ELECTRONIC DEVICES

ELECTRONICS

The branch of Science & engineering that deals with the flow of electrons through vaccum or gas or semiconductor is known as electronics.
Electronics is a branch which deals the flow of electronic devices & their utilization.

APPLICATION OF ELECTRONICS

Electronics plays a very important role in almost every sphere of our life. It has penetrated in every field. Some of the important applications of electronics are:-

a.) Communication & Entertainments:-
→ Telegraphy & telephony, Radio & TV Broadcasting
→ Recoders, record players, stereo systems etc. are other electronic gadgets used in entertaiments.

b.) Industrial Application:-
→ Automatic control circuits (electronic circuits) are used invariably in industries
→ eg:- lighting system, sound system, automatic door openers, saftey devices etc.

c.) Defence Applications:-
→ communication systems plays an important role during the war days.
example:- RADAR (Radio detection & Ranging) (with help of RADAR exact location of aircraft can be determined), anti-aircrafts guns & guided missiles etc.

d.) Application in Medical Science:-
(i) Electron microscope for analysing blood etc.
(ii) ECG
(iii) X-Ray
(iv) Oscilloscopes (for the display of heartbeat)

(e) Applications in automobiles :-

→ more and more electronic equipments are used in cars for charging of battery, power assists funcns, control of engine performance etc.

→ most important application in automobiles is electronic ignitation

(f) Digital Electronics :-

→ circuit for digital applications opereate with pulses of voltage or current

→ A pulse waveform is either completly ON or OFF because of the sudden changes in amplitude

eg :- digital clocks, calculators, computers etc.

(g) Instrumentation :-

→ CRO, freq. counter signal generator, p-H meter, strain gauges etc. are the electronic instruments widely used in reserach operations

ELECTRICAL COMPONENTS

All the electronic circuits (simple to complex) contains a few basic components such as resistor, capacitor, inductors & semiconductor devices.

Classification / Types → Passive components
→ Active components

Passive components :- The electronic components which are not capable of amplyfying or processing an electrical signals are called passive components
eg :- resistors, capacitors & inductors.

Active components :- The electronic components which are capable of amplyfying or processing an electrical signals are called active components
eg :- vaccum tubes, gas tubes, & semiconductor devices.

ATOMIC STRUCTURE

ATOM:- All the materials are composed of very small particles known as atoms.

NUCLEUS:- It is the central part of an atom and contains protons & neutrons. A proton is +vely charged particle while neutron has same mass as that of proton but has no charge.

Therefore nucleus of the atom is always +vely charged.

EXTRA NUCLEUS:- It is the outer part of an atom & contains electrons only.

ATOMIC NUMBER:- The no. of electrons or protons in an atom is called atomic no.

Atomic no. = no. of p^+ or e^- in an atom.

Arrangement of Electrons in any orbit

1.) The no. of electrons in any orbit is given by $2n^2$, where 'n' is the no. of the orbit.

eg:- First orbit contains $= 2 \times 1^2 =$ 2 electrons
2nd orbit contains $= 2 \times 2^2 =$ 8 electrons
3rd " " $= 2 \times 3^2 =$ 18 electrons

Properties of an Electron :-

→ charge on an electron, $e = 1.602 \times 10^{-19} C$
→ Mass of an electron, $m = 9.0 \times 10^{-31}$ kg
→ Radius of an electron, $r = 1.9 \times 10^{-15}$ m

Energy of an Electrons :-

Electron moving around the nucleus possesses two types of energies
(i) K.E. due to its motion
(ii) P.E. due to the charge on the nucleus.

Total energy = K.E + P.E.

→ Energy of an electron increases as its distance from the nucleus increases. Electron in last orbit possesses very high energy as compared to the electrons in the inner orbits.

The K.E. of the electron is given by:-

$$K = \frac{1}{2}mv^2 = \frac{Ke^2}{2r}$$

The P.E. of electron proton system is:-

$$U = \frac{-Ke^2}{r}$$

$$\underset{(n^{th}\,state)}{T.E} = K + U = \frac{Ke^2}{2r_n} - \frac{Ke^2}{r_n}$$

$$E_n = \frac{-Ke^2}{r_n}$$

$$\boxed{E_n = \frac{-13.6}{n^2}\ eV}$$ orbital energy or binding energy of the electron for nth orbit.

Valence Electrons

The electrons in the outermost orbit of an atom are known as valence electrons. The valance electrons determine the physical, chemical & electrical properties of the material.

On the basis of electrical conductivity, materials are generally classified into conductors, insulators & semiconductors.

- when the no. of valance electrons of an atom is less than 4, the material is usually a metal and a conductor.

eg:- Na, Mg and Al, which have 1, 2 and 3 valence electrons.

- When the no. of valence electrons of an atom is more than 4, the material is usually a non-metal and an insulator.

  eg:- nitrogen, sulphur & Neon which have 5, 6 or 8 electrons (Valence)

- When the no. of valence electrons of an atom is 4, the material has both mettalic as well as non-mettalic character and is usually a semiconductor.

  Eg:- Ge and Silicon.

Free Electrons

The Valance electrons which are loosely attatched to the nucleus are known as free electrons.

- conductor has a large no. of free electrons.
- insulators has practically no free electron at ordinary temp.
- semiconductor is a substance which has very few free electrons at room temp.

Hole

A vacancy left in the Valance band because of shifting of an electron from Valance band to conduction Band is known as hole.

ENERGY BANDS IN SOLIDS

1) Valance Band:-

The electrons in the outermost orbit of an atom are known as valence electrons. Under normal cond's of atom, valance band contains the electrons of highest energy. This band may be filled completely or partially.

