

Electrical Conductivity in Solids

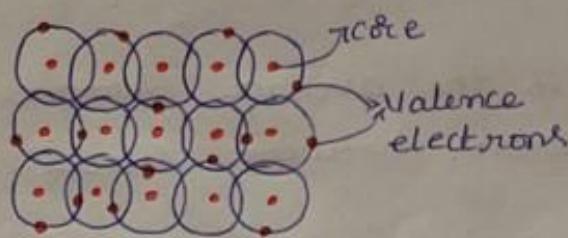
Review of classical free electron theory

Concept of Free electron / Drude - Lorentz Theory

All metal atoms consist of valence electrons. These valence electrons are responsible for electrical conduction in the bulk state of a metal.

We can consider the case of copper as an example for metals. A copper atom consists of 29 electrons out of which 28 electrons fill the first 3 shells & form the core part. The remaining lone electron of the atom will be present in the fourth shell & it is called as the valence electron of the copper atom. It is very loosely bound in the atom.

When a large number of copper atoms join to form a metal, the boundaries of the neighbouring atoms slightly overlap on each other. Due to such overlapping, though the core electrons remain unaffected, the valence electrons find continuity from atom to atom, and thus can move easily throughout the body of the metal.



Boundary overlapping

The free movement of electrons means that none of them belongs to any atom in particular, but each of them belongs to the metal to which they are confined to. Thus, each such electron is named a free electron. Since the free electrons are responsible for electrical conduction in a solid, they are also called conduction electrons.

Lattice: The disconnection of one electron from the parent atom, results in a virtual loss of one negative charge for that atom. Consequently, the electrical neutrality of the atom is lost & it becomes an ion. The structure formulation due to the array of such fixed ions in three dimension is called Lattice.

Thermal velocity (v_{th})

The velocity with which the free electrons keep moving due to thermal agitation is called thermal velocity.

Drift velocity (v_d)

When an electric field is applied, there will be a net displacement in the randomly moving free electron positions with time in a direction opposite to the direction of the field. This displacement per unit time is called drift velocity.

Mean free path (λ)

Mean free path is the average distance travelled by the conduction electrons between successive collisions with the lattice ions.

Mean collision time (τ)

The average time that elapses b/w two consecutive collisions of an electron with the lattice points is called mean collision time.

$$\tau = \frac{\lambda}{v}$$

$\lambda \rightarrow$ Mean free path

$v \rightarrow$ total velocity [Thermal velocity + Drift velocity]

Relaxation Time (T_r)

Relaxation time is the time required for the average velocity of free electrons to reduce to $(1/e)$ times its value that existed when the field is just turned off.

Current Density (J)

It is the current density per unit area of cross section of an imaginary plane held normal to the direction of current in a current carrying conductor.

$$J = \frac{I}{A} \text{ A/m}^2$$

$I \rightarrow$ current flowing in conductor

$A \rightarrow$ Area of cross section

Electric field (E)

The potential drop per unit length of a conductor is known as electric field.

$$E = \frac{V}{L}$$

$V \rightarrow$ potential difference b/w two ends

$L \rightarrow$ Length of a conductor of uniform cross section

Electrical Conductivity (σ)

It is a physical property that characterizes the conducting ability of a material. It is given by the inverse of resistivity.

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

$$\sigma = \frac{L}{RA}$$

Mobility of electrons (μ)

The mobility of electrons is defined as the magnitude of the drift velocity acquired by the electrons in a unit field.

$$\mu = \frac{v_d}{E}$$

$v_d \rightarrow$ Drift velocity

$E \rightarrow$ Applied field

Expression for Drift velocity is given by,

$$v_d = \frac{eE}{m} \tau$$

$$\therefore \mu = \frac{1}{E} \left(\frac{e\tau}{m} \right)$$

$$\boxed{\mu = \frac{e\tau}{m}}$$

Assumptions of free electron gas model

- 1) A metal contains a large number of free electrons which are free to move about in entire volume of the metal like the molecules of a gas in a container.

Hence they are assumed to obey the laws of kinetic theory of gases.

$$\frac{3}{2} kT = \frac{1}{2} m v_{th}^2$$

- 2) The free electrons move in random directions & collide with either positive ions fixed in the lattice or other free electrons. All the electrons are elastic & there is no loss of energy.

- 3) The free electrons are moving in a completely uniform potential field due to the ions fixed in the lattice.
- 4) The velocity & the energy distribution of free e^- s obey the classical Maxwell Boltzmann statistics.

Expression for the electrical conductivity

When an electric field ' E ' is applied to an electron of charge ' e ' of a metallic rod, the electron moves in opposite direction to the applied field with a velocity v_d .

Lorentz force acting on the electron,

$$F = eE \rightarrow ①$$

This force is known as the driving force of the electron.

Due to this force, the electron gains acceleration ' a '.

From Newton's second law of motion,

$$F = ma \rightarrow ②$$

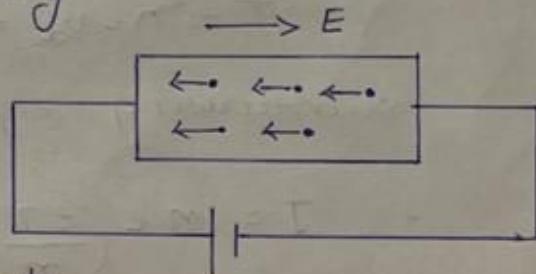
Equating eqns ① & ②, we get

$$ma = eE$$

$$a = \frac{eE}{m} \rightarrow ③$$

$$\text{Acceleration} = \frac{\text{Drift velocity}}{\text{Relaxation Time}}$$

$$a = \frac{v_d}{\tau}$$



$$v_d = a\tau \rightarrow ④$$

Substituting eqⁿ ③ in ④, we get

$$v_d = \left(\frac{e\tau}{m}\right) E \rightarrow ⑤$$

According to Ohm's law, current density can be expressed as,

$$J = \sigma E$$

$$\sigma = \frac{J}{E} \rightarrow ⑥$$

$\sigma \rightarrow$ Electrical conductivity of the electron.

But, the current density in terms of drift velocity is given as,

$$J = nev_d \rightarrow ⑦$$

Substituting eqⁿ ⑤ in ⑦, we get

$$J = ne \left(\frac{e\tau}{m}\right) E$$

$$\frac{J}{E} = \frac{ne^2\tau}{m} \rightarrow ⑧$$

Comparing eqⁿ ⑥ and ⑧, we get

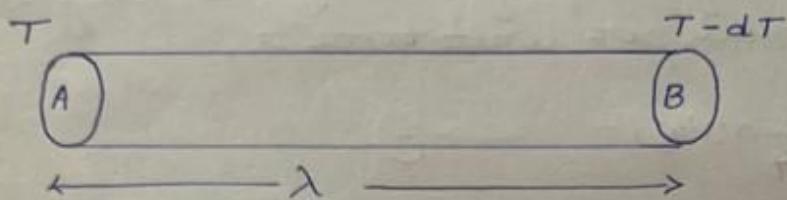
$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

Hence, the required expression.

Thermal Conductivity (K)

Thermal conductivity is defined as the amount of heat flowing per unit time through the material having unit area of cross-section per unit ~~temp~~ gradient.

Expression for Thermal Conductivity of a Metal



Consider two cross sections A and B in a uniform metallic rod AB separated by a distance λ. Let 'A' at a high temperature 'T' and 'B' at low temperature ($T - dT$). Now heat conduction takes place from A and B by the electrons.

Let the conduction electron per unit volume is n and average velocity of these electrons is v . During the movement of electrons in the rod, collision takes place. Hence, the electrons near 'A' lose their kinetic energy while electrons near 'B' gain kinetic energy.

