3\ C^{-1}$. The –ve sign indicates it is n type of semiconductor. Calculate the density and mobility of charge carrier if $\sigma = 200\ \Omega^{-1}\ m^{-1}$.

Given :

$R_H = 7.35 \times 10^{-5}\ m^3C^{-1}$, $\sigma = 200\ \Omega^{-1}\ m^{-1}$.

Solution :

$$n_e = \frac{-1}{eR_H} = \frac{-1}{1.602 \times 10^{-19}(-7.35 \times 10^{-5})}$$

$$n_e = 8.492 \times 10^{22}\ /m^3$$

$$\therefore \mu_e = \frac{\sigma}{n_e e}$$

$$= \frac{200}{8.492 \times 10^{22} \times 1.602 \times 10^{-19}}$$

$$\mu_e = 0.0147\ m^2\ v^{-1}\ s^{-1}$$

PROBLEM : 5

A silicon plate of thickness 1mm, breadth 10 mm and length 100 mm is placed in a magnetic field of 0.5 Wb/m^2 acting perpendicular to it's thickness. If 10^{-2} A current flows along it's length. Calculate the Hall voltage developed if the Hall coefficient is 3.66×10^{-4} m^3 / coulomb.

Given :

$R_H = 3.66 \times 10^{-4}\ m^3/C$, $I = 10^{-2}\ A$, $B = 0.5\ Wb/m^2$, $t = 1\ mm$, $V_H = ?$

Solution :

$$R_H = \frac{V_H\ t}{I_x\ B}$$

$$V_H = \frac{R_H\ I_x\ B}{t}$$

$$= \frac{3.66 \times 10^{-4} \times 10^{-2} \times 0.5}{1 \times 10^{-3}}$$

$$V_H = 1.83\ mV$$

PROBLEM : 6

A sample of n type semiconductor has a resistivity of 10^{-3} ohm - m and a Hall coefficient of $10^{-4} m^3/C$. Assuming only electrons as charge carriers, determine the electron density and mobility.

Given :

$R_H = 10^{-4}\ m^3/C$, $\rho = 10^{-3}$ ohm/m, $n = ?$, $\mu = ?$

Solution :

$$R_H = \frac{1}{ne}$$

$$n = \frac{1}{eR_H} = \frac{1}{1.602 \times 10^{-19} \times 10^{-4}}$$

$$n = 6.24 \times 10^{22}/m^3$$

$$\sigma = n\,e\,\mu$$

$$\rho = \frac{1}{\sigma} = \frac{1}{ne\mu}$$

$$\mu = \frac{1}{ne\rho} = \frac{1}{6.24 \times 10^{22} \times 1.602 \times 10^{-19} \times 10^{-3}}$$

$$\boxed{\mu = 0.1 \, m^2/Vs}$$

PROBLEM : 7

Find the resistance of an intrinsic germanium rod 1 cm long, 1 mm wide and 1mm thick at 300 K.

For germanium $n_i = 2.5 \times 10^{19}/m^3$

$\mu_e = 0.39 \, m^2V^{-1}s^{-1}$

$\mu_e = 0.19 \, m^2V^{-1}s^{-1}$ **at 300K**

Given data :

Intrinsic carrier concentration $n_i = 2.5 \times 10^{19}/m^3$

Electron mobility $\mu_e = 0.39 \, m^2V^{-1}s^{-1}$

Hole mobility $\mu_e = 0.19 \, m^2V^{-1}s^{-1}$

Solution :

We know that the electrical conductivity of an intrinsic semiconductor (Germanium)

$$\sigma = n_i e (\mu_e + \mu_h)$$

Substituting the given values, we have

$\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.39 + 0.19)$

$\sigma = 2.32 \, \Omega^{-1}m^{-1}$

Resistance $R = \frac{\rho l}{A}$ or $R = \frac{l}{\sigma A}$ $\left(\because \sigma = \frac{1}{\rho}\right)$

where

l → length of the rod = 1 cm = 1×10^{-2} m

A → Area of cross-section (width x thickness)

$A = (1 \times 10^{-3} m)(1 \times 10^{-3} m)$

$$R = \frac{1 \times 10^{-2}}{2.32 \times (1 \times 10^{-3} \times 1 \times 10^{-3})}$$

$= 4310 \, \Omega$

$$\boxed{\text{Resistance of germanium} = 4310 \, \Omega}$$

PROBLEM : 8

For an intrinsic semiconductor with a band gap of 0.7 eV, determine the position of E_F at T = 300K if $m_h^* = 6m_e^*$.