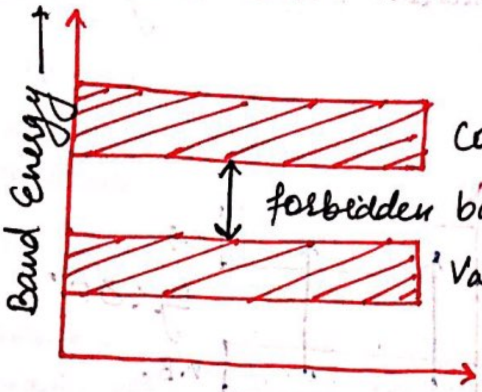
The energy band which possesses the valance electrons is called valance band.

2) Conduction Band:-

* In some of the materails (eg. metals) electrons are loosely attatched to the nucleus and can be detatched easily. These electrons are known as free electrons and are responsible for conduction of currents. for this reasons, the electrons are also known as conduction electrons.
* The energy band which possesses the conduction (or free) electrons is called conduction band.

3) Forbidden Energy Gap:-

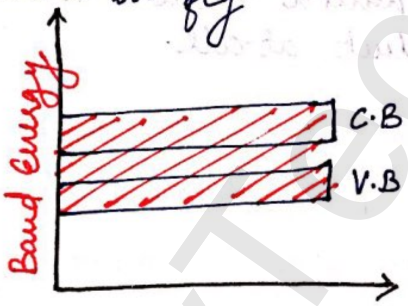
* The energy gap b/w the valance band and conduction band is known as forbidden energy gap.
* forbidden energy gap is a region in which no electron can stay as there is no allowed energy state
* The width of forbidden energy band gap represents the bondage of valance electron to the atom.
* The greater the forbidden energy band gap more tightly the valance electrons are bound to the nucleus.



CLASSIFICATION OF SOLIDS BASED ON BAND THEORY

1. CONDUCTORS:

The substances (like cu, Al, Silver etc) which allow the passage of current through them are known as conductors In case of conductors electrons can easily move from V.B. to C.B and the V.B. of these substances overlap with the C.B. as shown in fig.



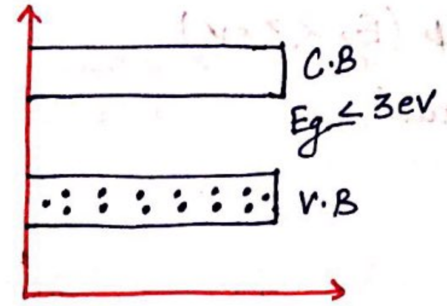
Due to this overlapping a large no. of free electrons are available for conduction.

2. SEMICONDUCTORS:

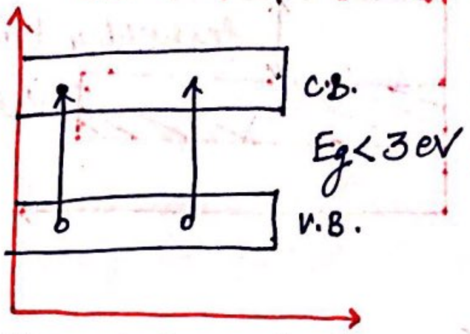
→ At absolute zero
The V.B. of these substances is almost full and C.B. is almost empty, But the forbidden energy gap b/w V.B. and C.B. is very small (nearly 1eV)

→ At room temp.
Some of the e^- gains energy and move over to conduction band, as temp. is increased more valance electrons cross over to the C.B. and the conductivity of material increases

when electrons move to conduction band they leave a vacancy called hole.



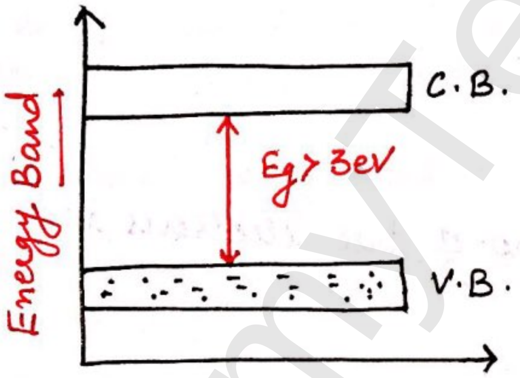
(a) at absolute zero



(b) at room temp.

3. INSULATOR

The Valance band of these substances is completely filled whereas the C.B. is completely empty. Moreover the forbidden energy band gap is very large (nearly 6ev). Therefore a very large amt. of energy is required to push the valance e^- to C.B. due to which such materials under ordinary cond^{n}s, do not conduct at all.



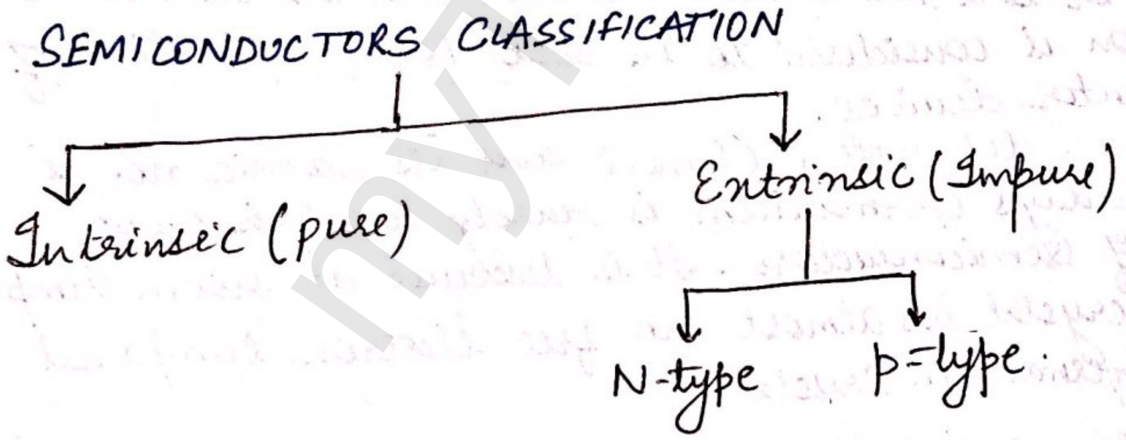
THEORY OF SEMICONDUCTORS

The substances which have resistivity (10^2 to 0.5 Ω-m) in between conductors & insulators are known as Semiconductors.

