

Chapter 3

INTRODUCTION TO SOLIDS

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3.1 FREE ELECTRON THEORY OF METALS

Classical Approach: The most characteristic properties of metals are their high electrical and thermal conductivities. For example, the electrical conductivity at room temperature of silver is $0.6 \times 10^8 \text{ ohm}^{-1} \text{ m}^{-1}$ as compared to $\approx 10^{-16}$ for a good insulator and 2×10^{-2} for a semiconductor such as germanium. The idea that the large electrical and thermal conductivity of metals might be explained by the presence of mobile electrons (also called "free" or "conduction" electrons) in the metal was first put forward by Drude, well before the introduction of quantum theory. The implications of this hypothesis were subsequently studied extensively by Lorentz in his theory of electrons.

Lorentz and Drude considered that about 95% of whole volume of solid is occupied by the electrons and only 5% of the volume is occupied by ion cores. Hence, according to free electron theory, the solids behave as free electron gas.

Drude and Lorentz apply Maxwell-Boltzmann statistics in which at lowest possible temperature all electrons can occupy lowest energy level.

The pressure exerted by the electron gas (in the absence of an external field) at a temperature T according to classical theory is:

$$P = \frac{1}{3} \rho (\bar{C})^2 \quad \dots(1)$$

For molar volume of the metal, $\rho = \frac{M_A}{V_m}$ (density)

$$P = \frac{1}{3} \left(\frac{M_A}{V_m} \right) (\bar{C})^2 \quad \dots(2)$$

where M_A is the mass of N_A atoms and V_m is the molar volume.

Thus,

$$PV_m = \frac{1}{3} m N_A (\bar{C})^2 = RT \quad \rho V_m = \frac{1}{3} N_A (\bar{C})^2 = RT$$

i.e.,

$$m(\bar{C})^2 = \frac{3RT}{N_A} = 3K_B T$$

$$\therefore \frac{M_A (\bar{C})^2}{m} = \frac{3RT}{N_A} \quad (\because N_A = m \cdot \frac{3}{M_A})$$

where R is universal gas constant, N_A is Avogadro's number and K_B is Boltzmann constant.

The kinetic energy of the electron is

$$\left(\because \frac{1}{2} m(\bar{C})^2 = \frac{3}{2} K_B T \right) \quad \dots(4)$$

where \bar{C} is the root mean square velocity of the electron.

$$\boxed{\bar{C} = \sqrt{\frac{3K_B T}{m}}}$$

At room temperature,

$$T = 300 \text{ K}, K_B = 1.38 \times 10^{-23} \text{ J/K}, m = 9.1 \times 10^{-31} \text{ kg}$$

Thus

$$\bar{C} = \sqrt{\frac{3 \times 1.38 \times 10^{-23} \times 300}{9.1 \times 10^{-31}}} = 1.17 \times 10^5 \text{ m/sec.}$$

Ohm's Law ; Electrical Conductivity and Resistivity

As the electric field is applied, the current starts flowing and when we stop applying electric field the current stops, this means that every material has resistance to the flow of current.

As we know, Ohm's law

$$V = IR$$

relates the potential difference V (in volts) with the electrical resistance R (in ohms) and current (in amperes).

$$R = \rho \frac{l}{A} \quad \dots(6)$$

where l is the length of the conductor, A is its cross-sectional area, and ρ is specific resistance of resistivity.

$$\text{As resistivity } \rho = \frac{1}{\sigma} \text{ (ohm m)} \quad \dots(7)$$

Using equations (6) and (7), we have

$$\frac{V}{l} = \rho \frac{l}{A} = \frac{1}{\sigma} \frac{l}{A}$$

$$\text{or } \sigma = \frac{I l}{V A} = \frac{A}{V} = \frac{J}{E} \quad \tau = \frac{I l \times A}{V A \times l} = \frac{I A}{V l} = \frac{I}{E A} \quad (\because E = \frac{V}{l}) \quad \dots(9)$$

$$J = \sigma E$$

where J is current density and E is electric field.

This is Ohm's Law in terms of conductivity.

In order to calculate the conductivity of a metal on the basis of classical theory, we suppose that the electrons are in a cylindrical bar of unit area of cross-section and length l , across which there is a potential difference V . This potential difference is equivalent to an electric

field, $E = \frac{V}{l}$, which exerts a force $F = eE$ on each electron and accordingly produces an acceleration given by:

$$a = \frac{eE}{m} \quad F = m a \quad \dots(10)$$

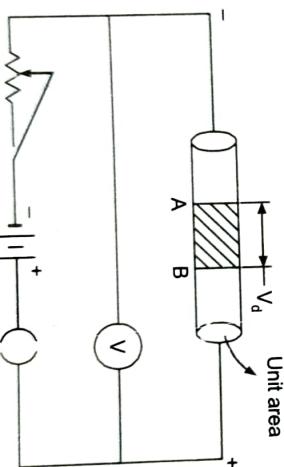


Fig. 3.1.

Now considering the collision of electron with an ion core. Let λ be the mean free path and mean time between collision is given by $\tau = \frac{\lambda}{C}$. When electric field is applied on the metal, electron starts moving with velocity known as drift velocity v_d ,

$$v_d = \sigma \tau = \left[\frac{eE\tau}{m} \right] \quad \sigma = \frac{eE}{m} \quad \dots(11)$$

The expression for current density is:

$$j = nev_d = \frac{ne^2 E \tau}{m} \quad \dots(12)$$

Ohm's law may be written in the form : $(V = IR) \quad J = \sigma E$

$$\sigma = \frac{j}{E} = \frac{ne^2 \tau}{m}$$

$$\boxed{\sigma = \frac{ne^2 \tau}{m}}$$

This is the expression for electrical conductivity.

But,

$$\tau = \frac{\lambda}{C} \quad \dots(14)$$

$$\sigma = \left[\frac{ne^2}{m} \right] \left[\frac{\lambda}{C} \right]$$

$$= \left[\frac{ne^2 \lambda}{m} \right] \left[\frac{m}{3K_B T} \right]^{1/2}$$

$$\boxed{\sigma = \frac{ne^2 \lambda}{\sqrt{3m K_B T}}}$$

or resistivity
i.e.,

$$\boxed{\rho = \frac{\sqrt{3m K_B T}}{ne^2 \lambda}} \quad \dots(15)$$

Equations (15) and (16) are classical expressions for electrical conductivity and electrical resistivity of metals in terms of mean free path.

