

## SEMICONDUCTOR MATERIALS

**Semiconductors:** Energy bands in Semiconductors, intrinsic and extrinsic Semiconductors. Carrier transport in Semiconductors: diffusion current, drift current, mobility, and resistivity, Generation and recombination of carriers, Hall Effect.

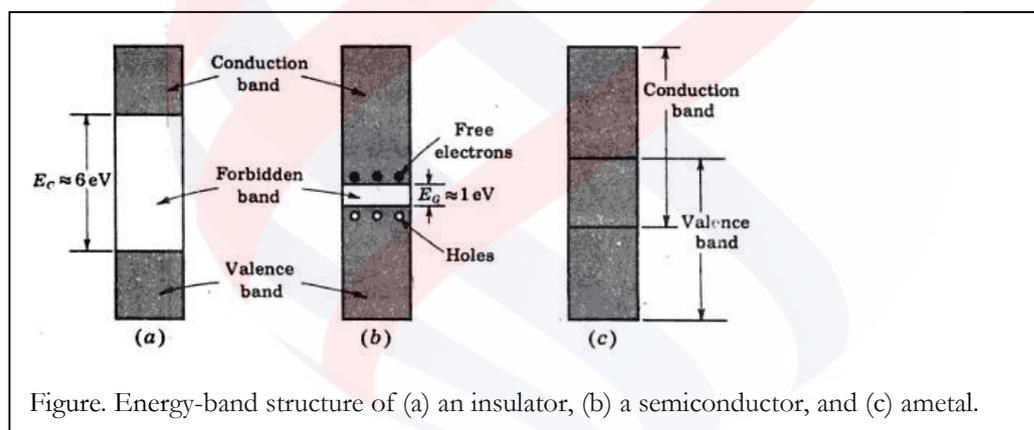
### 1. Classification of Materials Based on Energy Band Theory

#### Insulators, Semiconductors and Metals:

- A very poor conductor of electricity is called an insulator;
- An excellent conductor of electricity is a metal; and
- A substance whose conductivity lies between these extremes is a semiconductor.

A material may be placed in one of these three classes, depending upon its energy-band structure.

#### Insulator :



The energy-band structure of insulator is shown schematically in Fig. A large forbidden band ( $E_G \approx 6 \text{ eV}$ ) separates the filled valence region from the vacant conduction band. Practically it is impossible for an electron to jump from the valence band to the conduction band. Hence such materials cannot conduct and called insulators. Insulators may conduct only at very high temperatures or if they are subjected to high voltage. Such conduction is rare and is called breakdown of an insulator.

*Insulator has negative temperature coefficient of resistance.*

**Example :** Diamond ,glass, wood, mica, paper, Xenon etc

#### Semiconductor:

A substance for which the width of the forbidden energy region is relatively small (  $1 \text{ eV}$ ) is called a semiconductor. The most important practical semiconductor materials are germanium and silicon, which

have values of  $E_G$  of 0.785 and 1.21 eV, respectively, at 0°K. Energies of this magnitude normally cannot be acquired from an applied field. **Hence the valence band remains full, the conduction band empty, and these materials are insulators at low temperatures.** However, the conductivity increases with temperature. These substances are known as intrinsic (pure) semiconductors.

As the temperature is increased, some of these valence electrons acquire thermal energy greater than  $E_G$ , and hence move into the conduction band. These are now free electrons in the sense that they can move about under the influence of even a small applied field. The insulator has now become slightly conducting; it is a semiconductor. The absence of an electron in the valence band is represented by a small circle in Figure b, and is called a **hole**. The phrase “holes in a semiconductor” therefore refers to the empty energy levels in an otherwise filled valence band.

**Note:** It has been determined experimentally that  $E_G$  decreases with temperature.

- For silicon,  $E_G(T) = 1.21 - 3.60 \times 10^{-4}T$ ,  
where T is Temperature in °K

At room temperature (300°K),  $E_G = 1.1$  eV.