Properties of semiconductors :-

1. The resistivity of a semiconductor is less than insulators but more than a conductor.
2. Semiconductor have -ve temp. coefficient of Resistance The -ve temp. co-efficient of resistance means, the resistance decreases with the rise in temp. & vice-versa Acc. to this property, the semiconductor behave like an insulator at very low temp. but as a conductors at high temp.
3. When a suitable mettalic impurity (like arsenic, gallium etc.) is added to a semiconductor it changes the current conducting properties of the semiconductor. It is this property which is exploited to develop various solid state devices (eg diode, transistor, thyristor, diac, triac etc.)

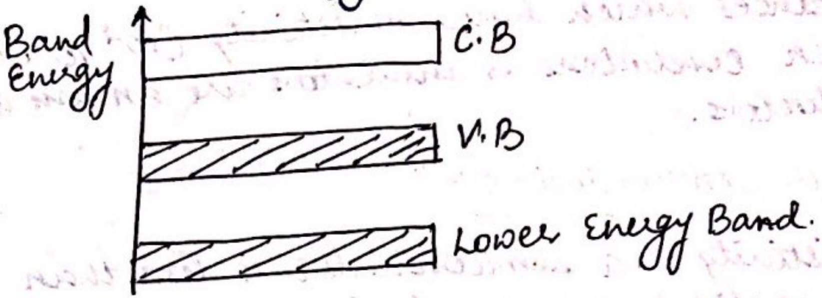
Classification of semiconductors :-



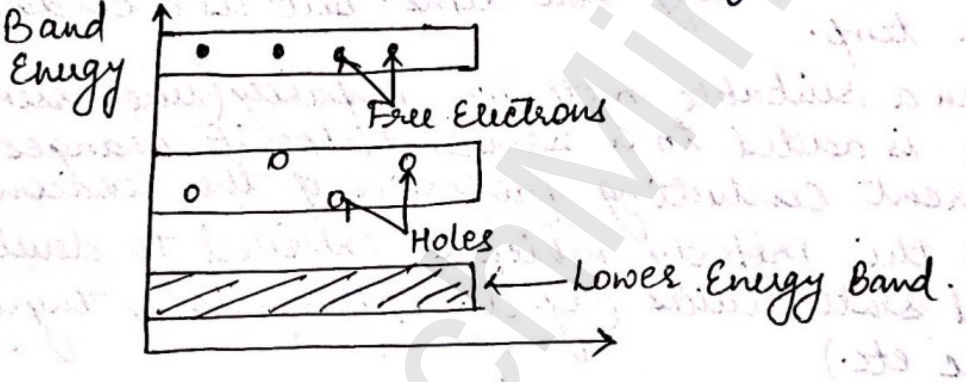
Intrinsic Semiconductor :-

An extremely pure semiconductor is called intrinsic semiconductor.

On the basis of energy band phenomenon, at absolute zero temp. is shown in fig. below



Its valance band is completly filled and the conduction band is completely empty. when the temp. is increased to the room temp. some of the valance electrons are lifted to conduction band leaving behind holes in the valance band as shown in fig. below.



Silicon 'Vs' Germanium

——— ———*———*

Silicon :- It is a tetravalent element and its atomic no. is 14. silicon is considered to be best for preparation of Semiconductor devices.

Germanium :- tetravalent element and its atomic no. is 32. Nowadays Germanium is rarely used in new designs of semiconductors. It is because at room temp. a silicon crystal has almost no free electron compared with the Germanium crystal.

* The electron-hole pairs are the root cause of leakeage current in solid state devices. This leakeage current affects the performance of the device. Since the formation of electron hole pair in silicon materail at room temp. is ~~negigo~~ negligibly small, the performance of silicon devices

is far better than the Germanium devices

EXTRINSIC SEMICONDUCTOR:

An Intrinsic Semiconductor is capable to conduct a little current even at room temp. but as it is, it is not ~~useful~~ useful for the preparation of various electronic devices. To make it conducting, a small amount of suitable impurity is added. It is then called extrinsic (impure) semiconductor.

Doping:- The process by which an impurity is added to a semiconductor is known as doping. If a pentavalent impurity (having 5 valance electrons) is added to a pure semiconductor a large no. of free electrons will exists in it whereas if trivalent impurity (having 3 valance e^-) is added a large no. of holes will exists in the semiconductor

Depending upon the type of impurity added Extrinsic semiconductors are classified as:-

(i) n-type semiconductor.