Mobility of the electron in the metal is defined as the steady-state drift velocity for unit electric field.

$$\mu = \frac{v_d}{E} = \frac{e\tau}{m}$$

Hence,

$$\sigma = ne \left(\frac{e\tau}{m} \right) \quad \text{or} \quad \sigma = \frac{ne^2 \gamma}{m} \quad \dots(16)$$

$$\boxed{\sigma = ne\mu}$$

...(18)

split apart and acquire a gap E_g (region D in Fig. 3.6). The energy bands again available lower and upper energy bands). Here the significant point is that there are available valence electrons exactly as many states in the lower band ($4N$) as there are available valence electrons from the atoms ($4N$).

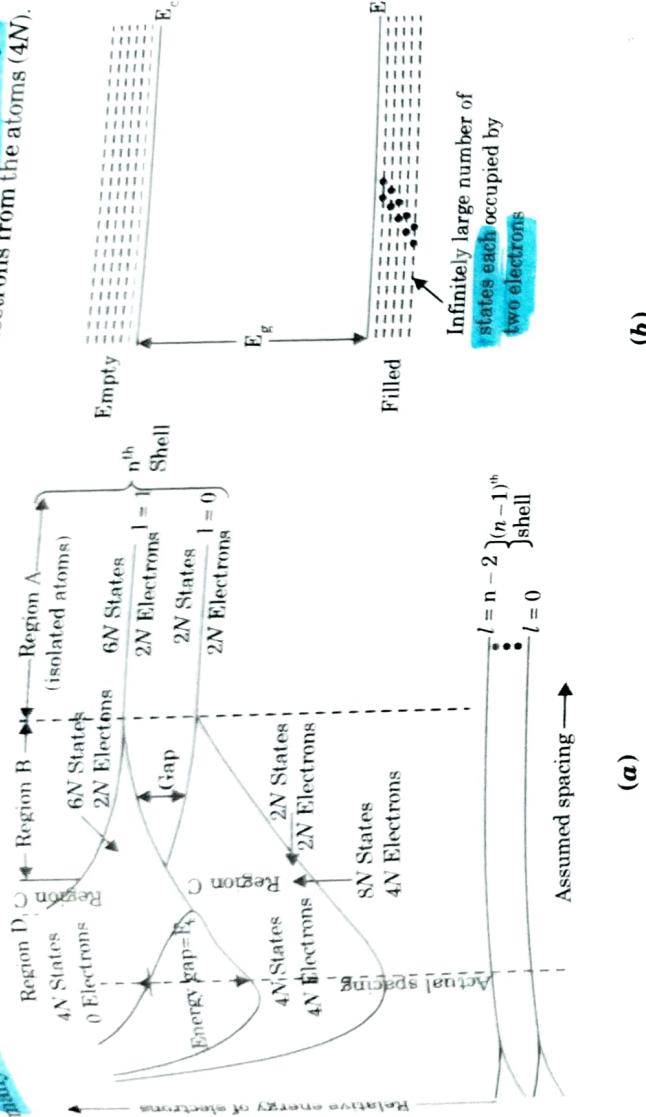


Fig. 3.6. (a) Evolution of energy from atomic energy levels as atoms come closer to each other to form a solid. (b) The energy band positions in a real solid. The upper band, called the conduction band consists of infinitely large number of closely spaced energy states. The lower band, called the valence band, consists of closely spaced completely filled energy states. Note that only two electrons are allowed in each energy state according to Paul's exclusion principle.

3.3 THE KRONIG-PENNEY MODEL (Qualitative Analysis)

In the previous section, we discussed qualitatively the splitting of allowed electron energies as atoms are brought together to form a crystal. The concept of allowed and forbidden energy bands can be developed more vigorously by considering Schrodinger's wave equation. This is an idealized, one-dimensional model of a crystal which exhibits the basis for the energy-band theory of semiconductors.

The potential function of a single, non-interacting, one-electron atom is shown in Fig. 3.7(a), in which discrete energy levels allowed for the electron are also shown. Fig. 3.7(b) shows the same type of potential function for the case when several atoms are in close proximity arranged in a one dimensional array. The potential functions of adjacent atoms overlap and the net potential functions of adjacent atoms overlap and the net potential function for this case is shown in Fig. 3.7(c). It is this potential function we would need to use in Schrodinger's wave equation to model a one-dimensional single-crystal material.

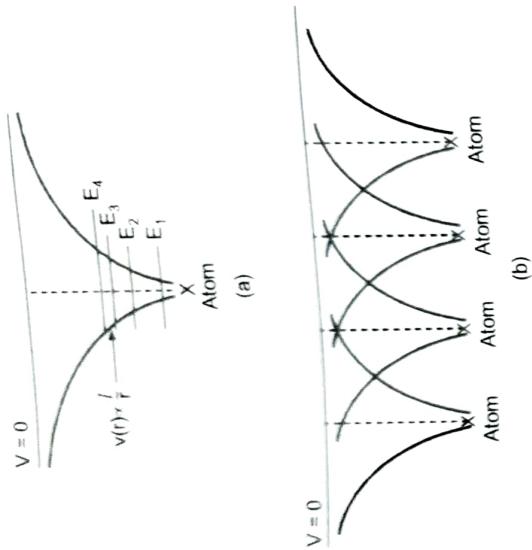
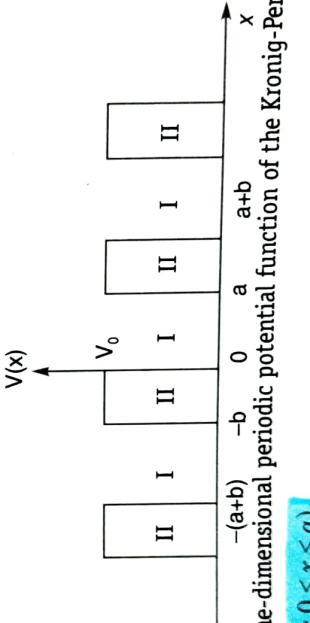


Fig. 3.7. (a) Potential function of a single isolated atom. (b) Overlapping potential functions of adjacent atoms. (c) Net potential function of a one-dimensional single crystal.

Figure 3.8 is the one-dimensional Kronig-Penney model of the periodic potential function, which is used to represent a one-dimensional single-crystal lattice.

Consider the potential energy $V(x)$ of an electron shown in the illustration with an infinite sequence of potential wells of depth V_0 and width a , arranged with a spacing b . The width and the curvatures of the allowed bands increase with energy.