Average Kinetic energy of an electron at A, is

$$KE_{(A)} = \frac{3}{2} K_B T \rightarrow ①$$

Average Kinetic energy of an electron at B, is

$$KE_{(B)} = \frac{3}{2} K_B (T - dT) \rightarrow ②$$

The excess of kinetic energy carried by the electron from A to B is,

$$\frac{3}{2} K_B dT \rightarrow ③$$

Number of electrons crossing per unit area per time from A and B is,

$$\frac{1}{6} nv$$

The excess of energy carried from (A to B) per unit area in time is $= \frac{1}{4} nv k_B dT \rightarrow ④$

Similarly, the deficient of energy carried from B to A per unit area per unit time is,

$$= -\frac{1}{4} nv k_B dT \rightarrow ⑤$$

Hence, the net amount of energy transferred from A to B per unit area per unit time is,

$$Q = \frac{1}{2} nv k_B dT \rightarrow ⑥$$

But from the basic definition of thermal conductivity, the amount of heat conducted per unit area per unit time is,

$$Q = K \frac{dT}{\lambda}$$

$$\text{ie } \frac{1}{2} nv k_B dT = K \frac{dT}{\lambda}$$

$$\therefore K = \frac{1}{2} nv k_B \lambda \rightarrow ⑦$$

We know that for the metals, $T = T_v$

$$T = \frac{\lambda}{v} \Rightarrow \lambda = T v \rightarrow ⑧$$

Substituting eqn ⑧ in ⑦, we get

$$K = \frac{1}{2} nv k_B (T v)$$

$$K = \frac{1}{2} nv^2 k_B T$$

Hence, the required expression

Density of States

The Density of states can be explained using quantum free electron theory.

According to quantum free electron theory, the electron is treated as wave and its energy and velocity is given by Fermi-Dirac distribution function. The electron must obey the pauli's Exclusion principle.

According to this theory, the energy of the particle (electron) is given by,

$$E_n = \frac{n^2 h^2}{8 m a^2} \rightarrow ①$$

The lowest energy of the particle is obtained by putting $n=1$, ie

$$E_1 = \frac{h^2}{8 m a^2}$$

Now, the density of state is defined as the number of electronic states per unit energy range.

WKT

$$E_n = \frac{h^2}{2m} \left(\frac{n}{2a} \right)^2 \quad [\text{From eq } ①]$$

Differentiating above eqⁿ,

$$dE_n = \frac{h^2}{2m} \left(\frac{n}{2a} \right) \frac{dn}{2a}$$

Where $\frac{dn}{dE_n}$ represents number of Energy level per unit energy.

$$\therefore g(E) = 2 \frac{dn}{dE_n} \rightarrow \text{Density of states of a free electron gas.}$$

Density of States $g(E)dE$

It is defined as the number of available electron states per unit volume in an energy interval E and $E+dE$. It is denoted by $g(E)dE$.

Carrier Concentration

The number of electrons per unit volume in a given energy interval is calculated by assuming the product of the density of states $g(E)$ & the occupation probability $F(E)$.

Such number of electrons per unit volume is known as carrier concentration.

$$n_e = \int g(E) F(E) dE$$

$$g(E) = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE$$

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

$$\therefore n_e = \int \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \frac{1}{1 + e^{(E-E_F)/kT}} dE$$

Wiedemann - Franz Law

The law states that the ratio of thermal conductivity to electrical conductivity of the metal is directly proportional to the absolute temperature of the metal.

WKT

$$\sigma = \frac{n e^2 \tau}{m} \rightarrow ①$$

$$K = \frac{1}{2} n v^2 k_B T \rightarrow ②$$

$$\frac{\text{Thermal conductivity}}{\text{Electrical conductivity}} = \frac{K}{\sigma} = \frac{\frac{1}{2} n v^2 k_B T}{n e^2 / m}$$

$$\frac{K}{\sigma} = \frac{1}{2} \frac{m v^2 k_B}{e^2} \rightarrow ③$$

WKT, Kinetic energy of an electron is given by

$$\frac{1}{2} m v^2 = \frac{3}{2} k_B T \rightarrow ④$$

Substituting eq. ④ in ③, we get

$$\frac{K}{\sigma} = \left(\frac{3}{2} k_B T \right) \frac{k_B}{e^2}$$

$$= \frac{3 k_B^2 T}{2 e^2}$$

$$= \frac{3}{2} \left(\frac{k_B}{e} \right)^2 T$$

$$\frac{K}{\sigma} = \kappa T$$

where $\kappa = \frac{3}{2} \left(\frac{k_B}{e} \right)^2$ is a constant if it is known as Lorentz number.

$$\therefore \boxed{\frac{K}{\sigma} \propto T}$$

Hence, it is proved that the ratio of thermal conductivity of a metal is directly proportional to the absolute temperature of the metal.

Limitations of Classical Free Electron Theory

- 1) The free electron theory completely fails to explain the heat capacity of conduction electrons & also electronic specific heat.
- 2) It fails to explain the superconducting properties of metals.
- 3) It fails to explain photo-electric, Compton effect & black body radiation.
- 4) Classical free electron model predicts the incorrect temperature dependence of σ .
- 5) It also fails to give correct mathematical expression for thermal conductivity.

Introduction to Semiconductors

Semiconductor

A semiconducting material has electrical conductivity considerably greater than that of an insulator but significantly lower than that of a conductor. The value of resistivity varies from 10^{-4} to 0.5 ohm metre.

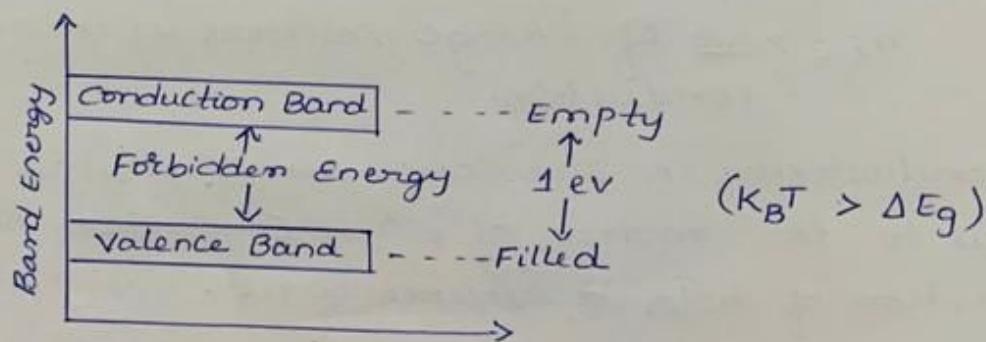
Properties of Semiconductor

- 1) The resistivity lies between 10^{-4} to 0.5 ohm meter.
- 2) At 0K, they behave as insulators.
- 3) The conductivity of a semiconductor increases both due to the temperature & impurities.
- 4) They have negative temperature coefficient of resistance.
- 5) In semiconductors both the electron & holes are charge carriers & will take part in conduction.

Types of Semiconductors

(i) Intrinsic Semiconductor

Semiconductor in a pure form is called intrinsic semiconductor.



At higher temperatures such that the thermal energy $K_B T$ is more than the Energy gap ΔE_g . Some of the valence electrons are also able to jump over the gap into the conduction band. This creates free electrons in the conduction band and free holes in valence band. Thus the electron-hole pairs are thermally generated & can carry a small current through the solid.

Therefore when the conductivity in crystalline semiconductor is only due to breaking of covalent bonds of electron in the valence band, then the substance is said to be intrinsic semiconductor.

The number of electrons in conduction band & the number of holes in valence band increase simultaneously with increase in temperature. So these semiconductors have negative temp coefficient.

No of electrons in conduction band (n) and no of holes in valence band (p) are always same.

$$\text{ie } n = p$$

$$n = p = n_i$$

$n_i \rightarrow$ No of charge carriers in intrinsic semiconductor.

Conductivity in intrinsic semiconductor is caused due to the motion of e^- s in conduction band and motion of holes in valence band.

Ex: Silicon, Germanium.

Fermi Level in an Intrinsic Semiconductor

The maximum energy that electrons may possess at 0 K is known as Fermi energy. The level corresponding to the Fermi energy is known as the Fermi level.

The position of Fermi level in an intrinsic semiconductor can be calculated in the following way that the Fermi level will be somewhere in the forbidden gap. Since all the valence band states are occupied and few electrons will be present in the conduction band.

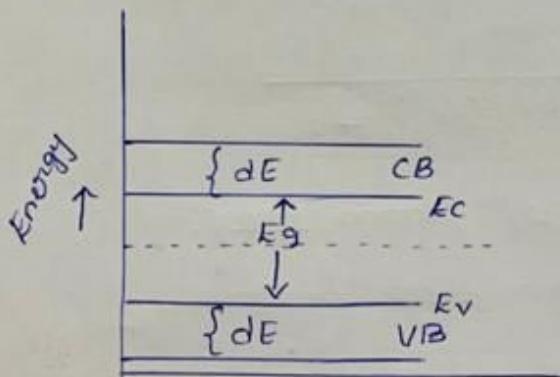
To check the position of Fermi level, a Fermi factor is introduced, which is the number that expresses the probability that a state of energy (E) is occupied by an electron under the condition of thermal equilibrium.