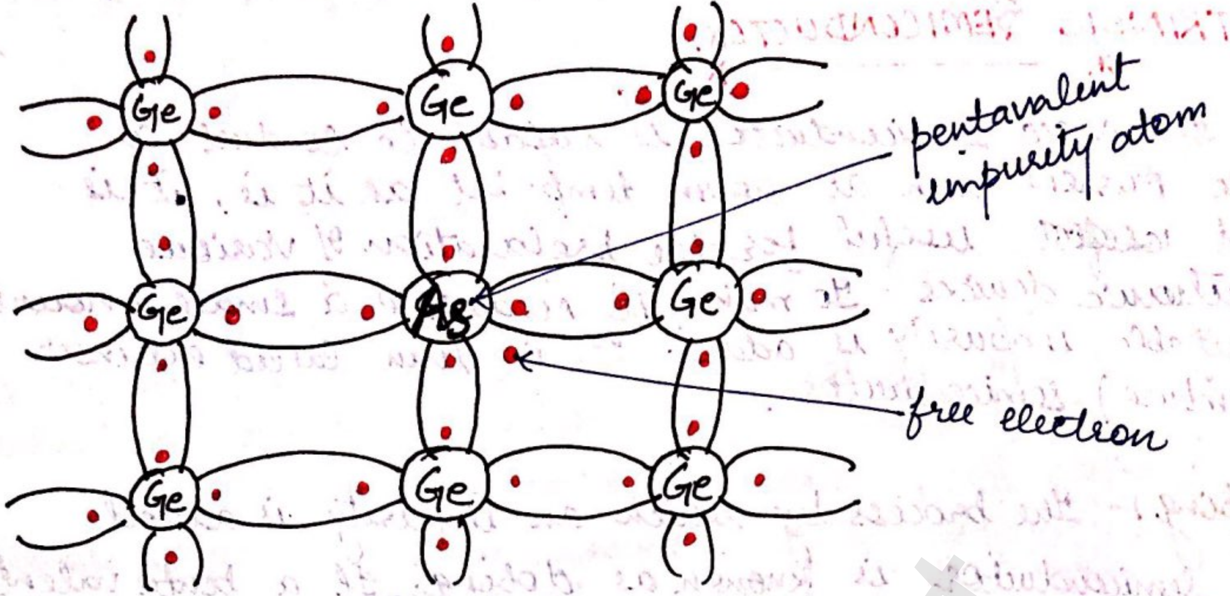
(ii) p-type semiconductor.

* n-type semiconductor:-

→ when a small amt of pentavalent impurity is added to a pure semiconductor providing a large no. of free electrons in it, the extrinsic semiconductor thus formed is known as n-type.

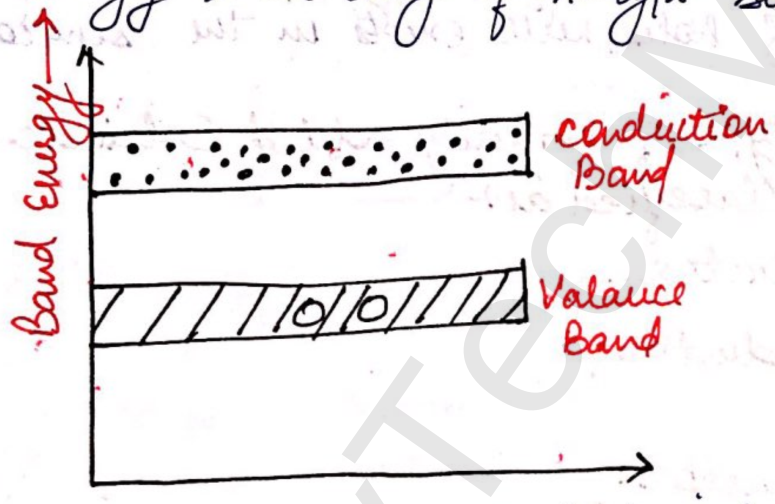
→ when a small amt. of pentavalent impurity like arsenic (At. no. 33 → 2, 8, 18, 5) having 5 electrons is added to Germanium crystal each atom of the impurity fits in the Germanium crystal in such a way that its 4 valance electrons forms covalent bonds with