Assume $E < V_0$ and using the time independent Schrödinger's wave equation, in regions I and II, we have:



Region I : (for $0 \leq x \leq a$)

$$\frac{d^2\psi(x)}{dx^2} + \frac{2m}{\hbar^2} E \psi(x) = 0 \quad \dots(32)$$

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Solution of this equation is

$$\psi(x) \approx A \sin(\alpha x) + B \cos(\alpha x) \quad \left[\text{where } \alpha = \frac{\sqrt{2mE}}{\hbar} \right] \quad \dots(33)$$

Region II : (for $-b \leq x \leq 0$)

$$\frac{d^2\psi(x)}{dx^2} + \frac{2m}{\hbar^2} (E - V_0) \psi(x) = 0$$

Solution of this equation is

$$\psi(x) = C \sinh(\gamma x) + D \cosh(\gamma x) \quad \left[\text{where } \gamma = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}} \right] \quad \dots(34)$$

where A, B, C, D are constants which can be eliminated by using boundary conditions.

To obtain the complete solution to Schrödinger's wave equation, we make use of a mathematical theorem by Bloch. The theorem states that all one-electron wave functions, for problems involving periodically varying potential energy functions, must be of the form $\psi(x) = u(x)e^{ikx}$

The parameter k is called a constant of motion. The function $u(x)$ is a periodic function

with period $(a + b)$.

For final solution we can use numerical or graphical technique.

To obtain an equation that is more susceptible to a graphical solution and thus will illustrate the nature of the results, let the potential barrier width $b \rightarrow 0$ and the barrier height $V_0 \rightarrow \infty$, but such that the product bV_0 remains finite, then Schrödinger's wave equation will have a solution only if following condition is satisfied:

... (37)

$$\left(\frac{mV_0b_a}{\hbar^2} \right) \frac{\sin aa}{aa} + \cos aa = \cos ka$$

We define a parameter P as

$$P = \frac{mV_0b_a}{\hbar^2}$$

Then, finally we have

$$P \frac{\sin aa}{aa} + \cos aa = \cos ka \quad \dots(38)$$

To understand the nature of the solution, initially consider the special case for which $V_0 = 0$. In this case $P = 0$, which corresponds to a free particle since there are no potential barriers.

From Eqn. (38), we have,

$$\cos aa = \cos ka$$

$$\alpha = k$$

or Since the potential is equal to zero, the total energy E is equal to the kinetic energy and

$$\alpha = \sqrt{\frac{2mE}{\hbar^2}} = \sqrt{\frac{2m\left(\frac{1}{2}mv^2\right)}{\hbar^2}} = \frac{p}{\hbar} = k \quad \dots(40)$$

where p is the particle momentum. The constant of the motion parameter k is related to the particle momentum for the free electron. The parameter k is also referred to as a wave number.

3.16

We can also relate the energy and momentum as

$$E = \frac{p^2}{2m} = \frac{k^2 h^2}{2m}$$

Figure 3.9 shows the parabolic relation of Eqn. (41) between the energy E and momentum p for the free particle. Since the momentum and wave number are linearly related, Fig. 4.9 is also the E versus k curve for the free particle.

We now want to consider the relation between E and k from Eqn. (38) for the particle in the single-crystal lattice. As the parameter P increases, the particle becomes more tightly bound to the potential well or atom. We may define the left side of Eqn. (38) to be a function $f(aa)$, so that

$$f(aa) = P \frac{\sin aa}{aa} + \cos aa \quad \dots(42)$$

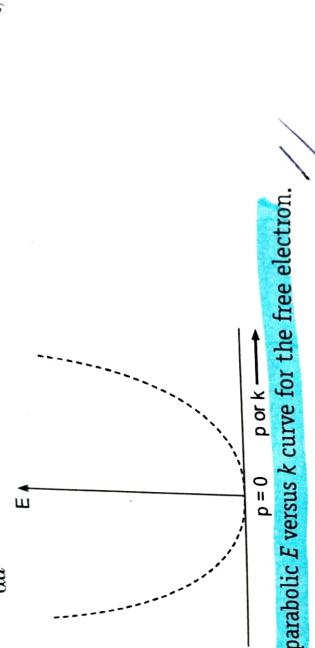


Fig. 3.9. The parabolic E versus k curve for the free electron.

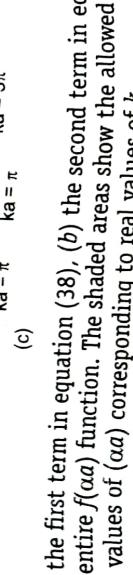
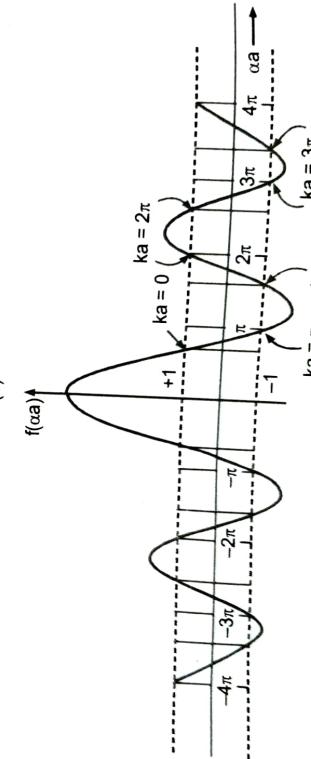
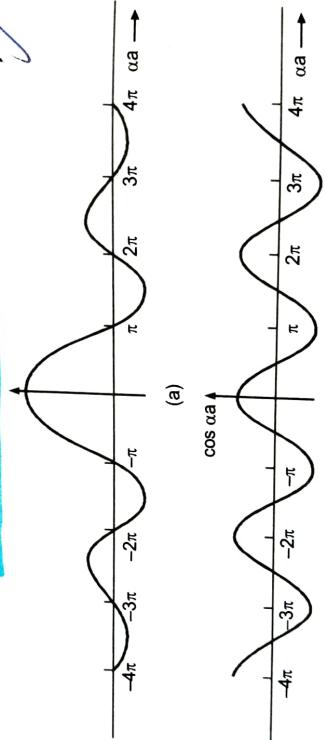


Fig. 3.10. A plot of (a) the first term in equation (38), (b) the second term in equation (38) and (c) the entire $f(aa)$ function. The shaded areas show the allowed values of (aa) corresponding to real values of k .

Each position of the curve may be called a *band*. The characteristics of the curves are that :

- They are horizontal at the top and bottom.
- They are parabolic near the top and the bottom with curvatures in opposite directions.
- $\frac{d^2E}{dk^2}$ is positive in the lower portion of the band and negative for the upper portion.

