

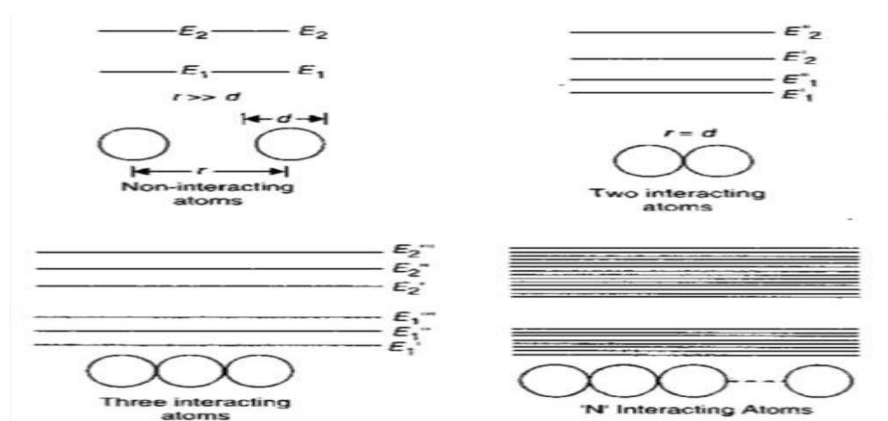
UNIT –V

Semiconductors

Band Theory of Solids / Formation of Energy bands in solids:

In 1928 Felix Bloch developed zone theory for the electrons moving in a periodic field provided by a crystal lattice. This theory is popularly called as the band theory of solids.

A single isolated atom has discrete energy level. When two identical atoms are considered which are far apart, the energy levels in an individual atom are not affected by the presence of other. But when the atoms are brought closer, they form a close packed structure; they begin to interact strongly due to close proximity to each other i.e. when two atoms come close together, one energy level splits into two energy levels. When three atoms come close, the original level splits into three levels; four atoms produce four levels and so on. More generally, N interacting cause an energy level to split into N levels as shown in Fig.



Thus

- The transformation of a single energy level into two or more separate energy levels is known as energy levelsplitting.
- The large number of energy levels resulting from splitting will be very closely spaced and form an energycontinuum that is called an energy band.

OR

- The range of energies that an electron may possess in an atom is known as the energy band.

The degree of splitting of energy level depends on its depth in an atom. i.e. The splitting of energy levels is the greatest for the outermost electrons and least for the innermost electrons.

Energy band Structure of Solid

Fig 2 shows the splitting of energy levels as a function of inter atomic distance and depth of energy level in atom. At large separation; the energy levels are identical and can be shown by single lines. If the distance is decreased; the levels start splitting due to interactions between the atoms. Thus bands corresponding to different energy levels are formed. This splitting increases with further decrease in the inter atomic distance and since splitting for outer levels is more as compared to core levels; the outer bands may overlap with each other to form a composite band (at distance a). For some materials; this is the equilibrium distance at which stable solid is formed. In some materials a stable solid is formed at further reduced distance (a_0). At this distance; the composite band again separates out.

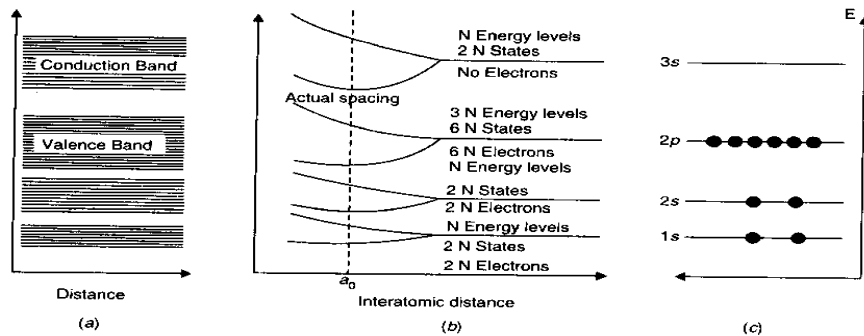


Fig 2: The splitting of energy levels as a function of inter atomic distance

The distance at which stable solid is formed is called lattice constant. The separation between these two bands depends on the value of lattice constant. Smaller the value of the lattice constant; larger is the separation.

The splitting of levels also depends on position of that level in atom. In inner levels splitting is less and they form narrow bands. They are always full and do not responsible for the conduction. While occupying the band; the electrons start filling from the lowest energy levels one after the other in ascending order. The valence electrons of all atoms occupy the lower band out of the two-separated band and

hence it is called VALENCE BAND. Depending upon the number of valence electrons; this band may get partially or completely filled. Upper band is left completely empty. If the electrons go into this band then they are said to be free electrons and are responsible for conduction. Hence this band is termed as CONDUCTION BAND. The number of electrons in this band decides the conductivity of the material. The two bands may be separated by an energy gap E_g .

Energy band Diagram:

Fig shows splitting for Si atom as a function of inter atomic distance. The electronic configuration of Si is $1s^2 2s^2 2p^6 3s^2 3p^2$. The valence shell orbital s and p contain two electrons each. Let N atoms come together to form solid. Thus there are 2N electrons in both; 3s and 3p orbital. At larger separation; there is no splitting of energy levels. If the separation is decreased; the energy levels start splitting. The outer s orbital splits into a band containing N energy levels and p orbital splits into 3N energy levels. Each band contains 2N electrons. At further reduced distance (a) these two bands overlap to form a composite band containing 4N energy levels. If the distance is further decreased to lattice constant (a_0); the two bands separate out with equal distribution of 2N energy levels in each band. The valence 4N electrons occupy lower band of 2N energy levels forming valence band. The upper band remains completely empty and forms the conduction band. They are separated by an energy gap of 1.12 eV. The inner energy levels do not get split to large extent. For germanium; the value of E_g is 0.72 eV.

Note: in the same way; the band pictures of different materials and hence their conductivities can be compared.