4 Germanium atoms as shown:



→ Hence each arsenic atom provides one free electrons in the Germanium crystal

→ The energy band diag. of n-type semiconductor is:-

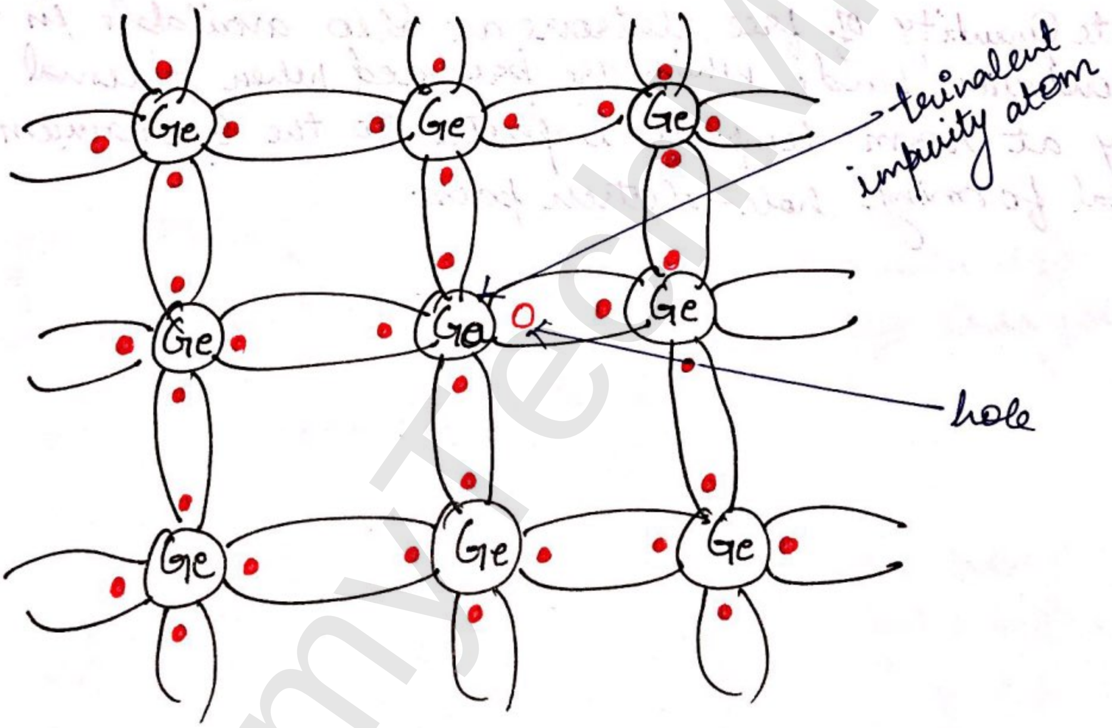


With the addition of pentavalent impurity a large no. of free electrons are made available in the conduction band

* p-type semiconductor

→ When a small amount of trivalent impurity is added to a pure semiconductor providing a large no. of holes in it, the extrinsic semiconductor thus formed is known as p-type semiconductor.

→ When a small amt of trivalent impurity like Gallium (At. no. 31 → 2, 8, 18, 3) having three valence electrons is added to Germanium crystal each atom of impurity fits in the Germanium crystal in such a way that its 3 valance e^- form covalent bonds with three surrounding Germanium atoms as shown ~~as~~ in fig

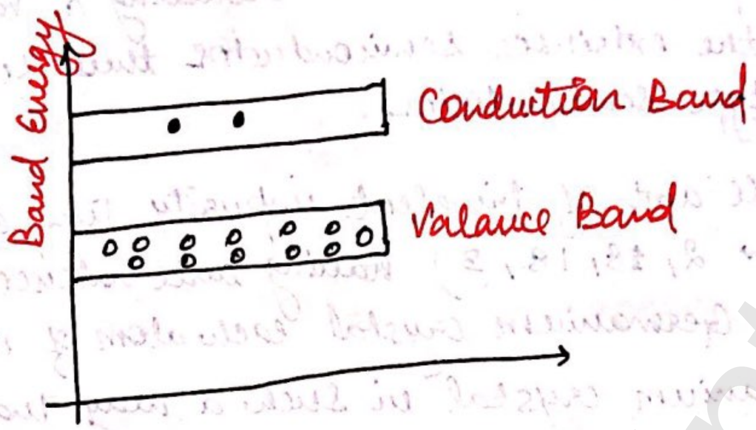


→ In fourth covalent bonds, only Germanium atom contributes one valance electron while Gallium atom has no valance electron to contribute as all its 3 valance electrons are already engaged in the co-valent bonds.

→ Hence, the 4th covalent bond is incomplete having one electron short. This missing electron is called a hole.

Energy Band Diag.

The energy band diag. of p-type semiconductor is shown:-

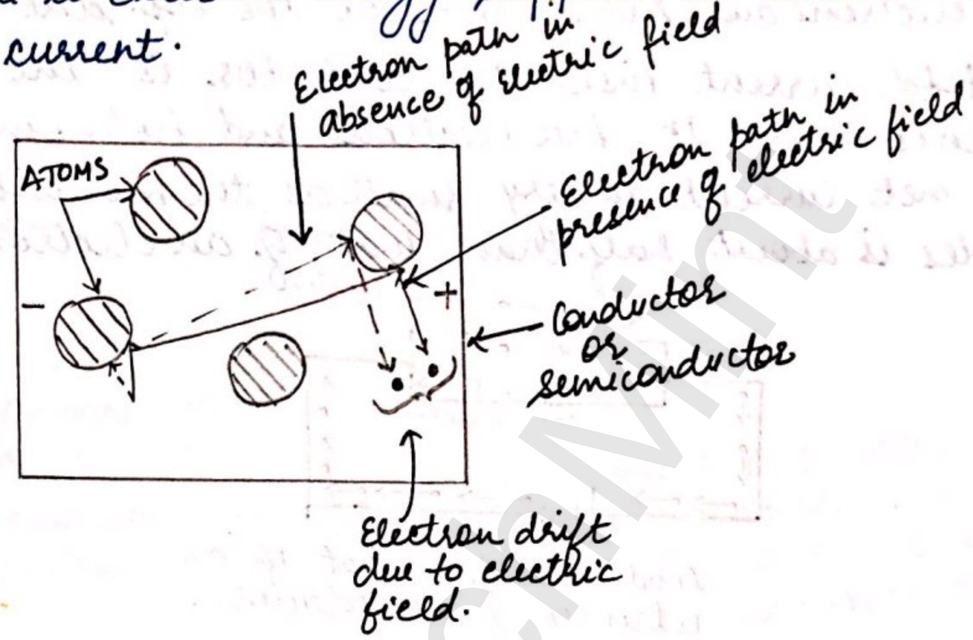


with addition of trivalent impurity a large no. of holes are made available in the crystal. However a minute quantity of free electrons are also available in the conduction band, which are produced when thermal energy at room temp. is imparted to the Germanium crystal forming hole-electron pair.