3.4 BLOCH'S THEOREM

Electrons in a lattice see a periodic potential due to the presence of the atoms. The potential model can be represented as:

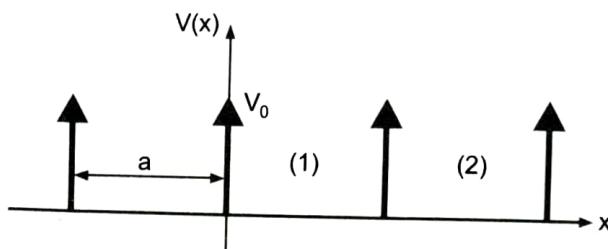


Fig 3.12

In region (1), the wavefunction is given by :

$$\psi_1(x) = Ae^{ikx} + Be^{-ikx}, \text{ where } k = \sqrt{\frac{2mE}{\hbar^2}}$$

This wavefunction can be connected to the one in region (2), using Bloch Theorem.

Bloch theorem states that for a periodic potential, the solutions to the wave equation will be of the following form :

$$\psi_1(x) = u(x)e^{ikx}$$

where $u(x)$ is the Bloch periodic part that has the periodicity of the lattice, i.e., $u(x+a) = u(x)$, and the exponential term is the plane-wave component.

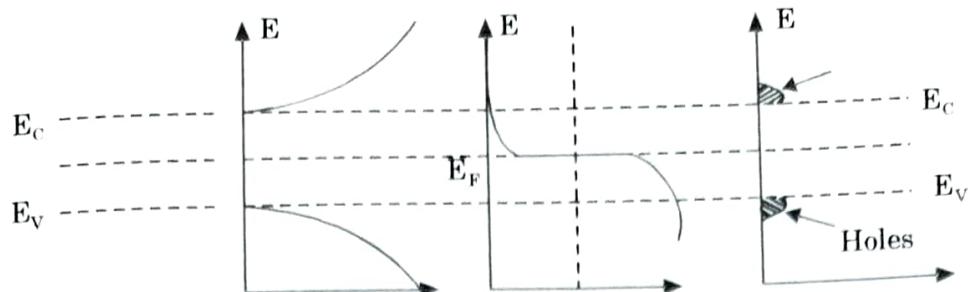
3.5 INTRINSIC AND EXTRINSIC SEMICONDUCTORS

The **intrinsic semiconductor** refers to **pure** materials (no impurities or lattice defects) whose electrical conductivity arises from thermal excitation and determined by their inherent conductive properties. Pure elemental silicon and germanium are intrinsic semiconducting materials.

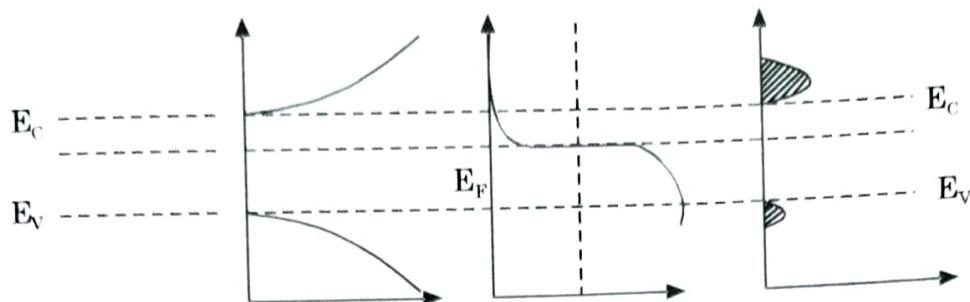
The intrinsic semiconductors have several limitations when it comes to their use for developing semiconductor based devices. These are :

- The number of intrinsic charge carriers (holes and electrons) is very small $\sim 10^{16} \text{ m}^{-3}$. Hence, these are low conductivity materials.
- The intrinsic charge carriers are always thermally generated and hence enough flexibility is not available to control their number.
- Since $n = p$ for intrinsic semiconductors, so there is a situation that these materials can never be such that they only have either predominant hole or electron conduction. So this limits the usefulness of such materials.

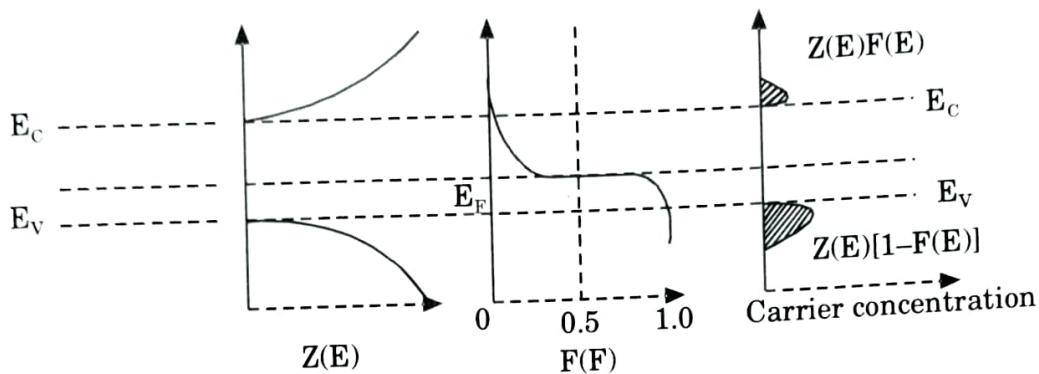
are shown in Fig.



(a) Intrinsic semiconductors



(b) n-type semiconductors



(c) p-type semiconductors

Fig. 3.20. Schematic band diagram, density of states, Fermi-Dirac distribution, and the carrier concentrations for (a) intrinsic, (b) n-type, and (c) p-type semiconductors at thermal equilibrium.

3.8 FERMI LEVEL IN AN INTRINSIC SEMICONDUCTOR

In an intrinsic semiconductor, the free electron and hole concentrations are equal.

$$n = p$$

$$\therefore N_C e^{-(E_C - E_F)/kT} = N_V e^{-(E_F - E_V)/kT} \quad \dots(62)$$

Taking log on both sides and rearranging the terms, we get

$$\frac{-(E_C - E_F)}{kT} = \ln \frac{N_V}{N_C} - \frac{(E_F - E_V)}{kT}$$

$$-E_C + E_F = kT \ln \frac{N_V}{N_C} - E_F + E_V$$

$$2E_F = kT \ln \frac{N_V}{N_C} + (E_C + E_V)$$

$$\therefore E_F = \frac{E_C + E_V}{2} + \frac{1}{2} kT \ln \frac{N_V}{N_C} \quad \dots(63)$$

Substituting the values of N_V and N_C , we get

$$E_F = \frac{E_C + E_V}{2} + \frac{3}{4} kT \ln \frac{m_p^*}{m_n^*} \quad \dots(64)$$

If $m_p^* = m_n^*$, then

$$E_F = \frac{E_C + E_V}{2} \quad \dots(65)$$

Thus, the Fermi level in an intrinsic semiconductor lies at the centre of the energy gap. Eqn. (65) can be written as

$$E_F = \frac{E_C + E_V + E_V - E_V}{2} = \frac{E_C - E_V}{2} + E_V$$

As

$$E_C - E_V = E_g$$

$$E_F = \frac{E_g}{2} + E_V \quad \dots(66)$$

If the top of the valence band E_V is taken as zero level

$$E_F = \frac{E_g}{2} \quad \dots(67)$$

Fermi energy is that energy for which Fermi-Dirac function equals 0.5 and it is the average energy possessed by charge carriers in a solid.