Given : $E_g = 0.7$ eV (or) 1.12×10^{-19} Joules, T = 300K, $\frac{m_h^*}{m_e^*} = 6$

Solution :

We know Fermi energy of an intrinsic semiconductor

$$E_F = \frac{E_g}{2} + \frac{3K_BT}{4}\log_e\left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \frac{1.12 \times 10^{-19}}{2} + \frac{3 \times 1.38 \times 10^{-23} \times 300}{4}\log_e 6$$

$$= 5.6 \times 10^{-20} + 5.5634 \times 10^{-21}$$

$$E_F = 6.15634 \times 10^{-20}\ \text{J (or)}\ E_F = \frac{6.15634 \times 10^{-20}}{1.6 \times 10^{-19}}\ \text{eV}$$

$$E_F = 0.3847\ \text{eV}$$

PROBLEM : 9

The energy gap of silicon is 1.1 eV. Its electron and hole mobilities at room temperatures are 0.48 and 0.013 $m^2 V^{-1}s^{-1}$. Evaluate the carrier concentration and its electrical conductivity.

Given data :

Energy gap $E_g = 1.1$ eV

Electron mobility $\mu_e = 0.48\ m^2 V^{-1}s^{-1}$

Hole mobility $\mu_h = 0.013\ m^2 V^{-1}s^{-1}$

Temperature T = (27°C) = 300 K

Boltzmann's constant $k = 1.38 \times 10^{-23}\ JK^{-1}$

Solution :

We know that intrinsic carrier concentration

$$n_i = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} e^{\left(\frac{-E_g}{2kT}\right)}$$

Substituting the given values, we have

$$n_i = 2\left(\frac{2 \times 3.14 \times 9.1 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{(6.626 \times 10^{-34})^2}\right)^{\frac{3}{2}} e^{\left(\frac{-1.1 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300}\right)}$$

$$= 2\left(\frac{2.3626 \times 10^{-50}}{4.39038 \times 10^{-67}}\right)^{\frac{3}{2}} e^{\left[\frac{-1.76 \times 10^{-19}}{828 \times 10^{-23}}\right]}$$

$$= 2 \times \left[5.3942 \times 10^{16}\right]^{\frac{3}{2}} e^{-21.256}$$

$$= 2 \times (1.2528 \times 10^{25})(5.8697 \times 10^{-10})$$

$$n_i = 1.4707 \times 10^{16}\ m^{-3}$$

Electrical conductivity $\sigma_i = n_i e(\mu_e + \mu_n)$

$$= 1.4707 \times 10^{16} \times 1.6 \times 10^{-9}(0.48 + 0.013)$$

$$\sigma_i = 1.160 \times 10^{-3}\ \Omega^{-1}m^{-1}$$

PROBLEM : 10

Find the intrinsic resistivity of Ge at room temperature 300K if the carrier density is 2.15 x 10^{13}/cm^3.

Given data :

Mobility of electron $\mu_e = 3900\ cm^2/Vs$

Mobility of hole $\mu_n = 1900\ cm^2/Vs$

Carrier density $n_i = 2.15 \times 10^{13}/cm^3$

Solution :

We know that $\sigma_i = e(\mu_e + \mu_h)\, n_i$

Substituting the given values, we have

$$\sigma_i = 1.6 \times 10^{-19} \times (3900 + 1900) \times 2.15 \times 10^{13}$$

$$= 1.6 \times 10^{-19} \times 5800 \times 2.15 \times 10^{13}$$

$$\sigma_i = 2.32 \times 10^{-2}\ \text{ohm/cm}$$

Intrinsic resistivity $\rho_i = \frac{1}{\sigma_i} = \frac{1}{2.32 \times 10^{-2}}$

$$\rho_i = 43\ \Omega\ cm$$

EXERCISE PROBLEMS

1. Calculate the intrinsic concentration in germanium at 300K, given that $m_e^* = 0.12\ m_0$, $m_h^* = 0.28\ m_0$ and $E_g = 0.67$ eV.

(Ans : $n_i = 4.69 \times 10^{18}/m^3$)

2. The intrinsic carrier density is $1.49 \times 10^{16}/m^3$. If the mobility of electrons and holes are 0.12 and 0.05 $m^2V^{-1}s^{-1}$. Calculate the conductivity.

(Ans : $\sigma = 4.05 \times 10^{-4}\ \Omega^{-1}\ m^{-1}$)

3. In a p-type germanium, $n_i = 2.1 \times 10^{19} m^{-3}$, density of boron 4.5×10^{23} atoms m^{-3}. The electron and hole mobilities are 0.4 and 0.2 m^2 / volt – s respectively. What is its conductivity before and after the addition of boron atoms ?

(Ans : $\sigma = 2.016\ \Omega^{-1}\ m^{-1}$; $\sigma = 1.44 \times 10^4\ \Omega^{-1}\ m^{-1}$)

4. A semiconducting crystal 12 mm long, 5 mm wide and 1 mm thick has a magnetic flux density of 0.5 Wb/m^2 applied from front to back perpendicular to largest faces. When a current of 20 mA flows length wise through the specimen, the voltage measured across its width is found to be 37 μV. What is the Hall coefficient of this semiconductor.

(Ans : $R_H = 3.7 \times 10^{-6} C^{-1} m^3$)

5. The donor density of an n-type germanium sample is $10^{21} / m^3$. The sample is arranged in a Hall experiment having magnetic field of 0.5 tesla and the current density is 500 Ampere/m^2. Find the Hall voltage if the sample is 3 mm wide.