DRIFT AND DIFFUSION CURRENTS

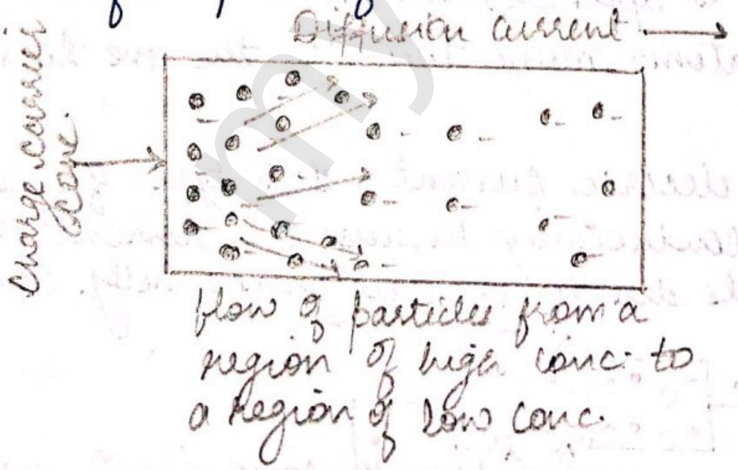
DRIFT CURRENT

The flow of current in the semiconductors constituted by the drift of free electrons available in the conduction band and holes available in the Valance band, which are formed due to external energy supplied to them is known as drift current.



DIFFUSION CURRENT

This type of current occurs when charge carriers diffuse from a point of conc., to spread uniformly throughout the vol. of a piece of material

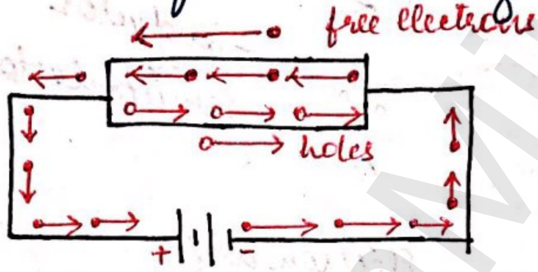


This type of movement of charge ~~particles~~ carriers is called the diffusion current.

CONDUCTION IN INTRINSIC SEMICONDUCTORS

When an external electric field is applied to a pure semiconductor, the conduction through the semiconductor is by both free electrons and holes. Free e^- moves towards the +ve terminal of the battery and holes in the V.B. moves towards the -ve terminal of the battery i.e. electrons and holes moves in the opp. direction.

The total current inside the conductor is the sum of currents owing to free electrons and holes and the net current is very small as the mobility of holes is about half than that of an electron.



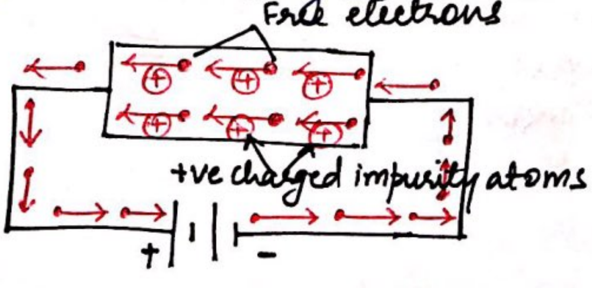
Conduction of current in an intrinsic semiconductor.

CONDUCTION IN EXTRINSIC SEMICONDUCTOR

N-type Conductivity

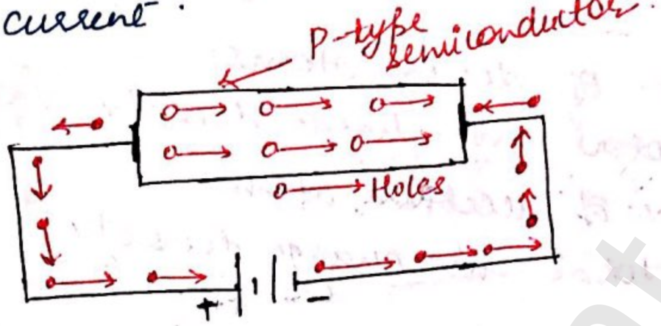
When an electric field is applied, the excess electrons donated by impurity atoms move towards the +ve terminal of the battery.

This constitutes the electric current. This type of conductivity is called negative conductivity because the current flows through the crystals due to free electrons (-vely charged particles)



* Positive or P-type conductivity :-

When an electric field is applied across a P-type semiconductor, the current conduction is primarily due to holes. Here holes are shifted from one covalent bond to another. As the holes are +vely charged they are directed towards the -ve terminal and constitute the hole current.



MASS ACTION LAW

Under thermal equilibrium the product of conc. of free electrons and conc. of holes is constant & is independent of the amount of doping by donor & acceptor impurities. This is known as mass action law,

Thus $np = n_i^2$

n_i = intrinsic conc. and is a func^n of Temp.

For an intrinsic semiconductor $n = p = n_i$

Acc to this law the addition of impurities to an intrinsic semiconductor increases the conc. of one type of carriers, which consequently become majority carriers and simultaneously decreases the conc. of the other carriers, which as a result becomes minority carriers.

$\{$also, $n_n p_n = n_i^2$ and $n_p p_p = n_i^2\}$.

CHARGE DENSITIES

Magnitude of +ve charge densities must be equal to magnitude of -ve charge densities.

$$\boxed{N_D + p = N_A + n} \quad \text{———} \quad (1)$$

N_D → conc. of donor atoms

$N_D + p$ → total +ve charge density

N_A → conc. of acceptor atoms

$N_A + n$ → total -ve charge density.

* In N-type semiconductor, there is no acceptor doping i.e. $N_A = 0$ also $n >> p$.

So, $n \simeq N_D$

i.e. in N-type semiconductors, the free electron conc. is approximately equal to the density of donor atoms.