With an increase in temperature, the Fermi level gets displaced toward the bottom edge of the conduction band if $m_p^* > m_n^*$ or downward to the top edge of the valence band if $m_p^* < m_n^*$ as shown in Fig. 3.21. Practically, the Fermi level in an intrinsic semiconductor is independent of temperature and may be regarded that it lies in the middle of the energy band gap (or forbidden gap).

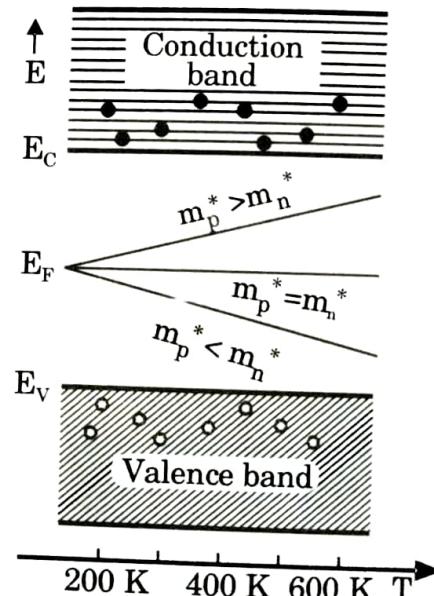


Fig. 3.21. Variation of Fermi level with temperature in an intrinsic semiconductor.

3.9 PN JUNCTION : VI CHARACTERISTICS

A p-n junction is formed by combining a p-type semiconductor with an n-type semiconductor.

$$2E_F = kT \ln \frac{N_V}{N_C} + (E_C + E_V)$$

$$E_F = \frac{E_C + E_V}{2} + \frac{1}{2} kT \ln \frac{N_V}{N_C}$$

...(63)

Substituting the values of N_V and N_C , we get

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...(65)

Thus, the Fermi level in an intrinsic semiconductor lies at the centre of the energy gap. Eqn. (65) can be written as

$$\begin{aligned} E_F &= \frac{E_C + E_V + E_V - E_V}{2} = \frac{E_C - E_V}{2} + E_V \\ \text{As } E_C - E_V &= E_g \\ E_F &= \frac{E_g}{2} + E_V \end{aligned} \quad \dots(66)$$

If the top of the valence band E_V is taken as zero level

$$E_F = \frac{E_g}{2}$$

...(67)

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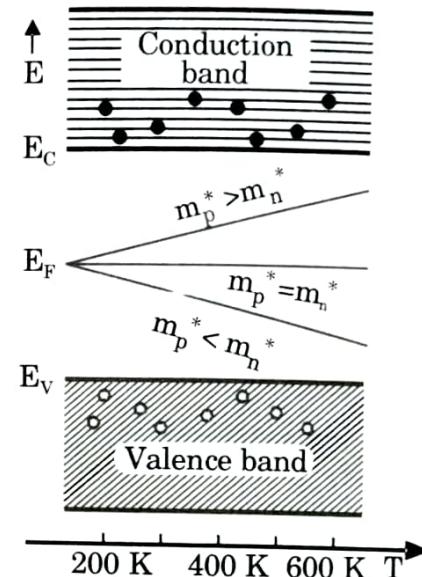


Fig. 3.21. Variation of Fermi level with temperature in an intrinsic semiconductor.

3.9 PN JUNCTION : VI CHARACTERISTICS

A p-n junction is formed by combining a p-type semiconductor having acceptor impurities and n-type semiconductor having donor impurities, in very close contact.

The term ***junction*** refers to the region where the two regions of the semiconductor meet. It can be thought of as the ***border region between the p-type and n-type blocks*** as shown in Fig. 3.22

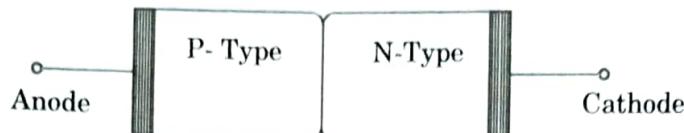
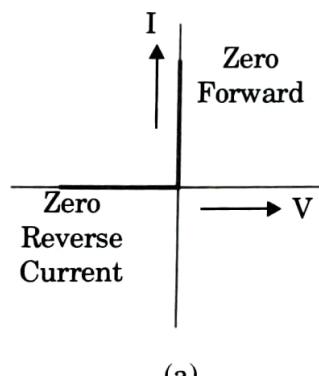


Fig. 3.22. A *p-n* junction.

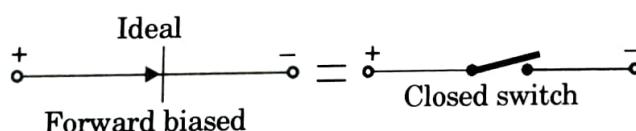
All the semiconductor devices contain one or more *pn* junctions. The ***pn junction is, in effect, the control element for semiconductor devices.***

A simple *p-n* junction behaves like a two terminal semiconductor device known as diode. A diode is said to be an ideal diode when it acts like a perfect conductor (with zero voltage across it) when forward biased and like a perfect insulator (with zero current through it) when it is reversed biased.

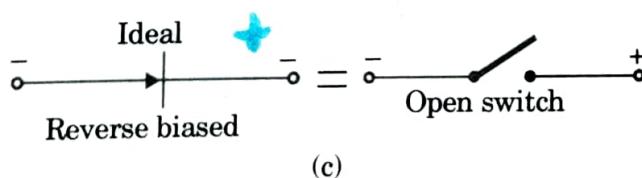
The V-I characteristics of an ideal diode are shown in Fig. 3.23 (a). In circuit terms, an ideal diode acts like a switch. When the diode is forward, it is just like a closed switch, as shown in Fig. 3.23 (b). Whereas, if it is reverse-biased, it acts like an open switch as shown in Fig. 3.23 (c).