(Ans : $V_H = 4.6875$ mV)

PART - A QUESTIONS & ANSWERS

1. What is a semiconductor?

The materials in which the electrical conductivity lies between conductors and insulators are called semiconductors. They have resistivity value between 10^{-4} to 0.5 ohm–m. The electrical conductivity of semiconductor increases when we add impurities and by increasing the temperature and it is contrary to the metals.

2. Define the properties of semiconductor?

1. The resistivity of semiconductors lies between that of a conductor and an insulator. (i.e.,) It varies from 10^{-4} to 0.5 Ω-m.

2. At 0K, semiconductors behave as insulators.
3. They have an empty conduction band and almost filled valence band at 0K.
4. Semiconductors have negative temperature coefficient of resistance.
5. If impurities are added, it will increase the electrical conductivity of semiconductors.
6. If we increase the temperature of semiconductor, its electrical conductivity also increases.

3. With increase of temperture the conductivity of semiconductor increases while that of metals decreases. Give reasons.

With increase of temperature more and more charge carriers are created and hence the conductivity of semiconductors increases. In the case of metals with increase of temperature the concentration of charge carriers remains the same. But due to increase of thermal energy the electrons make frequent collisions with lattice ions and hence the resistivity increases and conductivity decreases.

4. Mention any four advantages of semiconducting materials.

(i) It can behave as insulators at 0K and as conductors at high temperatures.

(ii) It possess some properties of both conductors and insulators.

(iii) On doping we can produce both n and p-type semiconductors with charge carriers of electrons and holes respectively.

(iv) It possess many applications in electronic field such as manufacturing of diodes, transistors, LED's, IC etc.

5. Distinguish between Elemental semiconductors and Compound semiconductors

S.No.	Elemental semiconductors	Compound semiconductors
1.	These are made from single element	These are made from compound (mixed) element
2.	These are made from IV group elements of periodic table	These are made from III and V [or] II and VI group elements of periodic table.
3.	These are called as indirect band gap semiconductor (electron–hole recombination takes place through traps)	These are called as direct band gap semiconductor (electron –hole recombination takes place directly)

4.	Heat is produced in the recombination	Photons are emitted during recombination
5.	Life time of charge carriers is more due to indirect recombination.	Life time of charge carrier's is less due to direct recombination.
6.	Current amplification is more	Current amplification is less.
7.	These are used for making diodes, transistor, etc. Examples : Ge, Si	These are used for making LED, laser diodes, etc. Examples : GaA, GaP

6. **What is an intrinsic semiconductors?**

   Semiconductor in an extremely pure form (without impurities) is known as intrinsic semiconductors

7. **What is pair production or electron - hole pair generation?**

   When an energy is supplied to the semiconductor, the covalent bonds are broken and the electrons are raised from valence band to conduction band and a vacant site is created in the valence band. It is called pair production or generation of electron –hole pair.

8. **Explain the concept of hole in semiconductor.**

   In intrinsic semiconductor, charge carriers are created due to breaking of covalent bonds. When a covalent bond is broken, an electron escapes to the conduction band leaving behind an empty space in the valence band. This missing electron is called a hole.

9. **Define effective mass of the electron.**

   When an electron moves through a crystal lattice, it experience a periodic potential and hence an internal force. The effect of this force is incorporated in the mass of the electron and such a mass is called effective mass of electron m*.

10. **State law of mass action.**

    It states that in an Extrinsic semiconductor, the product of electron concentration and hole concentration, produced by the doping process, is a constant.

    ie., $N_e N_h = n_i^2$ = a constant.

11. What is an extrinsic semiconductor?

A Semiconducting material in which impurity atoms added (doped) to the material to modify its conductivity is known as extrinsic semiconductors or impurity semiconductor.

12. What is an n-type semiconductor?

When a small amount of pentavalent inpurity is added to a pure semiconductor, it becomes extrinsic or impure semiconductor and it is known as n-type semiconductor.

13. What is an p-type semiconductor?

When a small amount of trivalent impurity is added to a pure semiconductor, it becomes extrinsic semiconductor and it is called p-type semiconductor.

14. What is meant by doping and doping agent?

The technique of adding impurities to a pure semiconductor is known as doping and the added impurity is called doping agent.

15. What is meant by donor energy level?

A pentavalent impurity when doped with an intrinsic semiconductor donates one electron which produces an energy level called donor energy level.

16. What is meant by acceptor energy level?

A trivalent impurity when doped with an intrinsic semiconductor accepts one electron which produces an energy level called acceptor energy level.

17. What are the differences between intrinsic and extrinsic semiconductor.

S.No.	Intrinsic semiconductors	Extrinsic semiconductors
1.	Semiconductor in a pure form is called intrinsic semiconductor. semiconductor.	Semiconductor which are doped with impurity is called extrinsic
2.	Here the charge carriers are produced only due to thermal agitation.	Here the charge carriers are produced due to impurities and may also be produced due to thermal agitation.