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

where $k \rightarrow$ Boltzmann Constant

$T \rightarrow$ Temp in Kelvin

$E_F \rightarrow$ Fermi level



The Energy Level E_C is conduction band & E_V is valence band which are symmetrically placed about the centre of the energy gap E_g .

The number of electrons in conduction band is

$$n(E_c) dE = g(E_c) f(E_c) dE \rightarrow ①$$

The number of holes in valence band is

$$p(E_v) dE = g(E_v) [1 - f(E_v)] dE \rightarrow ②$$

$g(E_c) = g(E_v)$ → Represents the no. of available states in conduction & valence region are same.

$f(E_c)$ & $f(E_v)$ → Represents the Fermi factor

$$\frac{n(E_c)}{p(E_v)} = \frac{f(E_c)}{[1 - f(E_v)]} \rightarrow ③$$

WKT $f(E_c) = \frac{1}{e^{(E_c - E_F)/k_B T} + 1}$ → Fermi factor

Since $E_c > E_F$, $\exp\left(\frac{E_c - E_F}{kT}\right) \gg 1$

$$\therefore f(E_c) = e^{-\left(\frac{E_c - E_F}{kT}\right)}$$

$$\& f(E_c) = e^{\left(\frac{E_F - E_c}{kT}\right)} \rightarrow ④$$

Similarly $E_v \rightarrow$ valence level is much below than E_F .

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

where $E_F - E_v \gg kT$ at room temp.

Hence the above expression becomes,

$$[1 - f(E_v)] \approx 1 - \left[1 - e^{\left(\frac{E_v - E_F}{kT}\right)} \right]$$

$$[1 - f(E_v)] \approx e^{\left(\frac{E_v - E_F}{kT}\right)} \rightarrow ⑤$$

\therefore eqⁿ ③ becomes,

$$\frac{n(E_c)}{p(E_v)} = \frac{e^{\left(\frac{E_F - E_c}{kT}\right)}}{e^{\left(\frac{E_v - E_F}{kT}\right)}}$$

Since $(E_c - E_F) \gg kT$ & $(E_F - E_v) \gg kT$ at room temperature,

$$\frac{n(E_c)}{n(E_v)} = \frac{E_F - E_c/kT}{E_v - E_F/kT} \rightarrow ⑥$$

For intrinsic semiconductor, $n_i = p_i$

$$\therefore \frac{n(E_c)}{p(E_v)} = \frac{n_i}{p_i} = 1$$

\therefore Eqⁿ ⑥ becomes

$$\frac{E_F - E_c}{kT} = \frac{E_v - E_F}{kT}$$

$$E_F - E_c = E_v - E_F$$

$$E_F + E_F = E_v + E_c$$

$$2E_F = E_v + E_c$$

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

This shows that Fermi level lies at the centre of energy gap for intrinsic semiconductor & it is independent of temperature.

Other form

For an intrinsic Semiconductor, the number of holes per unit volume in valence band is equal to number of electrons / unit volume in conduction band.

$$N_e = N_h$$

WKT

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

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

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

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

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

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

Taking natural logarithm on both sides, we get

$$\frac{2E_F - E_g}{kT} = \frac{3}{2} \ln \left(\frac{m_h^{*}}{m_e^{*}} \right)$$

$$2E_F - E_g = \frac{3}{2} kT \ln \left(\frac{m_h^{*}}{m_e^{*}} \right)$$

$$2E_F = \frac{3}{2} kT \ln \left(\frac{m_h^{*}}{m_e^{*}} \right) + E_g$$

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

under practical considerations, $m_e^* = m_h^*$, because of which the first term in the RHS of above equation goes to zero. Since $\ln 1 = 0$.

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

Thus, the Fermi level is in the middle of the band gap for an intrinsic semiconductor.

Extrinsic Semiconductors

The electrical conductivity of intrinsic semiconductors are very less. To increase the conductivity of intrinsic semiconductors, a small percentage of trivalent or pentavalent atoms are added to the pure semiconductor in the process of crystallization. Adding of impurities to the pure semiconductor is called as doping and it results in extrinsic semiconductor.

The conductivity of extrinsic semiconductor is much higher than pure semiconductor.

The impurity atom has a size which is almost of the same order of the host lattice. Basic structure of the crystal will not get altered after doping.

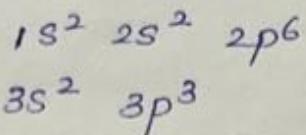
Types of Extrinsic Semiconductors

- 1) N-type
- 2) P-type

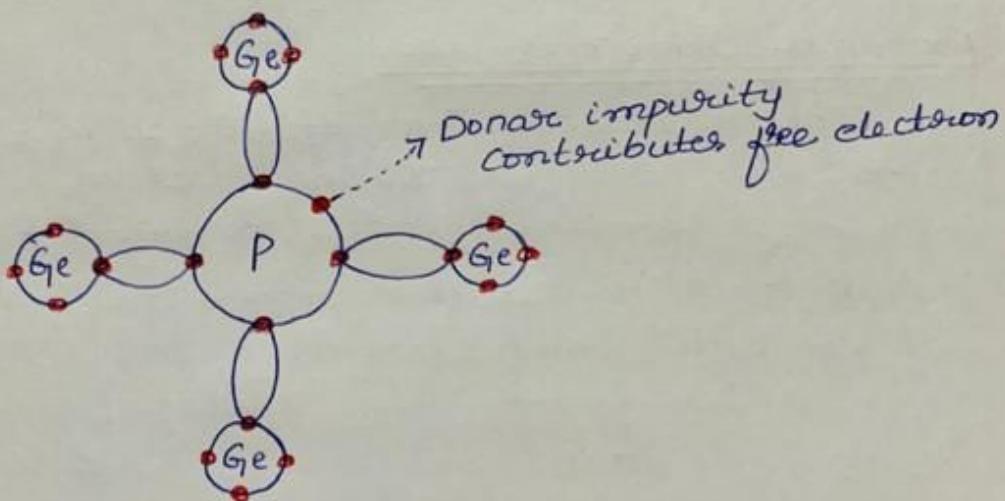
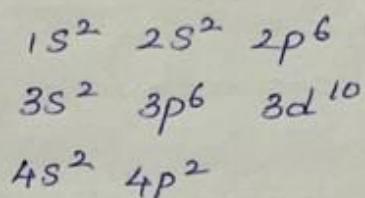
n-type Semiconductor

If a pentavalent impurity like phosphorous is introduced in the intrinsic semiconductor like Germanium, n-type semiconductor is obtained.

At no of phosphorous = 15



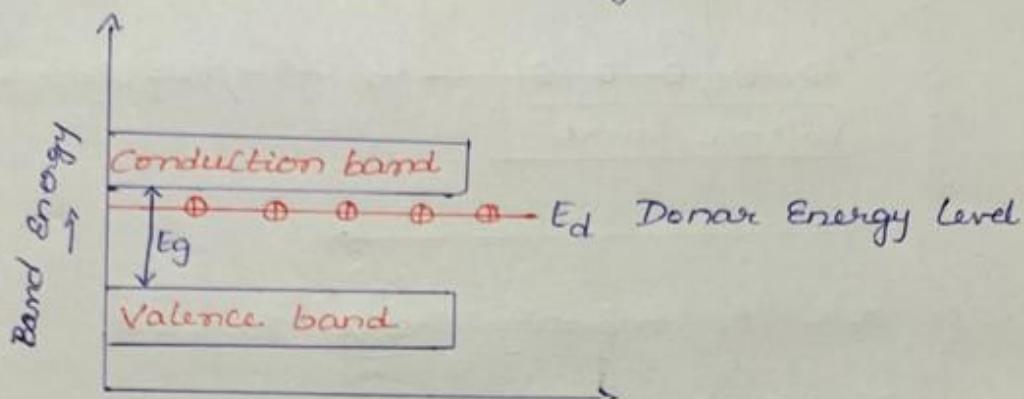
At no of Germanium = 32



out of 5 electrons of phosphorous, the 4 will form the covalent bond with the 4 electrons of Germanium, and 5th electron will be almost free. Thus every impurity atom contributes almost free electrons without creating a hole & these free electrons acts as carrier of current. A small amount of energy of Germanium is required to free the 5th electron from the impurity atom.