(a)



(b)



(c)

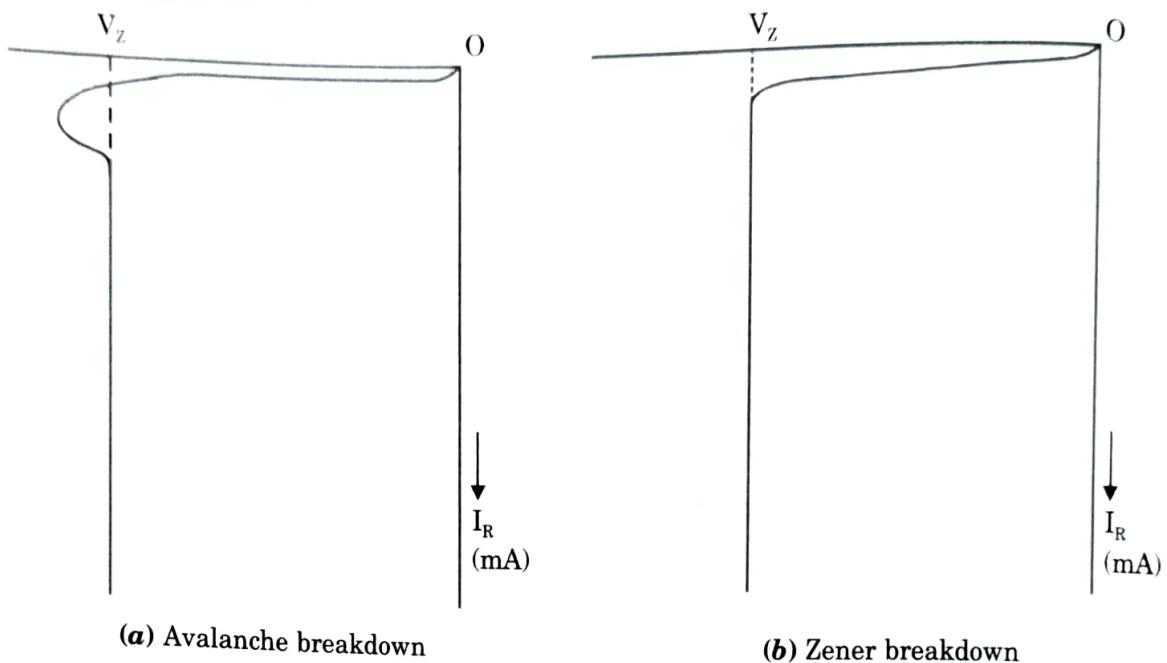
Fig. 3.23. Characteristics of an ideal diode.

3.10 BREAKDOWN MECHANISM

If a diode is sufficiently reverse biased, that is, if the voltage is made negative enough, the diode will allow the conduction of a wide range of currents in the reverse direction. Furthermore, the diode voltage remains approximately constant at some value, say $-V_z$, over the current range. This property, known as **breakdown**, is explained in the reverse-bias I-V diode characteristic shown in Fig. 3.24. The value V_z is called the (**reverse**) **breakdown voltage** of the diode.

The phenomenon of diode breakdown is due to two types of mechanisms :

- (i) Avalanche breakdown
- (ii) Zener breakdown.



(a) Avalanche breakdown

(b) Zener breakdown

Fig. 3.24. V-I characteristics under two breakdown mechanisms.

(A) Avalanche Breakdown

For *thicker junctions the breakdown mechanism is by the process of *avalanche breakdown*. In this mechanism, when the electric field existing in the depletion layer is sufficiently high, the velocity of the carriers (minority carriers) crossing the depletion layer increases. These carriers (electrons and holes) collide with the crystal atoms. Some collisions are so violent that electrons are *knocked off* the crystal atoms, thus creating electron-hole pairs. As the pair of electron-hole is created in the midst of the high field, they quickly separate and attain high velocities to cause further pair generation through more collisions. This is a cumulative process and as we approach the breakdown voltage, the field becomes so large that the chain of collisions can give rise to an almost infinite current with very slight additional increase in voltage. This process is known as *avalanche breakdown* as represented as by Fig. 3.24 (a). Once this breakdown occurs, the junction can not regain its original position. Thus, the diode is said to be burnt-off.

*Rectifier diodes are having thick junction.

(B) Zener Breakdown

Zener breakdown takes place in a very *thin junction, i.e. when both sides of the junction are very heavily doped and consequently the depletion layer is narrow. In the zener breakdown mechanism, the electric field becomes as high as 10^7 V/m in the depletion layer with only a small applied reverse bias voltage. In this process it becomes possible for some electrons to jump across the barrier from the valence band in p-material to some of the unfilled conduction band in n-material. This process is known as **zener breakdown** as represented by Fig. 3.24 (b). In this process, the junction is not damaged. The junction regains its original position when the reverse voltage is removed. This process is used in the zener diodes.

However, if the number of electrons jumping across the barrier (i.e., flow of current) increases beyond the rated capacity of the zener diode, then avalanche breakdown takes place which destroys the junction.

Thus, it is concluded that **zener breakdown** does not result in the destruction of the diode, as long as current through the diode is limited by the external circuit to a level within its power handling capabilities. Whereas, the **avalanche breakdown** destroys the diode.

Table 3.1 shows the comparison of zener and avalanche breakdown.

Table 3.1. Comparison of Zener and Avalanche Breakdown

S. No.	Zener Breakdown	Avalanche Breakdown
1.	This takes place in a very thin junction (the depletion layer is narrow).	This takes place in a thicker junction (the depletion layer is wide).
2.	This is observed in zener diodes at $V_z \sim 6$ V (or less).	This is observed in zener diodes at V_z greater than 6 V.
3.	In this, the carrier increase is the result of electric field strength (about 2×10^7 V/m).	In this, the carrier increase is the result of collisions.
4.	V-I characteristics with the zener breakdown is very sharp at V_z .	V-I characteristics with the avalanche breakdown is gradual near V_z .
5.	The breakdown voltage decreases with increase in temperature.	The breakdown voltage increases with increase in temperature.
6.	Zener breakdown does not result in the destruction of the diode.	Avalanche breakdown destroys the diode.

3.11 ZENER DIODE

The diodes especially fabricated to be operated in the breakdown region are known as **zener diodes** or **breakdown diodes** even though the breakdown may actually result due to avalanche mechanism or zener mechanism or both. When operated in the breakdown region, the zener diode maintains a constant voltage across its terminals. For this reasons the zener diode is also referred to a **reference diode** or a **constant voltage diode**.