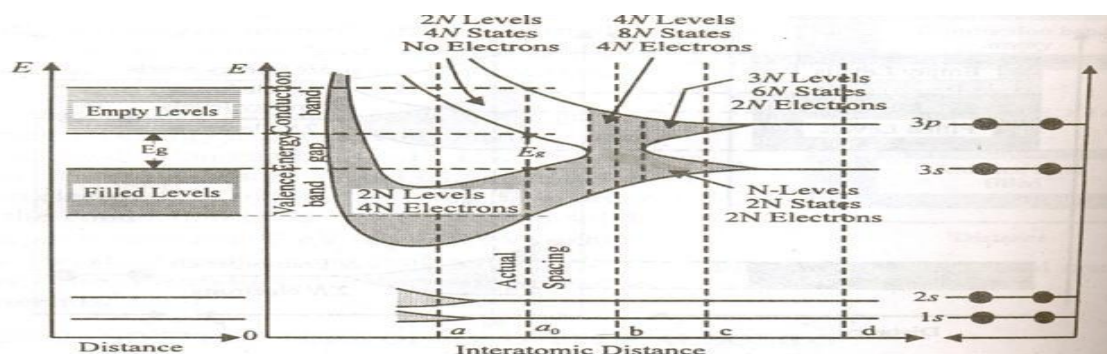


Fig : Energy Level Splitting and Energy Band Diagram in Silicon Crystal

CLASSIFICATION OF SOLIDS ON THE BASIS OF ENERGY BAND STRUCTURE :

Solids can be categorized into conductors, semiconductors or insulators. This classification of different materials into the above mentioned three categories depends on their ability to conduct electricity. The band theory of solids explains qualitatively the difference between these types of materials. Once we know the band structure of a given material we still need to find out which energy levels are occupied and whether specific bands are empty, partially filled or completely filled. Empty bands do not contain electrons. Therefore, they are not expected to contribute to the electrical conductivity of the material. Partially filled bands do contain electrons as well as available energy levels at slightly higher energies. These unoccupied energy levels enable carriers to gain energy when moving in an applied electric field. Electrons in a partially filled band therefore do contribute to the electrical conductivity of the material. Completely filled bands do contain plenty of electrons but do not contribute to the conductivity of the material. This is because the electrons cannot gain energy to move to unoccupied levels in the same band since all energy levels are already filled.

Based on the above discussion, we can classify the solids into 3 categories taking account of arrangement of electrons within bands and width of forbidden energy gaps.

1. Insulators
2. Conductors
3. Semiconductors

Conductors : The materials in which conduction and valence bands overlap are called conductors. (shown in figure)

The overlapping indicates a large number of electrons available for conduction. Hence the application of a small amount of

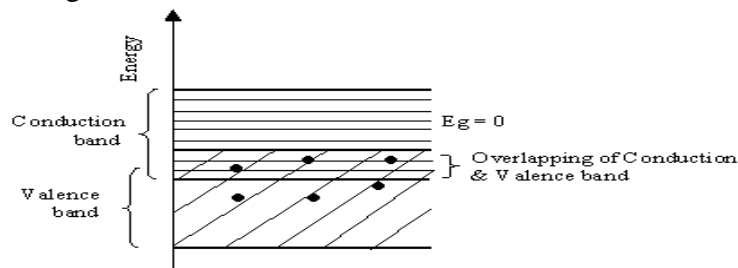


Fig.3: Energy band diagram of a typical conductor

voltage results in a large amount of current. Therefore these solids exhibit good electrical conductivity and are called conductors.

Insulators : The materials in which the conduction band and valence bands are separated by a wide energy gap (≥ 3 eV) as shown in figure below

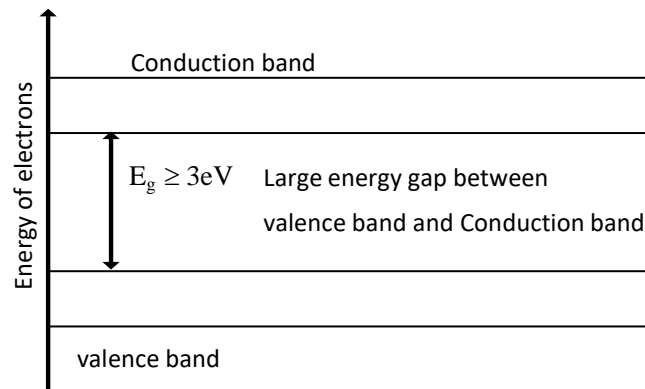


Fig.4: Energy band diagram of an insulator

A wide energy gap means that a large amount of energy is required, to free the electrons, by moving them from the valence band into the conduction band. Since at room temperature, the valence electrons of an insulator do not have enough energy to jump in to the conduction band, therefore insulators do not have an ability to

conduct current. Thus insulators have very high resistivity (or extremely low conductivity) at room temperatures. However if the temperature is raised, some of the valence electrons may acquire energy and jump in to the conduction band. It causes the resistivity of insulators to decrease. Therefore an insulator has negative temperature co-efficient of resistance.

Semiconductors : The materials, in which the conduction and valence bands are separated by a small energy gap (less than 2eV) as shown in figure are called semiconductors.

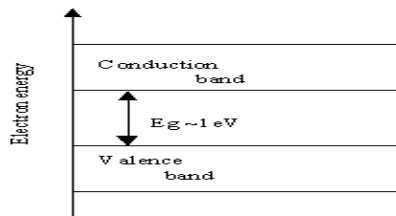


Fig.5: Energy band diagram of a semiconductor

Silicon (Bandgap is 1.12 eV) and germanium (0.72 eV) are the commonly used semiconductors. A small energy gap means that a small amount of energy is required to free the electrons by moving them from the valence band in to the conduction band. The semiconductors behave like insulators at 0K , because no electrons are available in the conduction band. If the temperature is further increased, more valence electrons will acquire energy to jump into the conduction band. Thus like insulators, semiconductors also have negative temperature coefficient of resistance. It means that conductivity of semiconductors increases with the increase in temperature.

Semiconductors

Semiconductors are materials having electrical conductivity considerably greater than that of an insulator but significantly lower than that of a conductor. IV group elements Germanium and silicon are the most widely used semiconductors. A pure semiconductor is known as intrinsic semiconductor and doped semiconductor is known as extrinsic semiconductor.

INTRINSIC SEMICONDUCTOR

Chemically pure semiconductors are known as intrinsic semiconductors. IV group elements pure Germanium and silicon are well known examples of intrinsic semiconductor. Silicon atom has 14 electrons and germanium atom 32 electrons. Each of them has four valence electrons and is tetravalent. Therefore, each atom can form covalent bonds with four neighboring atoms.