- For germanium,  $E_G(T) = 0.785 - 2.23 \times 10^{-4}T$

At room temperature(300°K),  $E_G = 0.72$  eV.

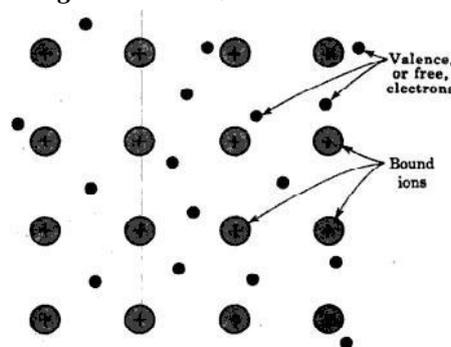
**Conductor (Metal):** In conductors, the conduction and valence bands are overlapped with each other ( $E_G = 0$ ). Hence even at room temperature, a large number of electrons are available for conduction. So without any additional energy, such metals contain a large number of free electrons and hence called good conductors. The conductors are unipolar i.e, conducts current by means of electrons only.

Conductors has positive temperature coefficient of resistance.

**Example:** Copper, silver, Aluminium etc.

## 2. MOBILITY:

The following figure is a two-dimensional schematic picture of the charge distribution within a metal. The shaded regions represent the net positive charge of the nucleus and the tightly bound inner electrons. The black dots represent the outer, or valence, electrons in the atom. These electrons wander freely from atom to atom in the metal. According to the electron-gas theory of a metal, the electrons are in continuous motion, the direction of flight being changed at each collision with the heavy (almost stationary) ions. Since the motion is random, **the average current is zero.**

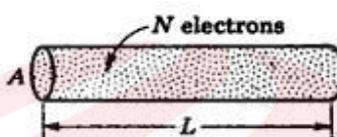


Now let us apply a constant electric field  $E$  (volts per meter) to the metal. As a result of this electrostatic force, the electrons would be accelerated and the velocity would increase indefinitely with time. However, at each inelastic collision with an ion, an electron loses energy, and a steady-state condition is reached where a finite value of **drift speed**  $V$  is attained. This drift velocity is in the direction opposite to that of the electric field. The average speed  $V$  is proportional to applied electric field  $E$ . Thus

$$\boxed{V = \mu E}$$
 where  $\mu$  is called *mobility* of charged particle.

## 2. DRIFT CURRENT DENSITY

Let us consider conductor of length ' $L$ ' having ' $N$ ' number of electrons and having a area of cross section ' $A$ '. Consider any cross section of the conductor. Let ' $N$ ' be the number electrons passing through area ' $A$ ' in time ' $T$ '. So number of electrons crossing the area in unit time is  $N/T$ .



Thus the total charge per second passing any area, which, by definition, is the current in amperes, is

$$I = Nq/T = Nqv/L; \quad \text{where } v = \text{drift velocity} = (L/T)$$

The current density  $J$  for the conductor is current per unit cross sectional area of the conducting material.

$$J = I/A \text{ ampere/m}^2 \Rightarrow J = Nev/LA ;$$

where  $L.A$  = volume of the conductor ;  $n$  = number of electrons per unit volume,

$$n = N/LA \Rightarrow \boxed{J = nev} \quad \text{but } v = \mu E; \text{ Therefore } \boxed{J = ne\mu E} \text{ ampere/m}^2 ;$$

This is the general expression for current density in a given material.

The current density is related to electric field  $E$  by relation,  $\boxed{J = \sigma E}$ ;

where  $\sigma$  = conductivity of the material in  $(\Omega^{-m})^{-1}$  and  $\boxed{\sigma = ne\mu}$ .

## 4. TYPES OF SEMICONDUCTORS :

1. **Intrinsic Semiconductor:** Pure semiconductors . Si, Ge
2. **Extrinsic Semiconductor :** Pure Semiconductor added with external impurity atoms like third and fifth group atoms which forms p and n type semiconductors respectively .