Fig. 3.25. Current symbol of a zener diode.

*Zener diodes are having thin junction.

By varying the doping level of silicon diode, a manufacturer can produce zener diodes with breakdown voltages from about 2 to 200 V.

Figure 3.25 shows the circuit symbol of a zener diode. It is similar to the symbol of an ordinary crystal diode except that its bar is just turned into Z-shape.

V-I characteristics of a Zener Diode

The V-I characteristics of a zener diode are shown in Fig. 3.26. The following points are worth-noting :

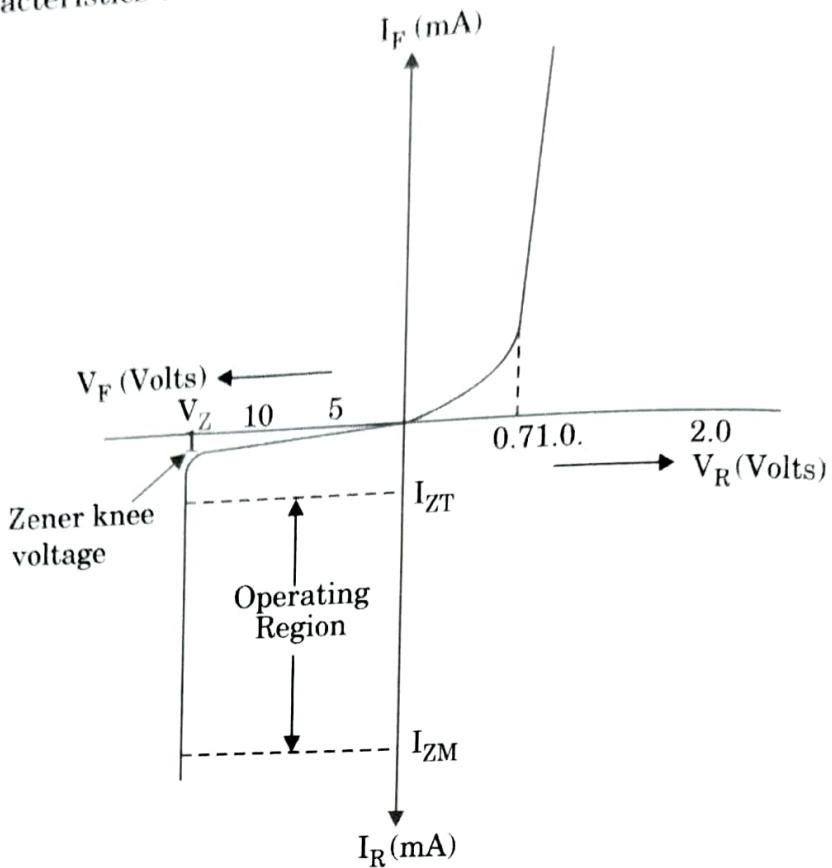


Fig. 3.26. V-I characteristics of a zener diode.

- (i) Its characteristics are similar to an ordinary rectifier diode with the exception that it has a sharp (or distinct) breakdown voltage called **zener voltage V_Z** .
- (ii) It can be operated in any of the three regions i.e., *forward, leakage or breakdown. But usually it is operated in the breakdown region as shown in Fig. 3.26.
- (iii) The voltage is almost constant (V_Z) over the operating region.
- (iv) Usually, the value of V_Z at a particular test current I_{ZT} is specified in the data sheet.
- (v) During operation it will not burn as long as the external circuit limits the current flowing through it below the **burn out value** i.e. I_{ZM} (the maximum rated zener current).

3.12 SOLAR CELL

The solar cell (or photovoltaic cell), is a device which converts light energy into electrical energy. This is an important photovoltaic device and is basically a *p-n* junction with a large surface area.

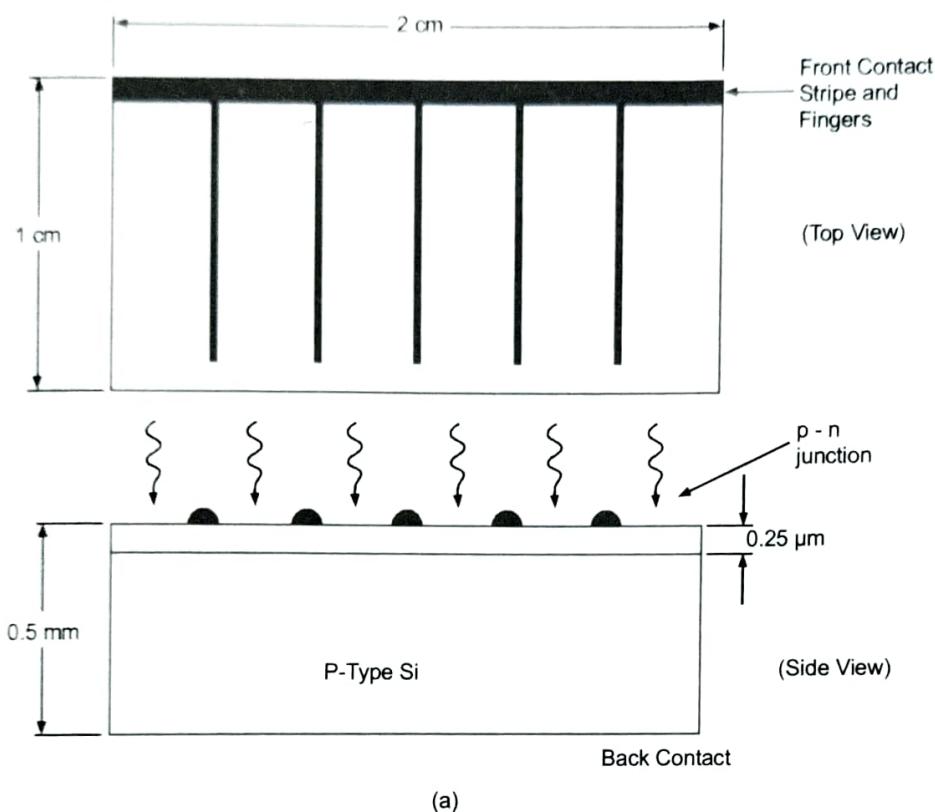
The high-efficiency solar cell was first developed by Chapin, Fuller and Pearson in 1954 using a diffused silicon *p-n* junction. Since then, solar cells have been developed and produced with polysilicon, CdTe and GaAs. In past four decades, a remarkable progress has been made.