A two-dimensional representation of silicon crystal is shown in Fig (11 a). Each silicon atom forms covalent bonds with four surrounding atoms. Circles represent the cores of the silicon atoms, dots represent the valence electrons, and the dashed curves indicate the bonds.

In terms of energy band diagram, a conduction band and a valence band separated by a smaller energy gap characterize a semiconductor (Fig. 11 b)

At 0K an intrinsic semiconductor behaves as a perfect insulator

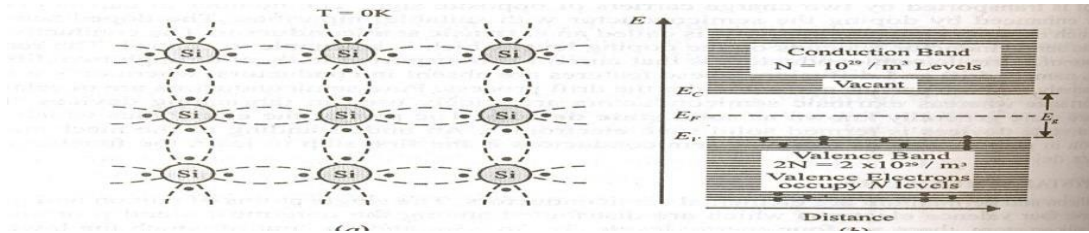


Fig : Energy Band diagram of intrinsic semiconductor at $T=0K$

At $0K$, all valence electrons are locked in covalent bonds and they are in the valence band (Fig).The energy available at $0K$ is not sufficient to break the covalent bonds. Therefore, there are no free electrons within the material at absolute zero. It implies that there are no electrons in the conduction band (Fig).Therefore, an externally applied electric field cannot cause flow of current through the crystal and the intrinsic semiconductor behaves as a perfect insulator at $0K$.

Mechanism of conduction in an intrinsic semiconductor (At $T>0K$)

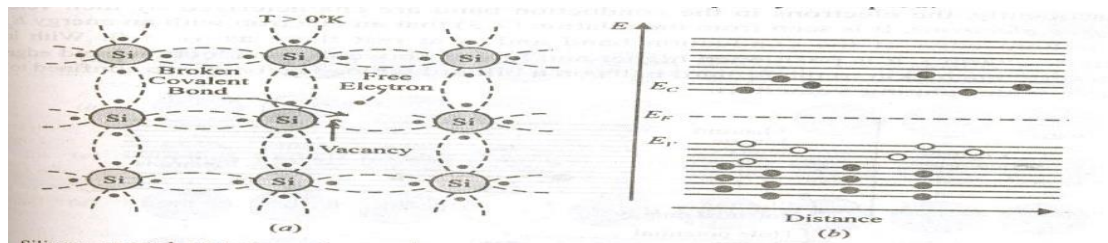


Fig : Energy Band diagram of intrinsic semiconductor at $T>0K$

At temperature above absolute zero, due to thermal energy few covalent bonds are broken (Fig).The higher the temperature, the more covalent bonds are broken and the valence electrons become free and thermally excited to the conduction band (Fig). When an electron from the valence band jumps to the conduction, an empty state arises in the valence band. This vacancy of electron is called a **hole**. The hole carries a positive charge and a mass same as that of an electron. Thus, in semiconductor two types of charge carriers, electrons and holes exist: electrons in the conduction band and holes in the valence band. Electron energy increases as it moves into upper levels and similarly, the energy of holes increases as it moves into lower levels. Free electrons and holes are produced due to breaking of covalent bonds; the number of free electrons is equal to the number of holes.

When a potential difference is applied, the current arises in semiconductor due to the movement of negatively charged electrons in the conduction band and the movement of positively charged holes in the valence band. In pure semiconductor all available charge carriers, electron and holes, arise only due to thermally ruptured bonds and these thermally generated electron-hole pairs cause electrical conduction.

Thus, an intrinsic semiconductor is a semiconductor crystal in which electrical conduction arises due to **thermally excited electrons and holes**.

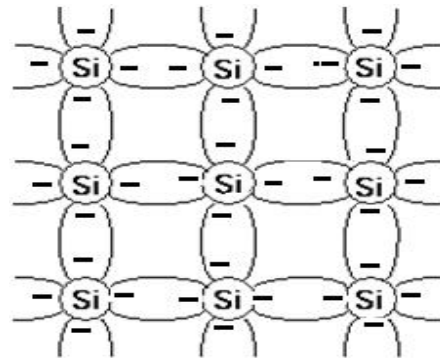
Significance of Band gap E_g

The band gap energy E_g is the minimum amount of energy required for breaking a covalent or the minimum energy required to excite an electron from valence band to conduction band. The energy required to break a covalent bond in germanium crystal is about 0.72 eV and that in Silicon 1.12 eV at $300K$.

INTRINSIC or PURE SEMICONDUCTOR

Let us consider 'Si' with atomic no. 14 and valence is 4. All the silicon atoms form covalent bonds with the neighboring Si atom and no electron is free for conduction at temperature 0 k. Hence pure silicon acts as *insulator* at absolute 0 k, as the temperature increases above 0 k, these covalent bonds break and some electrons are released. These electrons move in the crystal freely and responsible for conductivity. So they are called free electrons.

Each electron leaves behind an empty space called a hole which also acts as current carrier. These electrons and holes move in opposite directions under the effect of external field and constitute current.



ELECTRON CONCENTRATION IN THE CONDUCTION BAND OF INTRINSIC SEMICONDUCTOR

The no. of electrons per unit volume having energy in a range E and $E+dE$ in the conduction band of an intrinsic semiconductor is,

$$dn = Z(E)dE F(E) \text{ -----(1)}$$

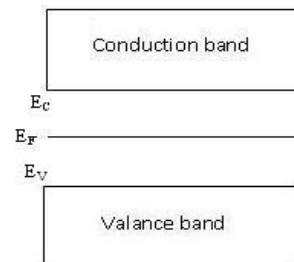
where $F(E)$ represents the Fermi distribution function gives the probability of occupation of electron with energy E .