As these impurities donate excess electrons, so are called as donor impurities (n-type)

When donor impurities are added, the additional discrete levels are introduced just below the conduction band in the forbidden region (Energy gap). Electrons are the majority charge carriers.



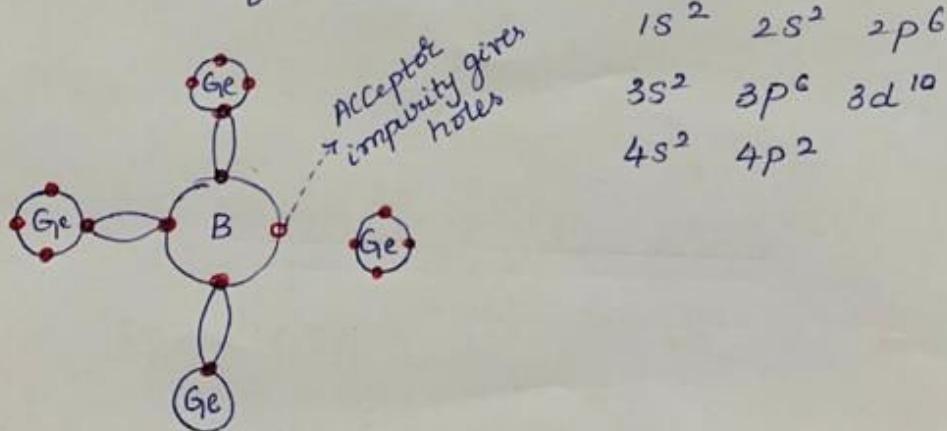
Ex: Sb, P, Bi and As

P-type Semiconductors

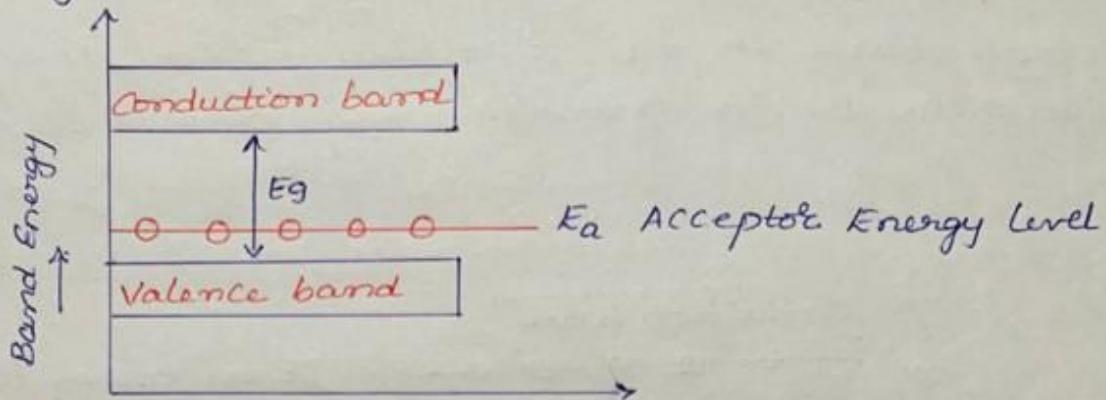
When trivalent impurity like Boron is added to the pure Germanium, results in p-type semiconductors. Here only 3 of the covalent bonds can be filled up and the vacancy that exist in the fourth bond contributes a hole.

At no of Boron = 5
 $1S^2 \ 2S^2 \ 2P^1$

At no of Germanium = 32



Triivalent impurity creates a hole called as acceptor impurity.



Holes are the majority charge carriers.

Ex: Ga, B, In, Al

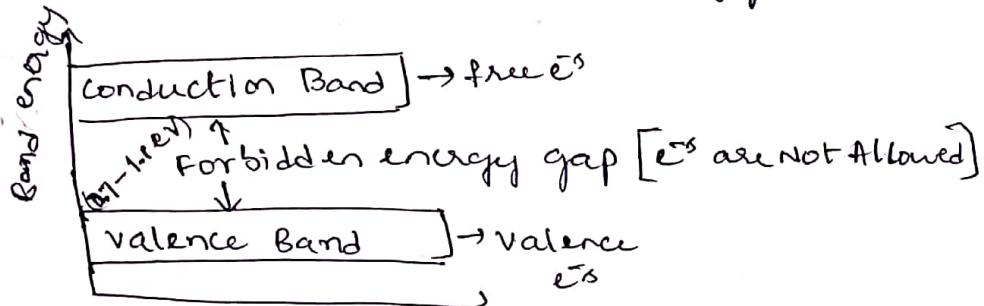
Introduction to Semiconductors

(1)

Semiconductors are materials which have a conductivity between conductors (generally metals) & insulators.

It depends on the forbidden energy bands.

"The range of energies possessed by an electron in a Solid' is known as energy bands.



Properties:

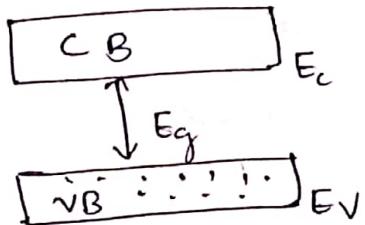
1. The Resistivity lies between 10^{-4} to $0.5\Omega \text{m}$
2. At OK, they behave as Insulators
3. The Conductivity of a Semiconductor increases both due to Temp & impurities
4. They have negative temp coefficient of resistance
5. In Semiconductor both the e^- & h^+ (holes) are charge carriers & will take part in conduction.

Types of Semiconductor

Intrinsic Semiconductor: Semiconductor in a pure form is called Intrinsic Semiconductor. Here the charge carriers are produced only due to thermal agitation.

they have low electrical conductivity.

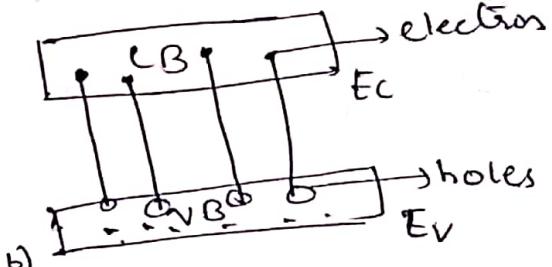
e.g. Si, Ge [elements of IV group of periodic table], ~~SiC~~ (Silicon Carbide), ~~GeAs~~ (Gallium Arsenide)



a) AT $T=0$

VB is completely filled

& CB is completely empty



b) At $T > 0$

some e^- s excited from VB to CB & holes appear in VB.

At $T=0K$ Intrinsic Semiconductor behaves as Insulators

At $T > 0$ (higher Temp) such that thermal energy $k_B T$ is more than that of energy gap ΔE_g . The excitation of e^- s from VB to CB takes place.

It creates equal no of holes in VB

& free e^- s in CB. Both holes & e^- s serve as charge carriers in electrical conductivity.

[hole \rightarrow empty space (energy levels) in VB]

For Intrinsic Semiconductor no of e^- s in CB (n) & no of holes in VB (p) are always same

mathematically, $n = p$

$n = p = n_i \xrightarrow{836}$ Intrinsic charge carriers

This leads to conduction & hole current.

Fermi Level in Semiconductor

(Q)

W.K.T. at $T=0\text{K}$ all the electronic states of the valence band are full & those of CB are empty. so, semiconductor behaves as insulator at 0K .

But as Temp increases some electrons from the VB get sufficient energy & become free. they move to CB & take part in conduction & give rise to conductivity in such

- * Now we want to discuss the phenomena quantum mechanically
→ classically all e^- have zero energy at 0K . but quantum mechanically e^- cannot have zero energy at 0K .

The maximum energy that electrons may possess at 0K is the Fermi energy (E_F)

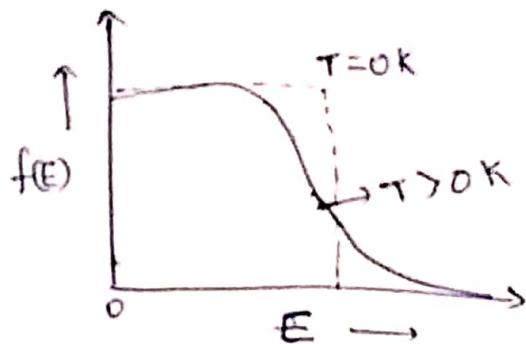
So, quantum mechanically, the electrons actually have energies extending from 0 to E_F at absolute zero Temp

Now in order to know how many of the electronic energy states in the valence Band & conduction band will be occupied at different Temperatures, we introduce a Fermi-factor ($f(E)$) or fermi function, which is the number that expresses the probability that a state of a given energy (E) is occupied by electrons under conditions of thermal equilibrium.