### 1. Electrons and Holes in an Intrinsic Semiconductor:

At a very low temperature (say  $0^\circ\text{K}$ ), semiconductor behaves as an insulator, since no free charge carriers of electricity are available. At room temperature, some of the covalent bonds will be broken because of the thermal energy supplied to the crystal, and conduction is made possible. The energy  $E_G$  required to break such a covalent bond is about  $0.72 \text{ eV}$  for *germanium* and  $1.1 \text{ eV}$  for *silicon* at room temperature.

Hole in a lattice is designed as vacancy created by removal of electron from covalent bond. The absence of the electron in the covalent bond (incomplete) is called a hole. The importance of the hole is that it may serve as a carrier of electricity comparable in effectiveness to the free electron.

The motion of the hole in one direction means the transport of a negative charge an equal distance in the opposite direction. The hole behaves like a positive charge equal in magnitude to the electronic charge. The holes are physical entities whose movement constitutes a flow of current.

In a pure (intrinsic) semiconductor the number of holes in a valence band is equal to the number of free electrons in the conduction band.

Thermal agitation continues to produce new hole – electron pairs, whereas other hole – electron pairs disappear as a result of recombination.

$$n = p = n_i$$

where  $n$  = Electron concentration;  $p$  = hole concentration.

$n_i$  = Intrinsic concentration of semiconductor.

At room temperature ;

$$n_i = 1.5 \times 10^{10} / \text{cm}^3 \text{ for Silicon}$$

$$n_i = 2.5 \times 10^{13} / \text{cm}^3 \text{ for Germanium.}$$

**Intrinsic concentration  $n_i$**  : The intrinsic concentration  $n_i$  varies with temperature as,

$$n_i^2 = A_0 T^3 e^{-E_{G_0}/KT} \quad \text{where } E_{G_0} = \text{energy gap at } 0^\circ\text{K in eV};$$

$K$  = Boltzmann constant in eV / $^\circ\text{K}$

$T$  = Temperature in degree Kelvin;  $A_0$  = Constant independent of  $T$ .

#### **4.2. EQUILIBRIUM CONCENTRATIONS**

The energy corresponding to the highest filled level at  $0^\circ\text{K}$  is called the “Fermi energy  $E_F$ ”. At  $0^\circ\text{K}$ , the free electrons occupy all the levels up to the Fermi level, leaving all those above it empty.

At temperature above  $0^\circ\text{K}$ , due to thermal excitation, there is a finite probability of some of the electrons from below the Fermi level moving to levels above  $E_F$ . This probability is given by the Fermi – Dirac statistics.

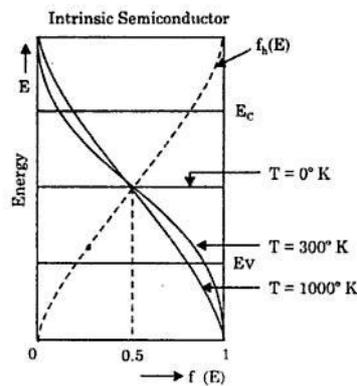


Figure. Plot of electron distribution.

The probability of occupation  $f(E)$  of an energy level  $E$  by an electron is given by

$$f(E) = \frac{1}{e^{(E-E_F)/KT} + 1}$$

The Fermi level can be defined as that level which has a 50% probability of occupation by an electron at any temperature.

**Case (1) :** At  $T = 0^\circ\text{K}$

$$f(E) = 1 / (1 + e^{\infty}) = 0 \quad \text{when } E > E_F$$

$$f(E) = 1 / (1 + e^{-\infty}) = 1 \quad \text{when } E < E_F$$

- Intrinsic semiconductor will act as insulator for  $0^\circ\text{K}$

**Case (2) :** At  $T = 300^\circ\text{K}$

$$f(E) = 0 \quad \text{when } E \gg E_F$$

$$f(E) = 1 \quad \text{when } E \ll E_F$$

- As temperature increases conduction increases in intrinsic semiconductor.