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{K_B T}\right)}$$

$Z(E)$ is the density of states i.e. no. of available states per unit volume of semiconductor.

$$Z(E) = \frac{4\Pi}{h^3} (2m)^{3/2} E^{1/2}$$

$$dn = \frac{4\Pi}{h^3} (2m)^{3/2} E^{1/2} \cdot \frac{1}{1 + \exp\left(\frac{E - E_F}{K_B T}\right)} dE$$



For conduction band,

$$dn = \frac{4\Pi}{h^3} (2m_e^*)^{3/2} (E-E_c)^{1/2} \cdot \frac{1}{1 + \exp\left(\frac{E-E_F}{K_B T}\right)} dE \text{ ----- (2)}$$

Where m_e^* is effective mass of electron in the conduction band.

in the above equation, for conduction band, $\exp\left(\frac{E-E_F}{K_B T}\right) \gg 1$ so 1 can be neglected in the denominator of the equ.(2).

$$dn = \frac{4\Pi}{h^3} (2m_e^*)^{3/2} (E-E_c)^{1/2} \exp\left(\frac{-(E-E_F)}{K_B T}\right) \text{ -----(3)}$$

To get the total no. of electrons per unit vol. in the conduction band is we have to integrate the above equ. Between the bottom of the conduction to top of the conduction band.

$$\therefore n = \frac{4\Pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} \exp\left(\frac{-(E-E_F)}{K_B T}\right) dE$$

$$dn = \frac{4\Pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} \exp\left(\frac{-(E-E_F+E_c-E_c)}{K_B T}\right) dE$$

$$n = \frac{4\Pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \int_{E_c}^{\infty} (E-E_c)^{1/2} \exp\left(\frac{-(E-E_c)}{K_B T}\right) dE$$

$$\text{put } x = \left(\frac{(E-E_c)}{K_B T}\right), \text{ so that } dE = K_B T dx$$

Lower Limit: when $E = E_c$, $x = 0$ and

Upper Limit: when $E = \infty$, $x = \infty$

$$\therefore n = \frac{4\Pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \int_0^{\infty} e^{-x} (x K_B T)^{1/2} K_B T dx$$

$$n = \frac{4\Pi}{h^3} (2m_e^* K_B T)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \int_0^{\infty} e^{-x} (x)^{1/2} dx$$

$$n = 4\Pi \left[\frac{2m_e^* K_B T}{h^2} \right]^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \frac{\sqrt{\pi}}{2}$$

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

$$n = N_c \exp \left(- \frac{(E_c - E_F)}{K_B T} \right)$$

$$\text{Where } N_c = 2 \left[\frac{2 \Pi m_e^* k_B T}{h^2} \right]^{3/2}$$

HOLE CONCENTRATION IN THE VALENCE BAND OF INTRINSIC SEMI CONDUCTOR

The no. of holes per unit volume having energy in a range E and E+dE in the valence band of an intrinsic semiconductor is,

$$dp = Z(E)dE [1-F(E)] \text{ -----(1)}$$

where [1-F(E)] represents the probability of absence of electron in the particular energy level with energy E.

$$[1-F(E)] = 1 - \frac{1}{1 + \exp \left(\frac{E - E_F}{K_B T} \right)} = \frac{\exp \left(\frac{E - E_F}{K_B T} \right)}{1 + \exp \left(\frac{E - E_F}{K_B T} \right)}$$

$$\text{For the valence band } 1 \gg \exp \left(\frac{E - E_F}{K_B T} \right).$$

So exponential term can be neglected in the denominator of the above equation.

$$\therefore [1-F(E)] = \exp \left(\frac{E - E_F}{K_B T} \right)$$

$$dP = \frac{4\Pi}{h^3} (2m)^{3/2} E^{1/2} \exp \left(\frac{E - E_F}{K_B T} \right) dE$$

For valence band,

$$dp = \frac{4\Pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} \exp \left(\frac{E - E_F}{K_B T} \right) dE$$

To get the total no. of holes in the V.B. we have to integrate the above equation between the limits bottom of the V.B. to top of the V.B.

$$p = \frac{4\Pi}{h^3} (2m_h^*)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \exp \left(\frac{E - E_F}{K_B T} \right) dE$$

$$p = \frac{4\Pi}{h^3} (2m_h^*)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \exp\left(\frac{E - E_F + E_v - E_v}{K_B T}\right) dE$$

$$p = \frac{4\Pi}{h^3} (2m_h^*)^{3/2} \exp\left(\frac{E_v - E_F}{K_B T}\right) \int_{-\infty}^{E_v} (E_v - E)^{1/2} \exp\left(-\frac{E_v - E}{K_B T}\right) dE$$

$$\text{put } \left(\frac{E_v - E}{K_B T}\right) = x; \quad dE = -dx K_B T$$

Lower Limit: when $E = -\infty$, $x = \infty$.

Upper Limit: when $E = E_v$, $x = 0$.

$$\therefore p = \frac{4\Pi}{h^3} (2m_h^*)^{3/2} \exp\left(\frac{E_v - E_F}{K_B T}\right) \int_{\infty}^0 e^{-x} (x K_B T)^{1/2} (-K_B T dx)$$

$$p = \frac{4\Pi}{h^3} (m_h^* K_B T)^{3/2} \exp\left(\frac{E_v - E_F}{K_B T}\right) \int_0^{\infty} e^{-x} x^{1/2} dx$$

$$p = \frac{4\Pi}{h^3} (2m_h^* K_B T)^{3/2} \exp\left(\frac{E_v - E_F}{K_B T}\right) \frac{\sqrt{\Pi}}{2}$$

$$p = 2 \left(\frac{2m_h^* \pi k_B T}{h^2} \right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_F}{K_B T}\right) \text{ or}$$

$$p = N_v \exp\left(-\frac{E_F - E_v}{K_B T}\right) \text{----- (2)}$$

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

Equ. (2) gives the no. of holes in the V.B of the intrinsic semi conductor.

LOCATION OF FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

In intrinsic semiconductor no. of electrons in the C.B and no. of holes in the V.B are equal.

$$\therefore n = p$$

$$N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right) = N_v \exp\left(-\frac{(E_F - E_v)}{K_B T}\right)$$

$$\exp\left(\frac{-E_c + E_F + E_F - E_v}{K_B T}\right) = \frac{N_v}{N_c}$$

$$\frac{2E_F}{K_B T} - \frac{(E_c + E_v)}{K_B T} = \ln \frac{N_v}{N_c}$$

$$E_F = \frac{(E_c + E_v)}{2} + \frac{K_B T}{2} \ln \frac{N_v}{N_c} \text{ ----- (1)}$$

At T = 0 K,

$$E_F = \frac{(E_c + E_v)}{2} \text{ ----- (2)}$$

Fermi energy level lies exactly in the middle of the forbidden gap at absolute zero K.