This number has a value between zero & unity & is a function of energy & Temp.

required: Set<Electrons>
equals: HashSet

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



$E \rightarrow$ given energy level

$E_F \rightarrow$ Fermi-energy level

$f(E) \rightarrow$ Fermi function

$K \rightarrow$ Boltzmann const, $T \rightarrow$ Absolute Temp

for (i) if $E \gg E_F$

(because $e^\infty = \infty$)

$$f(E) = \frac{1}{1+e^\infty} = 0$$

$$(ii) \quad E \ll E_F \quad f(E) = \frac{1}{1+\bar{e}^{-\infty}} = \frac{1}{1+0} = 1 \quad (\text{because } \bar{e}^{-\infty} = 0)$$

$$(iii) \quad E = E_F \quad f(E) = \frac{1}{e^0 + 1} = \frac{1}{2}$$

thus at $T=0K$, $f(E) = 1$, when $E < E_F$, which means all the levels below E_F , i.e., valence bands are filled up by electrons & $f(E)=0$, when $E > E_F$, that is (i.e.) all the electron levels above E_F i.e., conduction bands are empty.

Because, at 0K no heat energy is present, so no covalent bonds are being broken & the semiconductor behaves as insulator

(3)

Expression for Fermi-level in an Intrinsic Semiconductor

In an Intrinsic Semiconductor at a Temp well above 0K

~~choiceArray = (T[]) choices.toArray();~~

there are thermal electrons in the CB & equal number of holes in VB.

$$\text{i.e., } n_p = p_p \rightarrow (1)$$

$n_p \rightarrow e^-$ concentration
 $p_i \rightarrow$ hole conc

WKT electron concentration in CB is .

$$n_p = 2 \left(\frac{2\pi k_B T}{h^2} \right)^{3/2} (m_e^*)^{3/2} \exp\left(\frac{E_F - E_c}{k_B T}\right) \quad \hookrightarrow (2)$$

Also hole conc in VB is

$$p_p = 2 \left(\frac{2\pi k_B T}{h^2} \right)^{3/2} (m_p^*)^{3/2} \exp\left(\frac{E_v - E_F}{k_B T}\right) \rightarrow (3)$$

In Intrinsic Semiconductor

$$n_p = p_p = n_p$$

equate right hand sides

Hole = e^- = Intrinsic charges

$m_e \rightarrow e^-$ rest mass
 $m_p \rightarrow$ hole rest mass
 $E_v \rightarrow$ valence band energy
 $E_c \rightarrow$ CB energy
 $k \rightarrow$ Boltzmann Const
 $h \rightarrow$ Planck's const

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

$$(m_e^*)^{3/2} \exp\left(\frac{E_F - E_c}{k_B T}\right) = (m_p^*)^{3/2} \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

$$\frac{\exp\left(\frac{E_F - E_c}{k_B T}\right)}{\exp\left(\frac{E_v - E_F}{k_B T}\right)} = \left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$\frac{e^a}{e^b} = e^{a-b}$$

$$\exp\left(\frac{(E_F - E)}{k_B T} - \frac{(E_v - E_F)}{k_B T}\right)_{\text{RHS}} = \left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$\exp \left(\frac{E_F - E_C - E_V + E_F}{k_B T} \right) = \left(\frac{m_p^*}{m_e^*} \right)^{3/2}$$

$$\exp \left(\frac{2E_F - E_V - E_C}{k_B T} \right) = \left(\frac{m_p^*}{m_e^*} \right)^{3/2}$$

$$2 \frac{E_F - E_C - E_V}{k_B T} = \ln \left(\frac{m_p^*}{m_e^*} \right)^{3/2}$$

$$2E_F - E_C - E_V = (kT) 3/2 \ln \left(\frac{m_p^*}{m_e^*} \right)^{3/2}$$

when $m_p^* = m_e^*$

$(\ln 1 = 0)$
 $(E_C + E_V = E_g)$

$$2E_F - E_C - E_V = 0$$

$$2E_F = E_C + E_V$$

$$\text{or } E_F = \frac{E_C + E_V}{2} \quad \text{if } (E_F = \frac{E_g}{2})$$

Fermi level

In case $m_p^* = m_e^*$ then the Fermi level lies exactly in between VB & CB i.e. middle of the forbidden gap.
Or Energy gap.

However in general $m_p^* > m_e^*$, the Fermi level is raised slightly as T increases

Extrinsic Semiconductor

(1)

The electrical conductivity of intrinsic semiconductor is very small. To increase the conductivity of intrinsic semiconductor a small percentage of trivalent or pentavalent atoms (impurities) is added to the pure semiconductor in the process of recrystallisation, which is called doping & results the impure semiconductor being called extrinsic semiconductor.

The conductivity of extrinsic semiconductor is much higher, say for example 12 times than intrinsic semiconductor when an impurity is added 1 part in 10^8 .

The Impurity atom has a size which is almost of the same order of the host lattice. Since percentage of impurity atoms is very small, so every atom is surrounded by normal lattice. So basic structure of crystal will not get altered after doping.

There are two types of extrinsic Semiconductor

N-type & P-type.

N-type Semiconductor

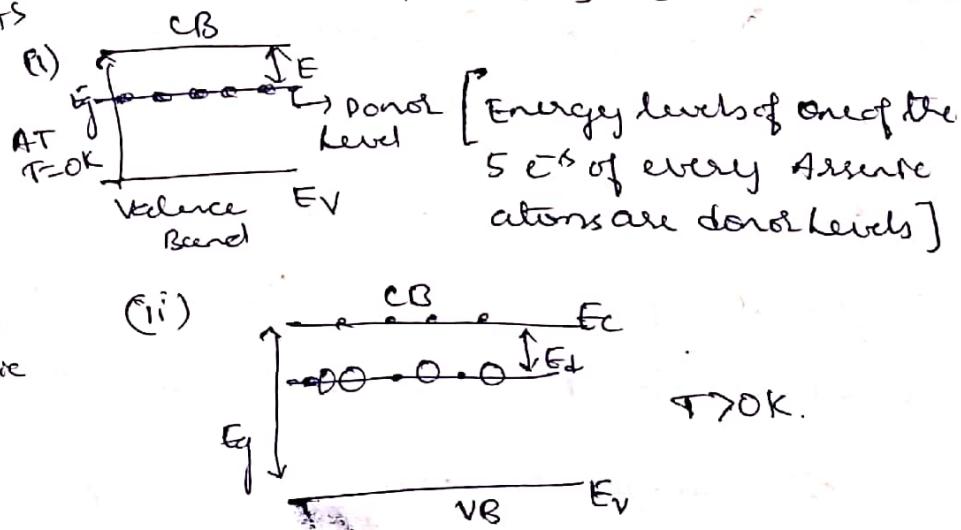
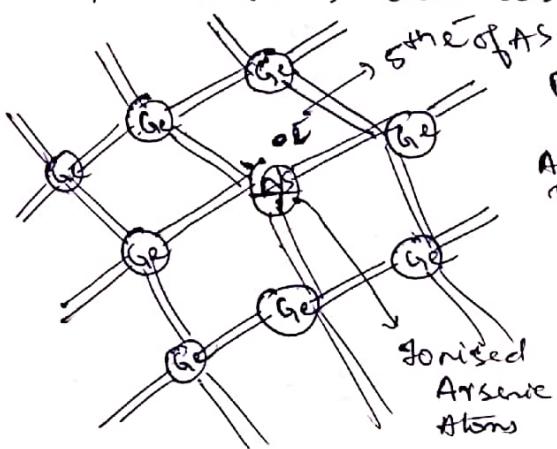
When intrinsic Germanium is doped. (It is a process of homogeneous mixing of a small quantity of known impurity into the host material) with one of the group V elements.

Since the host germanium atoms are tetravalent (4). only four of the five valence electrons of the

Impurity atoms are able to form covalent bond, leaving one electron weakly bound to its parent atom.

This electron can be easily excited into the CB by supplying an energy equal to $E_d = 0.013\text{eV}$.