$$KT = 0.026 \text{ eV}$$

For  $E \gg E_C$ ,  $E - E_F \gg KT$  and equation reduces to  $f(E) = e^{-\frac{(E-E_F)}{KT}}$

$E_C$  = lowest energy level in the conduction band

### **1. Concentration of Electrons:**

The carrier density, i.e., the number of electrons available for conduction in Conduction band is

$$n = \int_{E_C}^{\infty} f(E) N(E) dE \approx N_C e^{-(E_C - E_F)/KT}$$

$n$  = equilibrium electron carrier concentration;  $N(E)$  = density of states;

$f(E)$  = Fermi function;  $k$  = Boltzmann's const.

$$N_c = 2 \left( \frac{2f m_n kT}{h^2} \right)^{3/2} (1.602 \times 10^{-19})^3$$

= effective density of states in conduction band

## 2. Concentration of Holes

The carrier (free holes) density, i.e., the number of holes available for conduction in Valence Band is

$$p = \int_{-\infty}^{E_c} (1 - f(E)) N(E) dE \approx N_v e^{-(E_F - E_c)/kT}$$

Where

$$N_v = 2 \left( \frac{2f m_p kT}{h^2} \right)^{3/2} (1.602 \times 10^{-19})^3 = \text{effective density of states in valence band}$$

## 3. Fermi Level In Intrinsic Semiconductor ( $E_F$ )

For an intrinsic semiconductor  $n = p$ ; So

$$N_c e^{-(E_c - E_F)/kT} = N_v e^{-(E_F - E_c)/kT}$$

$$\ln \frac{N_c}{N_v} = \frac{E_c + E_v - 2E_F}{kT}$$

Taking logarithm of both sides, we obtain

Hence

$$E_F = \frac{E_c + E_v}{2} - \frac{kT}{2} \ln \frac{N_c}{N_v}$$

If the effective masses of hole and free electron are the same,  $N_c = N_v$ , then

$$E_F = \frac{E_c + E_v}{2}$$

Hence Fermi level  $E_F$  lies in the middle of forbidden energy band for intrinsic semiconductor.

## 4. Current Density of a Semiconductor:

In an Intrinsic semiconductor with each hole – electron pair created, two charge carrying particles are formed. One is negatively charged free electron with mobility  $\mu_n$ , and the other is positively charged hole having mobility  $\mu_p$ .

The current density  $\mathbf{J}$  due to both electron and hole is given by

$$\mathbf{J} = (n \mu_n + p \mu_p) q \mathbf{E} = \sigma \mathbf{E}$$

Where  $n$  = magnitude of free – electron (negative) concentration

$p$  = magnitude of hole (positive) concentration

= conductivity;  $\mathbf{E}$  = electric field and  $q$  = electron charge

$\mu_n$  = Mobility of electron and  $\mu_p$  = Mobility of hole

For Intrinsic Semi conductor,  $n = p = n_i$ ,

so that  $\mathbf{J} = n_i (\mu_n + \mu_p) q \mathbf{E} = \mathbf{E}$  and Conductivity =  $n_i (\mu_n + \mu_p) q$

**Resistivity** : The resistivity ...is inversely proportional to the conductivity and is given by

$$\rho = 1/\sigma = 1/(n\mu_n + p\mu_p)q$$

The conductivity of Silicon (Germanium) will increase approximately (8+06)% percent per degree with increase in temperature.

Semi conductors have a negative temperature coefficient of resistance where as that of a metal is positive and of much smaller magnitude. For most metals the resistance increases about 0.4 percent /°C increase in temperature.

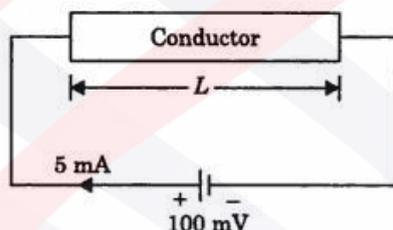
## 5. Variation of Mobility

### 1. Variation of Mobility with Temperature

The electron mobility is about three times the hole mobility it is due to mass of electron is less than mass of hole.