Now, conc. of holes, is

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

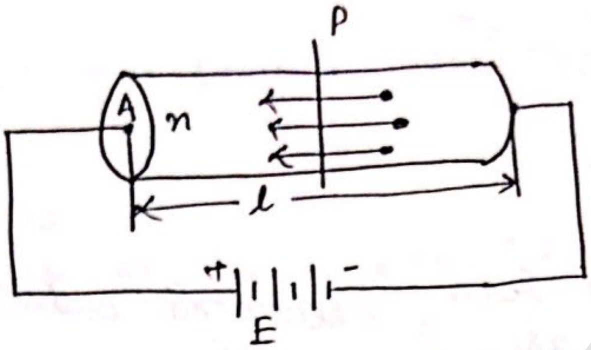
Similarly in case of P-type semiconductors

$P \simeq N_A$

and $n = \frac{n_i^2}{N_A}$.

CONDUCTIVITY OF METALS

Consider a conductor of length l and area of cross-Section A as shown in fig. Let n be the electron density and E be the applied electric field.



So, force F on the charged particle of charge q is

$F = qE$

for electron having charge e on it,

$F = eE$ ——— ①

also $F = ma$ ——— ②

from ① and ②

$$a = \frac{eE}{m}$$

If τ = relaxation or collision time, the avg. velocity of electrons known as drift velocity is :-

$$\boxed{v = a \times \tau = \frac{eE\tau}{m}}$$

Let I be the current flowing through the conductor on application of electric field E corresponding to drift velocity v

so, $dq = envA\,dt$

{$v\,dt$ = distance travel by electrons in time dt
$A\,v\,dt$ = vol. for no. of electron crossing a given area}

$$\frac{dq}{dt} = envA$$

also $\frac{dq}{dt} = I = envA$

current density J is defined as current per unit area

$$J = \frac{I}{A} = env$$

also, $J = \rho v$

where ρ = charge density in coulombs$/m^3$ = en

also $J = en \times \frac{eE}{m} \times \tau$

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

$\frac{ne^2\tau}{m}$ = Constant for a particular material = electrical conductivity (σ)

$\therefore J = \sigma E$

Also current density can be given as:-

$J = \frac{E}{\rho}$; ρ = resistivity
E = applied electric field

$$I = JA = \frac{EA}{\rho} = \frac{El}{R}$$

$\left(R = \frac{\rho l}{A} \Rightarrow \rho = \frac{RA}{l} \right)$

since $E = V/l$

$$I = \frac{V}{l} \times \frac{l}{R} = \frac{V}{R}$$

Electrical conductivity is also given as

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

where $\mu_e = \frac{e\tau}{m}$ is the mobility acquired by electrons due to the presence of electric field.

$$\mu_e = \frac{e\tau}{m} = \frac{v}{E}$$

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

CONDUCTIVITY OF SEMICONDUCTORS

Conductivity of a semiconductor depends upon:-

1) the conc. of mobile charge carriers electrons or holes

2) mobility of charge carriers

The conductivity σ_e of semiconductor due to electrons in conduction band is :-

$$\sigma_e = ne\mu_e$$

where n = no. of electrons per unit volume.
μ_e = electron mobility
e = charge of electron

Similarly, conductivity σ_h of the semiconductor due to holes is :-

$$\sigma_h = pe\mu_h$$

p = no. of holes per unit vol
μ_h = hole mobility.

Total conductivity $\sigma = \sigma_e + \sigma_h$

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

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

In intrinsic semiconductors,

$$n = p = n_i$$

$$\therefore \sigma_i = \sigma_e + \sigma_h$$

$$\boxed{\sigma_i = e(n_i\mu_e + n_i\mu_h) = n_i e(\mu_e + \mu_h)}$$

Current density $J = n_i e(\mu_e + \mu_h)E = \sigma E$

current, $I = JA$

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

$= n_i e(\mu_e + \mu_h) A \frac{V}{l}$

E = applied electric field
V = applied potential difference
A = area of cross-section

Conductivity of N-type semiconductor:-

In case of N-type semiconductor, hole conc. p_n is negligible and electron conc. $n_n = N_D$

so, $\boxed{\sigma_e = eN_D\mu_e}$

Conductivity of P-type semiconductor:-

In this case electrons conc. is negligible and hole conc. $p_h = N_A$.

so, $\boxed{\sigma_h = eN_A\mu_h}$

* Total current density due to drift of electrons and holes

J = current density due to hole drift J_h + current density due to electron drift J_e

$= Ep e\mu_h + En e\mu_e$

$$\boxed{J = Ee(p\mu_h + n\mu_e)}$$

Ques1. What is the conc. of holes in Si crystals having donor conc. of $1.4\times10^{24}/m^3$ when the intrinsic carrier conc. is $1.4\times10^{18}/m^3$. Find the ratio of electron to hole conc.

Solⁿ: Intrinsic carrier conc., $n_i = 1.4\times10^{18}/m^3$

donor conc., $N_D = 1.4\times10^{24}/m^3$

Conc. of electrons, $n \simeq N_D = 1.4\times10^{24}/m^3$

Conc. of holes, $p = \frac{n_i^2}{n}$

$$= \frac{(1.4\times10^{18})^2}{1.4\times10^{24}} = 1.4\times10^{12}/m^3$$

Ratio of electron to hole conc. :-

$$\frac{n}{p} = \frac{1.4\times10^{24}}{1.4\times10^{12}} = 1\times10^{12}$$ Ans.