INTRINSIC CARRIER CONCENTRATION (n_i) [law of mass action]

In the intrinsic semiconductor, $n = p = n_i$. Where n_i is known as intrinsic carrier concentration.

$$\therefore np = n_i^2$$

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

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

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

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

This equation shows that for a given semiconductor the product of holes and electron concentration at a given temp. is equal to square of the intrinsic semiconductor carrier concentration. This is called law of mass action and holds both for intrinsic and extrinsic semiconductors.

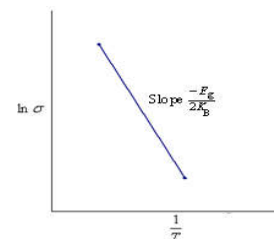
CONDUCTIVITY OF INTRINSIC SEMICONDUCTORS

When the electric field is applied to the semiconductor, charge carriers acquire velocity.

$$v_d \propto E$$

$$v_d = \mu E \text{ ----- (1)}$$

where μ is called mobility of charge carriers.



Current density $J = ne v_d$

$$J = ne\mu E \text{ ----- (2)}$$

This is in the form of $J = \sigma E$

Where $\sigma = ne\mu$ ----- (3) is conductivity

For electrons $\sigma_n = ne\mu_e$

For holes $\sigma_p = pe\mu_h$

Where μ_e, μ_h are mobilities of electrons and holes respectively.

$$\therefore \sigma = ne\mu_e + pe\mu_h$$

$$= (n\mu_e + p\mu_h)e$$

$$= n_i(\mu_e + \mu_h)e \text{ ----- (4) where } n_i \text{ is called intrinsic carrier concentration.}$$

$$\sigma = 2 \left[\frac{2 \Pi k_B T}{h^2} \right]^{3/2} (m_e^* m_h^*)^{3/4} \exp\left(\frac{-E_g}{2K_B T}\right) (\mu_e + \mu_h)e$$

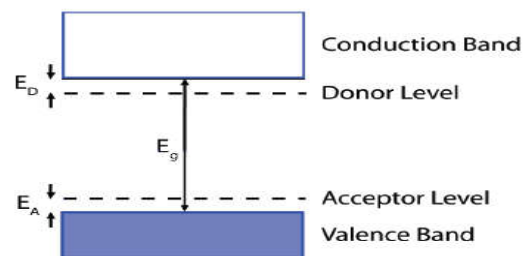
$$\sigma = \sigma_o \exp\left(\frac{-E_g}{2K_B T}\right) \text{ where } \sigma_o = 2 \left[\frac{2 \Pi k_B T}{h^2} \right]^{3/2} (m_e^* m_h^*)^{3/4} (\mu_e + \mu_h)e$$

$$\ln \sigma = \ln \sigma_o - \frac{E_g}{2K_B T} \text{ ----- (4)}$$

The above equ. gives the expression for conductivity of intrinsic semiconductor.

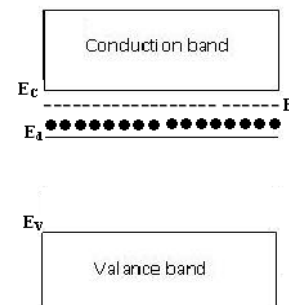
EXTRINSIC SEMICONDUCTORS

To increase the conductivity of pure semiconductors some impurities are added. This process is called doping. When impurities are added to semiconductor the available energy levels are altered. One or more energy levels are appeared in the band structure. Doping may create energy levels within the forbidden band.



N-TYPE SEMICONDUCTOR

When pentavalent impurities such as phosphorous, Arsenic or Antimony is introduced into Si, or Ge, four of its valence electrons form 4 covalent bonds with other 4 neighboring Si or Ge atoms while the fifth valence electron loosely bound to its nucleus. A small amount of energy is required to detach fifth electron from its nucleus and make it free to conduct. So pentavalent impurities are known as donor impurities. The energy level corresponding to the fifth valence electron lies in the band gap just below the C.B. edge as shown in figure.



ELECTRON CONCENTRATION IN N-TYPE SEMICONDUCTOR

The energy level diagram for n-type semiconductor is shown in fig. At 0k all donor levels are unionized state that is all donor levels are occupied with electrons. As temperature increases slightly some of the donors ionized and contribute electrons to the conduction band. Also some of the valence electrons may jump to the conduction band leaving hole in valence band. The no. of holes produced quite small in this process. Therefore Fermi level must lie near the middle of the donor level and bottom of the conduction band. Let there be N_d donors per unit volume occupying donor levels with energy E_d . The electron concentration in the conduction band is given by

$$n = N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right) \text{----- (1)}$$

The electron concentration must be equal to the sum of concentration of ionized donors in donor levels and concentration of thermally generated holes in valence band. i.e.

$$n = N_d^+ + p \text{----- (2)}$$

If donors concentration is high, the holes generated can be neglected.

$$\therefore n \approx N_d^+ \text{----- (3)}$$

The concentration of ionized donors can be written as

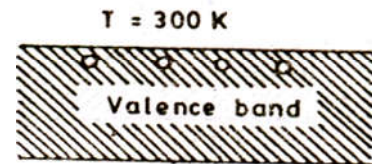
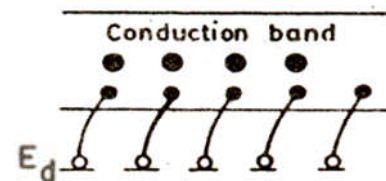
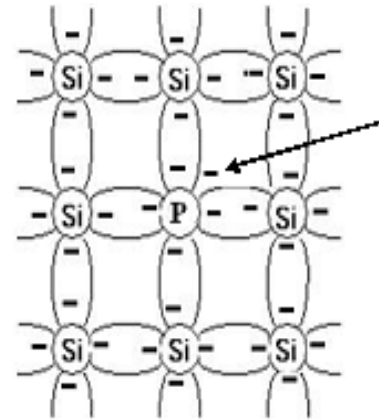
$$N_d^+ = N_d[1 - F(E_d)]$$

$$= N_d \left[1 - \frac{1}{1 + \exp\left(\frac{E_d - E_F}{K_B T}\right)} \right]$$

$$= N_d \left[\frac{\exp\left(\frac{E_d - E_F}{K_B T}\right)}{1 + \exp\left(\frac{E_d - E_F}{K_B T}\right)} \right]$$

$$= N_d \exp\left[-\left(\frac{E_F - E_d}{K_B T}\right)\right] \text{----- (4)}$$

In n-type semiconductor E_F lies above the E_d , $1 \gg \exp\left(\frac{E_d - E_F}{K_B T}\right)$. So exponential term can be neglected in the denominator of the above equation.