- The mobility  $\mu$  varies as  $T^{-m}$  over a temperature range of 100 to 400°K.  
 $m = 2.5$  (2.7) for electrons (holes) for silicon,  
 and  $m = 1.66$ (2.33) for electrons(holes)for germanium.

**Example 1.** A rectangular cross-section conductor has length/cross-sectional area ratio of  $700 \times 10^6 \text{ m}^{-1}$ . A current of 5 mA produces a voltage drop of 100 mV across the length. Determine the electron concentration given that the electron mobility is  $500 \text{ cm}^2/\text{V}\cdot\text{s}$ .



**Solution :** The given data is: Voltage  $V = 100 \text{ mV} = 0.1 \text{ V}$ ; Current  $= 5\text{mA} = 5 \times 10^{-3} \text{ A}$

$$\frac{\text{Length}}{\text{Cross-section}} = \frac{L}{A} = 700 \times 10^6 \text{ m}^{-1}.$$

$$\text{Mobility } \mu = 500 \text{ cm}^2/\text{V}\cdot\text{s} = 500 \times 10^{-2} \text{ m}^2/\text{V}\cdot\text{s};$$

We know that,

$$\rho = \frac{1}{\sigma} = \frac{L}{AR} \quad \left( \because R = \frac{\rho L}{A} \right)$$

$$= \frac{L}{A} \cdot \frac{I}{V} \quad \left( \because R = \frac{V}{I} \right)$$

$$= 3.5 \times 10^6 (\Omega\cdot\text{m})^{-1}$$

$$\text{and } n = \frac{\rho}{q\mu} = \frac{3.5 \times 10^6}{1.6 \times 10^{-19} \times 500 \times 10^{-4}} = 4.375 \times 10^{27} \text{ m}^{-3}$$

**Example 2.** A slice of intrinsic silicon bar is 3 mm long and has a rectangular cross-section  $50 \mu\text{m} \times 10 \mu\text{m}$ . At  $300^\circ\text{K}$ , determine the electric field intensity in the bar and the voltage across the bar when a steady current of  $2 \mu\text{A}$  is measured. Take the value of resistivity  $\rho = 2.30 \times 10^5 \text{ } \Omega\text{-cm}$  at room temperature ( $300^\circ\text{K}$ ).

**Solution:**

$$\text{As } J = \sigma E$$

$$\Rightarrow E = \frac{J}{\sigma} = \frac{I}{A} \dots = \frac{2 \times 10^{-6}}{(50 \times 10^{-6})(10 \times 10^{-6})} \cdot \frac{2.3 \times 10^5}{100} = 9.2 \times 10^6 \text{ V/m}$$

$$\text{Voltage across the bar } V_{\text{bar}} = EL = 27600 \text{ V}$$

### 6. Atomic concentration ( $n$ Atoms/ $\text{cm}^3$ ) of Silicon and Germanium :

Atomic concentration,  $n = (A_o d) / A \text{ atoms/cm}^3$

Where  $A$  = atomic weight ,  $d$  = density  $A_o$  = Avogadro number

For Germanium	For silicon
$A = 72.6$	$A = 28$
$d = 5.32 \text{ g/cm}^3$	$d = 2.33 \text{ g/cm}^3$
$A_o = 6.023 \times 10^{23} \text{ molecules/mole}$	$A_o = 6.023 \times 10^{23} \text{ molecules/mole}$
$n = A_o d / A = 4.4 \times 10^{22} \text{ atoms/cm}^3$	$n = A_o d / A = 5 \times 10^{22} \text{ atoms/cm}^3$

$n_{\text{Si}} > n_{\text{Ge}}$ , because atomic number of silicon is less than atomic number of Germanium.

### Mass Action Law

Regardless of the individual magnitudes of  $n$  and  $p$ , the product is always a constant at a fixed temperature which is called mass action law .

$$np = \text{constant}$$

For intrinsic material  $n = p = n_i$  , so that  $\boxed{np = n_i^2}$