This e⁻ leaves the atom & is free to move in the Germanium lattice. Such an e⁻ behaves as conduction e⁻.



In terms of band theory, the energy levels of 5 e⁻ of impurity atoms occupy positions between VB & CB as shown. These levels are at a distance E_d (0.013eV) below the CB.

At $T=0\text{K}$ all these levels are occupied but at even moderately low Temp most of the e⁻s move to CB becoz of small E_d . The remaining +ve charge (a hole) on Arsenic atoms is localized & does not take part in electrical conductivity.

The impurities are called donors which supply e⁻s without simultaneously creating holes. ∴ e⁻s are majority charge carriers & holes in VB is minority charge carriers. The semi-conductor doped with donor impurity is called n-type semiconductor.

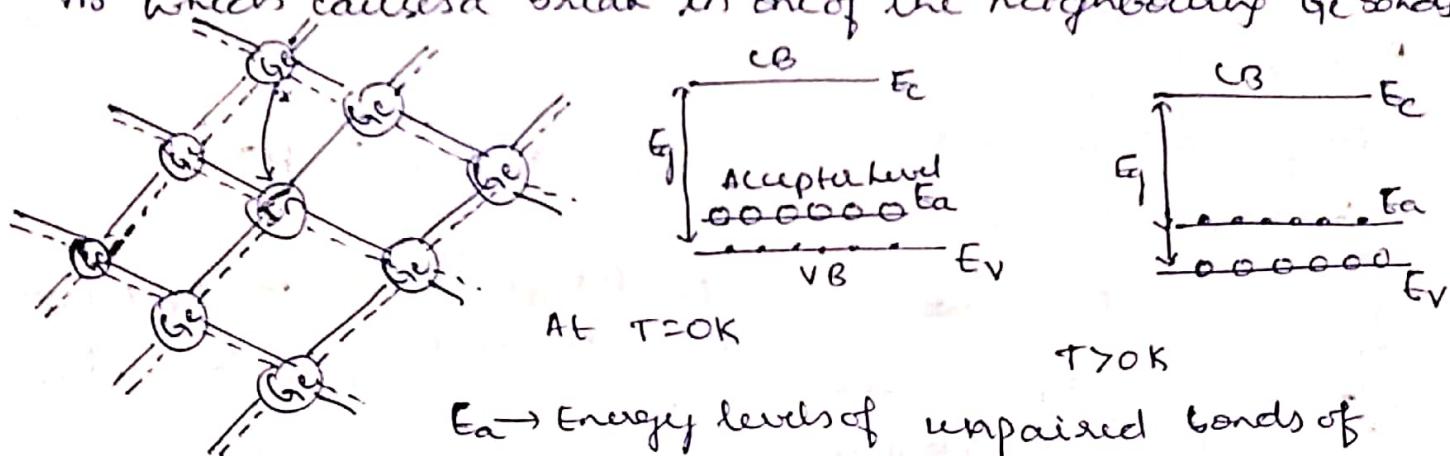
Ex!

p-type Semiconductor

(5)

When the Germanium/silicon is doped with a trivalent impurity such as Indium, it is found that impurity atoms occupy the sites normally occupied by Ge atoms. The Indium atom is short of one e^- to establish bonds with all the four nearest neighbours.

However, it can borrow the required e^- from a Ge atom if an energy equal to $E_a \approx 0.01\text{eV}$ is supplied to system. The transfer of an e^- from Ge atom leaves a hole in the VB which causes a break in one of the neighbouring Ge bonds.



$E_a \rightarrow$ Energy levels of unpaired bonds of Indium atoms are acceptor levels $\approx 0.01\text{eV}$

The impurities which trap e^- s & add holes to VB of parent atoms without simultaneously adding conduction e^- s are termed as acceptors.

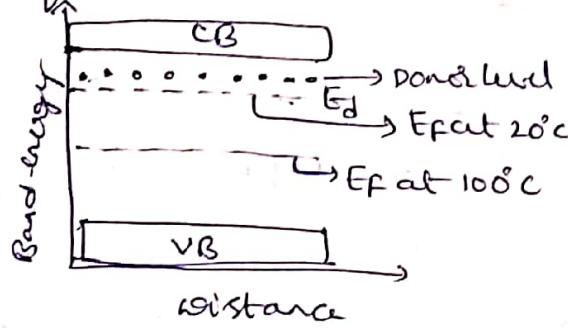
The semi-conductors doped with acceptor impurities are known as p-type semi-conductors.

In this case the holes are majority carriers in the VB & e^- s in CB (if any) are minority carriers.

Fermi-level in an Extrinsic Semiconductor

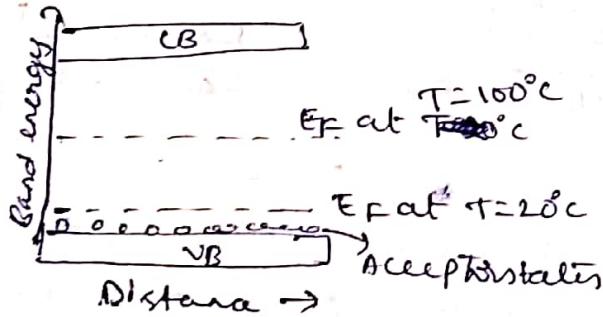
In an Intrinsic semi-conductor $(n = p) = n_i$
 $\cdot e^- = \text{holes}$

But in N-type extrinsic semi-conductor no of e^- is increased due to doping of pentavalent atoms $(N_e > n_i)$ & no. of holes is decreased by $(P_e < P_i)$



Why for P-type

No of electrons are decreased by $(N_e < n_i)$ & $(P_e > P_i)$



At low temp E_F lies closer to CB. $N_e > P_e$.

At high Temp E_F lies in between CB & VB.

for P-type ($P_e > P_i$) so E_F must move centre of E_g to closer to VB.

As the Temp rises the material becomes more & more intrinsic & Fermi level moves closer to Intrinsic position i.e., at the centre of Energy gap.

Charge carrier density in extrinsic Semiconductors

In both n-type & p-type semiconductors e^- which create the ions receive relatively higher energy than needed to create $(e-p)$ pairs. So it is possible to establish conductivity at low temp compare to Intrinsic. Hence the density of conduction e^- can be assumed to be equal to the density of Donor impurities (N_D). Likewise.

⑥

the density of holes in VB is equal to density of acceptor impurities (N_A).

It is to be noted that conc. of majority charges is increased over its intrinsic value by doping. The conc. of minority charges is found to decrease by by same amount to maintain conc. product $n_p^2 \cdot p = \text{const.}$

is, $n_p p_p = n_i^2 \xrightarrow{\text{mass Action Law}} (n_p p_p = n_i^2)$

where $n_i \rightarrow$ Intrinsic e density

$n_p, p_p \rightarrow$ e & hole densities in P-type material.

Based on the above considerations, the amount of reduction in minority charges can be determined by use of eqn expressing overall charge neutrality of material is.

$$p + N_D = n + N_A \xrightarrow{} (1)$$

Now use eqn (1) $n p = n_i^2$ we have

$$n = \frac{n_i^2}{p} \quad \& \quad p = \frac{n^2}{n_i}$$

So, eqn (2) becomes

$$p + N_D = \frac{n_i^2}{p} + N_A$$

$$p^2 + (N_D - N_A)p - n_i^2 = 0 \xrightarrow{} (3)$$

If it is n-type semiconductor

$$N_A = 0 \quad \& \quad n \gg p$$

$$\therefore N_D \approx n$$

where $n_n \rightarrow$ e conc in n-type
 $p_n \rightarrow$ hole conc in p-type

From mass action law $n \cdot p = n_i^2 \Rightarrow p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D}$
 Now for P-type $N_D = 0 \quad p \gg n \quad , \quad N_A \approx p$

$$n_p = \frac{n_i^2}{p_p} = \frac{n_i^2}{N_A}$$

consider eqn (2)

$$p + N_D = \frac{n_i^2}{p} + N_A$$

where
 $n = \frac{n_i^2}{p}$
 $N_D \rightarrow$ Donor conc
 $N_A \rightarrow$ Acceptor conc

$$p^2 + (N_D - N_A)p - n_i^2 = 0 \quad \rightarrow (3)$$

This is similar to quadratic eqn of the form $ax^2 + bx + c = 0$

$$\left\{ \begin{array}{l} n = -b \pm \sqrt{b^2 - 4ac} \\ 2a \end{array} \right.$$

$$\therefore p = \frac{(N_A - N_D)}{2} \pm \sqrt{\left(\frac{N_A - N_D}{4}\right)^2 + n_i^2} \quad \rightarrow (4)$$

$$p = \frac{(N_A - N_D)}{2} \pm \frac{1}{2} \sqrt{\left(\frac{N_A - N_D}{4}\right)^2 + n_i^2} \quad \rightarrow (5)$$

for Intrinsic sc $N_A = N_D = 0 \Rightarrow n = p = n_i$

case I n-type: $N_D \gg n_i \Rightarrow N_A \approx 0$

$$\therefore \text{eqn (5)} \Rightarrow p_n = -\frac{N_D}{2} + \sqrt{\frac{N_D^2}{4} + n_i^2}^{1/2}$$

$$p_n = -\frac{N_D}{2} + \frac{N_D}{2} \left(1 + \frac{4n_i^2}{N_D^2} \right)^{1/2} \quad \rightarrow (6)$$