From equations (3) and (4), we get

$$N_c \exp \left[- \left(\frac{E_c - E_F}{K_B T} \right) \right] = N_d \exp \left[- \left(\frac{E_F - E_d}{K_B T} \right) \right]$$

$$\exp \left(\frac{-E_c + E_F + E_F - E_d}{K_B T} \right) = \frac{N_d}{N_c}$$

$$\left(\frac{2E_F}{K_B T} - \frac{(E_c + E_d)}{K_B T} \right) = \ln \frac{N_d}{N_c}$$

$$E_F = \frac{E_c + E_d}{2} + \frac{K_B T}{2} \ln \frac{N_d}{N_c} \text{ ----- (5)}$$

Substitute the value of E_F in equ.(1)

$$n = N_c \exp \left(\frac{-E_c}{K_B T} + \frac{E_c + E_d}{2K_B T} + \frac{\ln \frac{N_d}{N_c}}{2} \right)$$

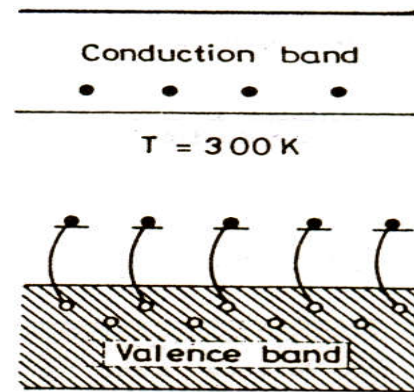
$$n = N_c \exp \left(\frac{-2E_c + E_c + E_d}{2K_B T} + \frac{\ln \frac{N_d}{N_c}}{2} \right)$$

$$n = N_c \exp \left(\frac{E_d - E_c}{2K_B T} + \ln \left(\frac{N_d}{N_c} \right)^{\frac{1}{2}} \right)$$

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

$$n = (N_c N_d)^{\frac{1}{2}} \exp \left(\frac{E_d - E_c}{2K_B T} \right) \text{ or ----- (6)}$$

$$n = (N_c N_d)^{\frac{1}{2}} \exp \left(\frac{-\Delta E}{2K_B T} \right) \text{ ----- (7)}$$



Where $-\Delta E = E_d - E_c$ represents the ionization energy of donors.

FERMI LEVEL IN EXTRINSIC SEMICONDUCTOR

The carrier concentrations in extrinsic semiconductors vary with temperature and impurity concentration. It means that the probability of occupancy of respective bands varies and consequently the position of Fermi level changes with temperature and impurity concentration.

a) Variation of Fermi Level with Temperature

n-type semiconductor

In the n-type semiconductor at low temperature, some donor atoms are ionized and provide electrons to the conduction band while other remains neutral. As electrons in the conduction band are only due to the transitions from the donor levels, the Fermi level must lie between the impurity donor levels and the bottom of the conduction band.

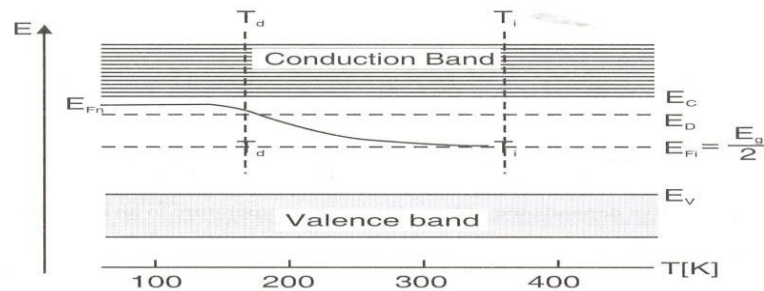


Fig : Variation of Fermi level with temperature in n-type

When $T = 0K$, E_{Fn} lies midway between the donor levels and the bottom of the conduction band. It is thus,

$$E_{Fn} = \frac{E_C + E_D}{2} \quad \text{at } T = 0K \text{-----(17)}$$

E_D is the energy of the donor level measured from the bottom of the conduction band.

As the temperature increases the donor levels gradually get depleted and the Fermi level moves downward. At the temperature of complete depletion of donor levels, T_d , the Fermi level coincides with the donor level E_D .

Thus $E_{Fn} = E_D$ at $T = T_d$ ----- (18)

As temperature grows above T_d , the Fermi level shifts downward in an approximately linear fashion.

At a temperature T_i , the extrinsic behavior disappears as intrinsic behavior take over. In the intrinsic region, the electron concentration in conduction band increases exponentially and the Fermi level approaches the intrinsic value

$$E_{Fn} = \frac{E_g}{2} \quad \text{at } T \geq T_i \text{ -----(19)}$$

At higher temperatures, the n-type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. The variation of Fermi level E_{Fn} in an n-type semiconductor with temperature is illustrated in

Fig.

p-type semiconductor:

In the p-type semiconductor at low temperature, holes in the valence band are only due to the transitions of electrons from the valence band to the acceptor levels.

As the valence band is the source of electrons and the acceptor levels are the recipients for them, then, the Fermi level must lie between the top of the valence band and the impurity acceptor levels.

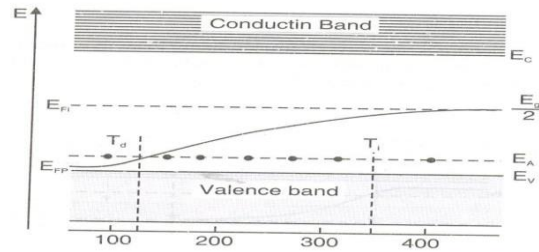


Fig : Variation of Fermi level with temperature in p-type

When $T = 0K$, E_{Fn} lies midway between the acceptor levels and the top of the valence band. Thus,

$$E_{Fp} = \frac{E_A + E_v}{2} \quad \text{at } T = 0K \text{-----} (20)$$

E_A is the energy of the acceptor levels measured from the top of the valence band.