Megawatt solar power generating plants have been built, solar cells are being combined with building materials, and are now the most important long-duration power supply for satellites and space vehicles. Over 95% of solar cells in production are silicon based.

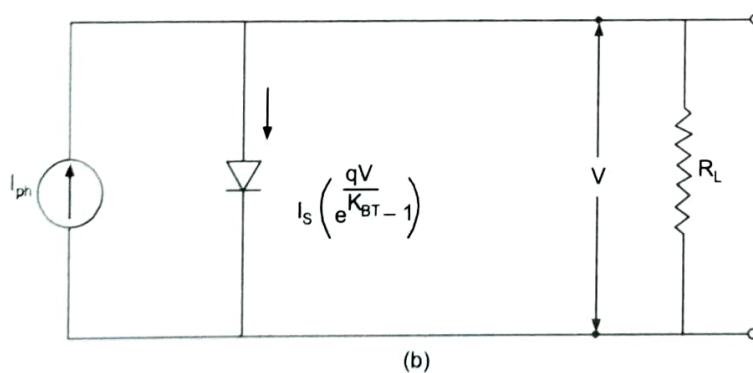
A solar cell can deliver powers of the order of 1 kW/m^2 . The schematic of the typical junction solar cell, with its top finger contacts, is shown in Fig. 3.27(a). The photovoltaic energy conversion process may best be expressed by the equivalent circuit shown in Fig. 3.27(b). An ideal diode is connected in parallel with a constant current (or voltage) source, which represents the photovoltaic energy generated, and with a load resistor.

(A) Basic Characteristics

The solar cell as shown in Fig. 3.27(a) consists of a shallow p-n junction formed by diffusion or epitaxy, on the surface a front ohmic contact stripe and fingers, and a back ohmic contact which covers the entire back surface. Fig. 3.27(b) represents the simplest equivalent circuit of the cell and contains the constant current source I_{ph} , the load current I , and the reverse saturation current of the diode I_s .



(a)



(b)

Fig. 3.27. (a) Schematic representation of a solar cell (Top and side view).
 (b) The idealized equivalent circuit of a solar cell.

and the efficiency equals :

$$\eta = \left| \frac{I_{mp} V_{mp}}{P_{in}} \right|$$

where $I_{mp} = I_s \left[\exp\left(\frac{qV_{mp}}{kT}\right) - 1 \right] - I_{ph}$ $\quad [\because I_s = 10^{-12} \text{ A}, I_{ph} = 25 \text{ mA}]$

$$= 0.024 \text{ A}$$

$$\eta = \frac{0.54 \times 0.024}{0.1} = 13\%.$$

$$\text{Fill factor} = \frac{V_{mp} I_{mp}}{V_{oc} I_{ph}} = \frac{0.54 \times 0.024}{0.62 \times 0.025} = 83\%.$$

where the open circuit voltage is calculated using eqn. (64) and $I = 0$. The short circuit current equals the photocurrent.

3.13 HALL EFFECT

Definition. When a metal or a semiconductor carrying a current I is placed in a transverse magnetic field B , a potential difference is produced in the direction normal to both the current and magnetic field directions. This phenomenon is called **Hall effect**.

Hall effect measurements showed that it is the negative charge carriers namely electrons that are responsible for electrical conduction in metals. It also showed that there exists two types of charge carriers in semiconductors.

Importance. The importance of Hall effect is that it helps to determine the :

- (i) sign of charge carriers,
- (ii) charge carriers concentration and
- (iii) mobility of charge carriers if conductivity of the material is known.

Experimental Determination of Carrier Concentration and Mobility

Let us consider an n -type semiconductor in which the conduction is predominated by electrons. Suppose an electric current j flows in the positive x -direction and a magnetic field B is applied normal to this electric field in z -direction (Fig. 3.29). A force, called the Lorentz force is exerted on each electron which causes the electron paths to bend. As a result of this, the electrons accumulate on one side of the slab and are deficient on the other side.

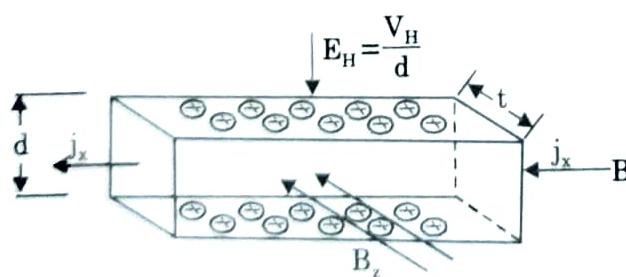


Fig. 3.29. Schematic view of an n -type semiconductor bar.

Thus, an electric field is created in the y -direction which is called the **Hall field**. In equilibrium condition

Hall Force = Lorentz force

$$\begin{aligned} F_H &= F_L \\ -qE_H &= v_x B_z q \end{aligned}$$

where v_x is the velocity of the electrons, and q the electronic charge

$$E_H = v_x B_z \quad \dots(75)$$

As current density $j_x = -Nv_x q$

$$\left(\text{Putting } v_x = \frac{E_H}{B_z} \right) \quad \dots(76)$$

$$j_x = -\frac{NE_H q}{B_z}$$

$$N = -\frac{j_x B_z}{q E_H} = -\frac{j_x B_z}{q(V_H / d)} \quad \dots(77)$$

$$V_H = -\frac{j_x B_z d}{Nq} = -\frac{IB_z d}{NqA} \quad \dots(78)$$

[A = Area of cross-section of end face]

If t is the thickness of the semiconductor specimen, $A = dt$ and the above equation reduces to

$$V_H = -\frac{B_z I}{Nqt} \quad \dots(79)$$

Hall field per unit current density per unit magnetic induction is called **Hall coefficient** R_H . Thus,

$$R_H = \frac{E_H}{j_x B_z} = +\frac{V_H / d}{j_x B_z} = -\frac{B_z I}{j_x B_z d \cdot Nqt}$$

$$R_H = -\frac{1}{Nq} \quad \dots(80)$$

In terms of Hall coefficient, Hall voltage is given by

$$V_H = R_H \frac{BI}{t} \quad \dots(81)$$

The sign of the Hall coefficient R_H indicates whether electrons or holes predominate in the conduction process.

If R_H = negative, then electrons are the predominant charge carriers.

If R_H = positive, then holes are the predominant charge carriers.

The electron mobility is given as

$$\mu_n = \frac{\sigma}{N|q|}$$

Hence

$$\mu_n = |R_H| \sigma$$

$\dots(82)$

Thus, the magnitude of μ_n may also be determined if the conductivity σ has also been measured.