Second term under radical is less than unity expand in power series

$$p_n = -\frac{N_D}{2} + \frac{N_D}{2} \left(1 + \frac{1}{2} \left(\frac{4n_i^2}{N_D^2} \right) \pm \dots \right)$$

$$p_n = -\frac{N_D}{2} + \frac{N_D}{2} \left(1 + 2 \frac{n_i^2}{N_D^2} \right) = \frac{n_i^2}{N_D} \quad \rightarrow$$

$$\boxed{p_n = \frac{n_i^2}{N_D}} \rightarrow (7)$$

Similarly

$$n_n = \frac{N_D}{2} + \frac{N_D}{2} \left(1 + 2 \frac{n_i^2}{N_D^2} \right) = N_D + \frac{n_i^2}{N_D}$$

Fermi level in Intrinsic - Semiconductors

In Intrinsic Semiconductors

$$N_e = N_h \rightarrow \text{Rep. concentration of electrons}$$

\downarrow holes.

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

after cancellation,

$$(m_e^*)^{3/2} e^{\frac{(E_F - E_g)}{kT}} = (m_h^*)^{3/2} e^{-\frac{(E_F - E_g)}{kT}}$$

$$\frac{e^{\frac{(E_F - E_g)}{kT}}}{e^{-\frac{(E_F - E_g)}{kT}}} = \left(\frac{m_h^*}{m_e^*} \right)^{3/2} \quad \left. \begin{array}{l} m_h^* + m_e^* \text{ is } 1 \text{ a.u.} \\ \text{effective mass of} \\ \text{holes + electrons} \end{array} \right\}$$

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

Taking natural log on both sides.

$$\frac{2E_F - E_g}{kT} = \frac{3}{2} \ln \left(\frac{m_h^*}{m_e^*} \right)$$

$$2E_F - E_g = \frac{3}{2} \ln \left(\frac{m_h^*}{m_e^*} \right) kT$$

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

$$\text{as } m_h^* = m_e^* \quad (\because \ln 1 = 0)$$

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

$$\boxed{E_F = E_g/2}$$

charge carrier density or carrier concentration,
denotes - the number of charge carriers in per volume

Carrier Concentration in Intrinsic Semiconductor

Inside a semiconductor, e & holes are generated with thermal energy. The electron & hole concentration at temperature T_k . in intrinsic semiconductor $n = p = n_i$, where n_i is called intrinsic semiconductor.

Also the product $n_p = n_i^2$ — (1)

where $n = n_c = 2 \left(\frac{2\pi m_e^+ k T}{h^2} \right)^{3/2} e^{-(E_c - E_F)/kT}$

$$p = n_v = 2 \left[\frac{2\pi m_h^+ k T}{h^2} \right]^{3/2} e^{-(E_F - E_v)/kT}$$

$$n = N_c e^{-(E_c - E_F)/kT}, \quad p = N_v e^{-(E_F - E_v)/kT}$$

on substituting n & p in eqⁿ(1).

$$n_i^2 = (N_v N_c) e^{-(E_F - E_v)/kT} \cdot e^{-(E_c - E_F)/kT}$$

$$n_i^2 = (N_v N_c) e^{-(E_F - E_v + E_c - E_F)/kT}$$

$$n_i^2 = (N_v N_c) e^{-(E_c - E_v)/kT}$$

$$n_i^2 = (N_v N_c) e^{-[E_g]/kT}$$

$$\text{or } n_i^2 = [N_v N_c]^{1/2} e^{-E_g/2kT}$$

Substituting N_v & N_c

$$n_i = 2 \left[\frac{2\pi k T}{h^2} \right]^{3/2} [m_h^+ \cdot m_e^+]^{3/4} e^{-E_g/2kT}$$

If $m_e^+ = m_h^+ = m$ is the rest mass of e^- . the eqⁿ becomes

$$n_i = 2 \left[\frac{2\pi k T \cdot m}{h^2} \right]^{3/2} e^{-E_g/2kT}$$

$$\Rightarrow n_i = 2 \left[\frac{2\pi m k}{h^2} \right]^{3/2} T^{3/2} e^{-E_g/2kT}$$

$$n_i = 2 \left(\frac{2\pi m k}{h^2} \right)^{3/2} T^{3/2} e^{-E_g/2kT}$$

$$n_i = C T^{3/2} e^{-E_g/2kT}$$

$$C = 2 \left(\frac{2\pi m k}{h^2} \right)^{3/2} = 4.83 \times 10^{21}$$

carrier concentration [Extrinsic Semiconductors]

As in fair production $n = p = n_i$

Also the product $n p = n_i^2 \rightarrow \textcircled{1}$

n_i - intrinsic concentration.

Suppose N_D & N_A are concentration of donor atom in n-type semiconductor and concentration of acceptor atom in p-type semiconductor.

n-type: Since in n-type semiconductor, majority charge carriers are electrons.
The hole concentration will be less as comparison to electron concentration. If electron concentration is equal to donor atom concentration. i.e

$$n = N_D$$

substituting in $\textcircled{1}$

$$p = \frac{n_i^2}{n}$$

p-type - majority charge carrier are holes. the electron concentration 'n' in comparison to holes is less. Hole concentration is equal to the acceptor atoms in p-type

$$p = N_A$$

substituting in $\textcircled{1}$

$$n = \frac{n_i^2}{p} . \underline{\hspace{2cm}} \times \underline{\hspace{2cm}} \times \underline{\hspace{2cm}}$$

Law of Mass action

The product of electron and hole concentrations, for a given material, is constant at a given temperature.

$$n_e \times n_p = 4 \left(\frac{2\pi k_B T}{h^2} \right)^3 (m_e^* m_h^*)^{1/2} \exp\left(\frac{-E_g}{k_B T}\right)$$

= constant at constant temp.

If impurity is added to increase 'n', there will be corresponding decrease in 'p', so that product 'np' remains constant. This is known as law of mass action.

∴ In an intrinsic semiconductor

$$\boxed{n_p = n_i p_i = n_i^2}$$

The product 'np' remains constant for a semiconductor irrespective of its being extrinsic or intrinsic.

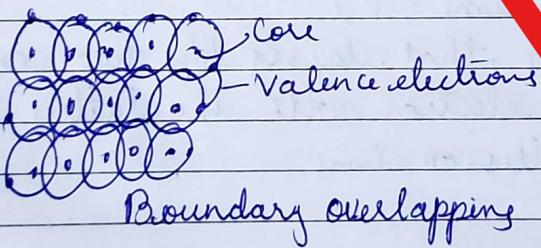
Unit - II Electrical Conductivity in Solids

* Concept of Free electron / Drude-Lorentz Theory

All metals atoms consists of valence electrons. These valence electrons are responsible for electrical conduction in the bulk state of a metal.

We can consider the case of copper as an example for metals. A copper atom consists of 29 electrons. Out of which 28 electrons fill 3 s shells & forms the core part. The remaining lone electron of the atom will be present in the fourth shell & it is called valence electron of copper atom. It is very loosely bound in the atom.

When a large no. of copper atoms join to form a metal, the boundaries of the neighbouring atoms slightly overlap on each other. Due to such overlapping through the core electrons find continuity from atom to atom and thus can move easily throughout the body of the metal.