As the temperature increases the acceptor levels gradually get filled and the Fermi level moves upward. At the temperature of saturation T_s , the Fermi level coincides with the acceptor level E_A . Thus

$$E_{Fp} = E_A \quad \text{at } T = T_s \text{-----} (21)$$

As temperature grows above T_s , the Fermi level shifts upward in an approximately linear fashion.

At a temperature T_i , the extrinsic behavior disappears as intrinsic behavior take over. In the intrinsic region, the hole concentration in valence band increases exponentially and the Fermi level approaches the intrinsic value

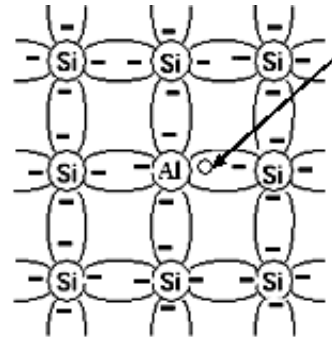
$$E_{Fp} = \frac{E_c}{2} \quad \text{at } T = T_i \text{-----}(22)$$

At higher temperatures, the p-type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. The variation of Fermi level E_{Fp} in an p-type semiconductor with temperature is illustrated in Fig.

P-TYPE SEMICONDUCTOR

When trivalent impurity such as aluminum, boron, gallium or indium is added to pure silicon, it forms 3 covalent bonds with the neighboring 3 silicon atoms while the fourth bond is not completed due to the deficiency of one electron. Thus the trivalent impurity atom has a tendency to accept one electron from neighboring silicon atom to complete the fourth covalent bond. The energy level corresponding to the electron deficiency that is 'hole' is located above the valence band and is called acceptor level.

In this type of semiconductor majority charge carriers are holes and minority charge carriers are electrons, called p-type semiconductor.



CONDUCTIVITY OF EXTRINSIC SEMICONDUCTORS

The expression for conductivity for n-type semiconductors is

$$\sigma_e = ne\mu_e \text{ ----- (1) and}$$

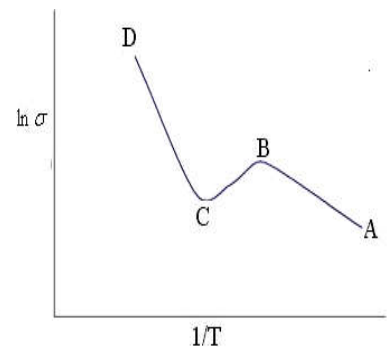
For p-type material is $\sigma_p = ne\mu_h \text{ ----- (2)}$

Where μ_e and μ_h are mobilities of electrons and holes.

Under the condition of thermal equilibrium electron and holes are uniformly distributed in semiconductor and the average velocity of charge carriers is zero, no current flows.

Conductivity is temperature dependent as shown in figure.

At low temp the conductivity increases with increase of temperature. This is due to increase in the no. of conduction electrons due to ionization of donor impurities. Conductivity reaches maximum value B in the graph all donors is ionized. Conductivity decreases further increase with temperature. This is due to decrease of mobility because of scattering of electrons from the periodic potential field. A sharp rise in conductivity from C to D is due to large increase in intrinsic conductivity.



DRIFT & DIFFUSION

The net current that flows across semi conducting crystal has two components.

- (i) Drift current
- (ii) Diffusion current

DRIFT CURRENT

When voltage is applied electrons attracted towards the positive potentials and holes attracted towards the negative potential. This net movement of charge carriers is called drift.

Due to the application of voltage charge carriers attain drift velocity V_d , which is proportional to the electric field E .

$$V_d \propto E$$

$$V_d = \mu E \text{ ----- (1)}$$

Where μ is mobility of charge carriers. The drift current density J_e due to electrons is defined as the charge flowing across unit area per unit time due to their drift under the influence of field is given by

$$J_{e(\text{drift})} = ne V_d \text{ or}$$

$$J_{e(\text{drift})} = ne\mu_e E \text{ ----- (2)}$$

Where μ_e is mobility of electrons. The drift current density due to holes in the valence band is

$$J_{h(\text{drift})} = pe\mu_h E \text{ ----- (3)}$$

So the total drift current is

$$\begin{aligned} J_{(\text{drift})} &= J_{e(\text{drift})} + J_{h(\text{drift})} \\ &= e(n\mu_e + p\mu_h) E \text{ ----- (4)} \end{aligned}$$

The above equation is applicable to intrinsic as well as extrinsic semiconductors. Drift current depends upon two variables

- (i) carrier concentration
- (ii) electric field

DIFFUSION CURRENT

In addition to the drift motion, the charge carriers in semiconductor move by diffusion of charge carriers from high concentration to low concentration region. Current produced by the diffusion of the charge carriers is called diffusion current.

Suppose when light or temperature is incident on the semiconductor, additional electron and hole pairs generated and they diffuse throughout the semiconductor to restore the equilibrium condition.

Let Δn , Δp be the excess charge of electron and holes respectively. According to Fick's law, diffusion current is proportional to rate of flow of excess charge.

$$\therefore \text{rate of flow of excess charge} \propto - \frac{\partial}{\partial x} (\Delta n) \text{ or}$$

$$\text{Rate of flow of excess charge} = -D_e \frac{\partial}{\partial x} (\Delta n)$$

$$\therefore J_{e(\text{diff.})} = (-e) \text{ rate of flow of excess electrons}$$

$$= eD_e \frac{\partial}{\partial x} (\Delta n) \text{ ----- (1)}$$

Similarly diffusion current density due to holes is

$$J_{h(\text{diff.})} = (e) \text{ rate of change of excess holes}$$

$$= -D_h \frac{\partial}{\partial x} (\Delta p) \text{ ----- (2)}$$

∴ Total current density in semiconductor due to electrons is $J_e = J_{e(\text{drift})} + J_{e(\text{diff.})}$

$$= ne\mu_e E + eD_e \frac{\partial}{\partial x} (\Delta n)$$

$$= (n\mu_e E + D_e \frac{\partial}{\partial x} (\Delta n)) e \text{ ----- (3)}$$

Current density due to holes is

$$J_h = J_{h(\text{drift})} + J_{h(\text{diff.})}$$

$$= pe\mu_h E + (-D_h \frac{\partial}{\partial x} (\Delta p))$$

$$J_h = (p\mu_h E - D_h \frac{\partial}{\partial x} (\Delta p)) e \text{ ----- (4)}$$

EINSTEIN'S RELATION

Einstein's relation gives the direct relation between diffusion coefficient and mobility of charge carriers. At equilibrium condition drift current balances and opposite to the diffusion current .

$$\therefore ne\mu_e E = -eD_e \frac{\partial n}{\partial x} \text{ ----- (1)}$$

$$ne\mu_e E = -(1/\mu_e) eD_e \frac{\partial n}{\partial x} \text{ ----- (2)}$$

Einstein compared the movement of charge carriers with the gas molecules in a container.