The free movement of electrons means that none of them belongs to any atom in particular, but each of them belongs to the metal to which they are confined to. Thus each such electron is named a free electron since the free electrons are responsible for electric

condition in a solid, they are also called conduction electrons

- * Lattice

- * Thermal velocity : (v_{th})

The velocity with which the free electrons keep moving due to thermal agitation is called thermal velocity.

- * Drift velocity (v_d)

When an electric field is applied, there will be a net displacement in randomly moving free electrons positions with time in direction opposite to the direction of the field. This displacement per unit time is called drift velocity

- * Mean free path (λ)

Mean free path is the avg. distance b/w successive collision with lattice ions.

- * Mean collision time (τ)

The avg. time that elapses b/w two consecutive collisions of an electron with the lattice points is called mean collision time

$$\tau = \frac{\lambda}{v}$$

$\lambda \rightarrow$ Mean free path

$v = v_{th} + v_{drift}$

* Relaxation time (T_1)

Relaxation time is the time required for the avg velocity of free electrons to reduce to ($\frac{1}{e}$) times its value that existed when the field is just turned off.

* Current density (j)

It is the current density per unit area of cross section of an imaginary plane held normal to the direction of current in a current carrying conductor

$$j = \frac{I}{A} \quad \text{S/m}$$

$I \rightarrow$ Current flowing in conductor

$A \rightarrow$ Area of cross section

* Electric field (E)

The potential drop per unit length of a conductor is known as electric field

$$E = \frac{V}{L}$$

* Electrical conductivity (σ)

It is a physical property that characterizes the conducting ability of a material. It is given by the inverse of resistivity

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

$$\sigma = \frac{L}{RA}$$

* Mobility of electrons (μ)

The mobility of electrons is defined as the magnitude of the drift velocity acquired by the electrons in a unit field.

$$\mu = \frac{V_d}{E}$$

V_d → Drift velocity
 E → Applied field

Expression for drift velocity is given by

$$V_d = \frac{eE}{m} T$$

$$\therefore \mu = \frac{e}{m}, \mu = \frac{1}{k} \left(\frac{eT}{m} \right)$$

$$\boxed{\mu = \frac{eT}{m}}$$

* Assumptions of free electron gas model

(i) A metal contains a large number of free electrons which are free to move about in entire volume of the metal like the molecules of a gas in a container.

Hence they are assumed to obey the laws of kinetic theory of gases.

$$\frac{3}{2} kT = \frac{1}{2} m v_{th}^2$$

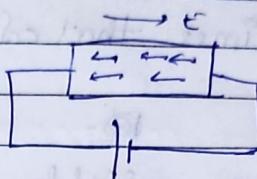
(ii) The free electrons move in random directions & collide with either positive ions fixed in the lattice or other free electrons.

- (iii) The free electrons are moving in a completely uniform potential field due to the ions fixed in the lattice
 (iv) The velocity & the energy distribution of free e⁻s obey the classical Maxwell-Boltzmann

* Expression for the ^{electrical} conductivity

Lorentz force acting on the electron

$$F = eE \rightarrow ①$$



From Newton's 2nd law

$$F = ma \rightarrow ②$$

Equating ① & ②

$$eE = ma$$

$$a = \frac{eE}{m} \rightarrow ③$$

$$\text{Acceleration} = \frac{Vd}{T}$$

$$Vd = aT \rightarrow ④$$

Sub. eqn ③ in ④, we get

$$Vd = \left(\frac{eT}{m} \right) E \rightarrow ⑤$$

According to Ohm's Law, Current density can be expressed as

$$J = \sigma E$$

$$\sigma = \frac{J}{E} \rightarrow ⑥$$

* Numericals on electrical conductivity

Q Calculate the total no. of energy states per unit volume in silicon b/w the lowest level in the conduction band & in level KT above at $T = 300K$, the effective mass of the electron in conduction band is 1.08 times that of a free electrons.

Soln: $T = 300K$ $\textcircled{a}:$

The no. of available states b/w E_c & $[E_c + KT]$
given by $E - E_c = KT$

$$1.38 \times 10^{-23} \times 300 \\ = 4.14 \times 10^{-21} \text{ J}$$

$$n = \frac{(8\pi m_e^*)^{3/2}}{3h^3} [E - E_c]^{3/2}$$

$$n = \frac{8\pi m_e^*}{3 \times (6.626 \times 10^{-34})^3} [4.14 \times 10^{-21}]^{3/2}$$

$$n = 2.11 \times 10^{25}$$

Q Calculate the probability that an energy band
 (a) kT (b) $3kT$ (c) $10kT$

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

where $(E - E_c) = kT = P(E)$

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

Reduce to form

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

(ii) $3KT$

$$f(E) = \frac{1}{e^{\frac{3KT}{KT}} + 1} = \frac{1}{e^3 + 1}$$

$$= 0.047$$

$$(iii) \frac{1}{e^{\frac{10KT}{KT}} + 1} = 4.5 \times 10^{-5}$$

Q The fermi level in a Semiconductor is 0.35 eV above the valence band. What is the probability of non-occupation of energy state at the top of the valence band?

(a) 300 K (b) 400 K

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

~~$$= 1 - \frac{1}{e^{(0.35)/e^{(EV)}} + 1}$$~~

$$= 1 - \frac{1}{e^{(\frac{0.35}{0.0257})} + 1}$$

$$= 1.353 \times 10^{-6}$$

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

$$0.35 \times 10^{-5}$$

$$\textcircled{b} \quad 3.9 \times 10^{-5}$$

Q for copper at 1000K

(a) Find the energy at which the probability $p(E)$ that a conduction electron state will be occupied is 90%

(b) For this energy, what is the value of $n(E)$, the distribution in energy of available states. For the same energy, what is $n_0(E)$

Sol: Fermi factor

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

$$f(E) = 0.90$$

$$E_C = E_F + \frac{(E-E_F)/kT}{0.9}$$

$$0.9 = \frac{1}{e^{(E-E_F)/kT}}$$

$$e^{(E-E_F)/kT} = \frac{1}{0.9} - 1$$

$$e^{(E-E_F)/kT} = 0.1$$

$$\frac{E - E_f}{kT} = \ln 0.111$$

$$E = E_f + kT \ln(0.11)$$

$$= 0.76 \times 1.6 \times 10^{-19} + 1.38 \times 10^{-23} \times 1000 \ln(0.11)$$

$$E_f = 0.76 \text{ eV} \quad (\text{Given})$$

(Gauge)

$$E = 6.87 \text{ eV}$$

$$\textcircled{a} \quad n(E) = \frac{\pi m_e^{3/2}}{h^3} \frac{2}{\pi} \left(\frac{E}{2}\right)^{1/2}$$

$$= \frac{\pi (9.11 \times 10^{-31})^{3/2}}{(6.63 \times 10^{-34})^3} \frac{2}{\pi} (6.87 \times 1.6 \times 10^{-19})^{1/2}$$

$$n(E) = 1.78 \times 10^{28} \text{ m}^{-3} \text{ eV}^{-1}$$

Q An intrinsic semiconductor has energy gap

$$\textcircled{b} \quad 0.74 \text{ eV} \quad \textcircled{c} \quad 0.71 \text{ eV}$$

Calculate the probability of E_f at CB

- (a) 0°C (b) 50°C (c) 100°C

Sol: $f(E) = \frac{1}{e^{(E-E_f)/kT} + 1}$

~~$$f(E) = \frac{1}{e^{(0.76 + 6.87 \times 10^{-19}) / (1.38 \times 10^{-23} \times 273)} + 1}$$~~

~~$$f(E) = 0.25 \quad 8.0 \times 10^{-14} \quad 9.873 \times 10^{-8}$$~~

$$f(E) = \frac{1}{e^{\frac{(E - 0.2) \times 1.6 \times 10^{-9}}{kT}} + 1}$$

$$f(E) = 2.07 \times 10^{-4}$$

$$f(E) = \frac{1}{e^{\frac{(E - 0.2) \times 1.6 \times 10^{-9}}{kT}} + 1}$$

$$f(E) = 7.64 \times 10^{-4}$$

$$f(E) = \frac{1}{e^{\frac{(E - 0.2) \times 1.6 \times 10^{-9}}{kT}} + 1}$$

$$= 2 \times 10^{-4}$$

- Q Calculate the energy level at conduction band for Silicon, the Fermi level 0.6 eV
 Also calculate the probability of function for $f(E)$ at $T = 273\text{ K}$