According to Boltzmann's statistics the concentrations of gas molecules can be written as

$$n = C \cdot \exp\left(\frac{-Fx}{K_B T}\right) \text{ where } x \text{ is distance and } F = eE \text{ is force acting on the charge carriers}$$

$$\frac{\partial n}{\partial x} = C \cdot \exp\left(\frac{-eEx}{K_B T}\right) \cdot \left(\frac{-eE}{K_B T}\right), \quad \frac{\partial n}{\partial x} = n \cdot \left(\frac{-eE}{K_B T}\right) \text{ ----- (3)}$$

$$F = neE = K_B T \frac{\partial n}{\partial x} \text{ ----- (4)}$$

$$\therefore ne\mu_e E = neD_e \left(\frac{eE}{K_B T}\right)$$

$$\frac{D_e}{\mu_e} = \frac{K_B T}{e} \text{ ----- (2) for electrons}$$

$$\frac{D_h}{\mu_h} = \frac{K_B T}{e} \text{ ----- (3) for holes}$$

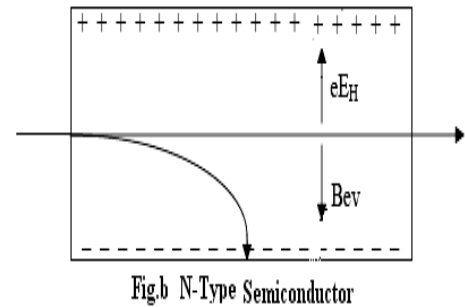
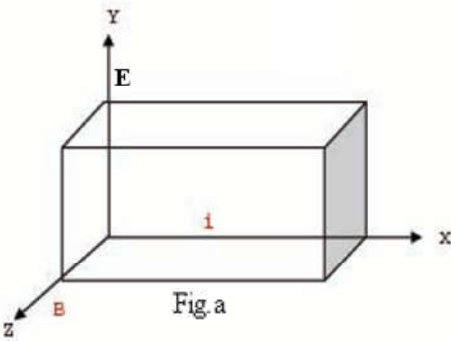
HALL EFFECT

When a semiconductor carrying current 'i' is placed in a magnetic field which is perpendicular to the direction of current, an electric field is developed across the material in a direction perpendicular to both the current direction and magnetic field direction. This phenomenon is known as Hall Effect.

Explanation

Consider a piece of semiconductor in which current passing along x-axis. When a magnetic field B is applied along z-direction an electric field is appeared along y-direction.

If the sample is p-type semiconductor holes move with velocity v in x-direction. As they move across the semiconductor these holes experience a transverse force due to magnetic field. This force drives the holes on the lower surface as shown in figure. As a result the lower surface becomes positively charged and upper surface becomes negatively charged and creating Hall field along y-direction.



If the sample is an n-type semiconductor majority charge carriers are electrons, these electrons experience a force 'Bev' in downward direction and lower face gets negatively charged and upper face gets positively charged which is shown in fig.b

Consider a rectangular slab of n-type semiconductor carrying current in positive x-direction under the magnetic field electrons are deflected to the lower surface because of force 'Bev' due to magnetic field and upper surface gets positively charged because of this electric field a force 'eE_H' acts on electrons in upward direction. The two opposing forces 'Bev' and 'eE_H' establish equilibrium. So

$$Bev = eE_H$$

$$Bv = E_H \text{ ----- (1)}$$

Let 'J' be the current density then

$$J = nev \quad \text{or} \quad v = \frac{J}{ne} \text{ ----- (2)}$$

$$\text{From (1) and (2), } \frac{BJ}{ne} = E_H \text{ ----- (3)}$$

Hall Effect depends on the current density J and magnetic field B.

$$E_H \propto JB$$

$$E_H = R_H JB \text{ ----- (4) Where } R_H \text{ is Hall coefficient.}$$

$$\text{From (3) and (4), } R_H = -\frac{1}{ne} \text{ ----- (5)}$$

-ve sign is used because the electric field developed in -ve y-direction.

For p-type semiconductors,

$$R_H = \frac{1}{pe} \text{ ----- (6) where p is hole density.}$$

DETERMINATION OF HALL COEFFICIENT (R_H)

If V_H be the Hall voltage across the sample of thickness 't'

$$E_H = \frac{V_H}{t} \text{ ----- (7)}$$

From (4) and (7),

$$R_H JB = \frac{V_H}{t} \quad \text{or} \quad V_H = R_H JB \times t \text{ ----- (8)}$$

If 'b' be the width of the sample then current density $J = \frac{I}{A}$

$$V_H = \frac{R_H I x B x t}{b x t} \quad \text{or}$$

$$R_H = \frac{V_H b x t}{I x B} \text{ ----- (9)}$$

SIGNIFICANCE OF HALL EFFECT

1. By means of Hall Effect we can assess the type of semiconductor whether it is n-type or p-type. Hall coefficient is negative for n-type material.
2. Charge carrier concentration can be evaluated by means of Hall Effect.

$$R_H = \frac{1}{ne} \quad \text{or} \quad n = \frac{1}{eR_H}$$

3. Mobility of charge carriers can be calculated by means of Hall Effect.

$$\sigma = ne\mu \quad \text{and} \quad R_H = \frac{1}{ne}$$

$$\therefore \mu = R_H \sigma$$

4. Hall Effect can be used to determine the power flow in electromagnetic wave