Ques2. A cu wire of 2mm diameter with conductivity of 5.8×10^7 S/m and electron mobility of $0.0032\,m^2/V\text{-}s$ is subjected to an electric field of 20mV/m

Find :- (i) the charge density of free electrons

(ii) the current density

(iii) the electron drift velocity

Solⁿ :- $d = 2mm = 0.002\,m$

conductivity of cu $= \sigma = 5.8\times10^7\,S/m$

$\mu_e = 0.0032\,m^2/V\text{-}s$

$E = 20mV/m = 0.02\,V/m$

(a) Charge density of free e^-, $n = \frac{\sigma}{e\mu_e}$

$$= \frac{5.8\times10^7}{1.6\times10^{-19}\times0.0032}$$

$$= 1.133\times10^{29}/m^3$$

(b) Current density $J = \sigma E$

$= 5.8 \times 10^7 \times 0.02$

$= 1.16 \times 10^6 A/m^2$

(c) Current flowing in the wire = $I = J \times$ area of cross-section of wire

$$I = \frac{J \times \pi d^2}{4}$$

$$= 1.16 \times 10^6 \times \frac{\pi}{4} \times (0.002)^2$$

$$= 3.644 A$$

(d) Electron ~~dip~~ drift velocity, $v = \mu_e \times E$

$= 0.0032 \times 0.02$

$= 6.4 \times 10^{-5} m/s$

Ques 3. The intrinsic resistivity of germanium at room-temp. is 0.47 Ω-m. The electron and hole mobilities at room temp. are 0.39 and 0.19 m²/V-s Calculate the density of electrons in the intrinsic semiconductor. Also calculate the drift velocities of these charge carriers for a field of 10kV/m

Intrinsic resistivity, $\rho_i = 0.47 \Omega\text{-}m$

Intrinsic conductivity, $\sigma_i = \frac{1}{\rho_i} = \frac{1}{0.47} = 2.12766 S/m$

$\mu_e = 0.39 m^2/V\text{-}s$

$\mu_h = 0.19 m^2/V\text{-}s$

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

$\therefore$ Density of electrons = Intrinsic conc. $= n_i = \frac{\sigma_i}{e(\mu_e + \mu_h)}$

$$n_i = \frac{2.1276}{1.6 \times 10^{-19}(0.39 + 0.19)}$$

$n_i = 2.293 \times 10^{19}/m^3$ Ans.

Drift velocity of electrons $= v_n = \mu_e E$
$= 0.39 \times 10^4 = 3900 m/s$

Drift velocity of holes, $v_h = \mu_h E$
$= 0.19 \times 10^4 = 1900 m/s.$

Ques4. Pure silicon has an electrical resistivity of $3{,}000 \Omega$-m. If the free electron density in it is $1.1 \times 10^6/m^3$ and electron mobility is three times that of holes mobility, calculate mobility values of electrons and holes.

Solⁿ:- Resistivity of silicon, $\rho = 3000 \Omega$-m
Electron density, $n = 1.1 \times 10^6/m^3$
$\mu_e = 3 \times$ mobility of holes
$= 3 \times \mu_h$

$$\rho = \frac{1}{(\mu_e + \mu_h) en}$$

$$\mu_e + \mu_h = \frac{1}{\rho en} = \frac{1}{3000 \times 1.6 \times 10^{-19} \times 1.1 \times 10^6}$$
$$= 1.894 \times 10^9 m^2/V\text{-}s$$

$\mu_e = 3\mu_h$

$3\mu_h + \mu_h = 1.894 \times 10^9$

$$\mu_h = \frac{1.894 \times 10^9}{4} = 4.735 \times 10^9 m^2/V\text{-}s$$

$$\mu_e = 3\mu_h = 3 \times 4.735 \times 10^9 m^2/V\text{-}s$$
$$= 1.42 \times 10^9 m^2/V\text{-}s.$$

Ques5: A pd of 10V is applied longitudinally to a rectangular specimen of intrinsic germanium of length 25mm, width 4mm and thickness 1.5mm Determine at room temp.

(i) electron & hole drift velocities

(ii) the conductivity of intrinsic germanium if intrinsic carrier density is $2.5 \times 10^{19}/m^3$

(iii) and total current

Given that, $e = 1.6 \times 10^{-19} C$, $\mu_e = 0.38\ m^2/Vs$

$\mu_h = 0.18 m^2/Vs$.

Solⁿ:- Applied Electric field, $E = V/l$

$= 10/0.025$

$= 400\ V/m$

Electron drift velocity, $v_e = \mu_e \times E$

$= 0.38 \times 400 = 152 m/s$

Hole drift Velocity, $v_h = \mu_h \times E$

$= 0.18 \times 400 = 72 m/s$.

$n_i = 2.5 \times 10^{19}/m^2$

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

$= 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.38 + 0.18)$

$= 2.24 / ohm\ m$

(iii) Total current, $I = \sigma_i E A$

$= 2.24 \times 400 \times 4 \times 10^{-3} \times 1.5 \times 10^{-3}$

$= 5.376 mA$ Ans

FERMI-DIRAC FUNCTION

It is important to know what energies are possessed by a mobile carries in a solid or semiconductor. This relationship is referred to as energy distribution func^n.

The fermi-Dirac state enables us to find the no. of free electrons dn_E per unit volume, within energy range E to E + dE at temp. T

The no. of free electrons per cubic metre of a metal

$$dn_E = f_E \, dE$$

where,

$dn_E \longrightarrow$ no. of free e$^-$ per cubic metre whose energy internal dE energies lies in the energy internal dE.

$f_E \longrightarrow$ density of e$^-$ in the energy internal dE.

The func^n f_E may be expressed as:-

$$f_E = N(E) \cdot f(E)$$

where N(E) = density of states (no. of states per eV per cubic metre) in the conduction band. and f(E) = prob. that a Quantum state with energy E is occupied by an electron

also, $N(E) \propto E^{1/2}$

or $N(E) = \gamma E^{1/2}$

γ = proportionality constant and is defined as

$$\gamma = 4\pi \left(\frac{2em}{h^2} \right)^{3/2}, \quad m = \text{mass of } e^-, \quad h = \text{planck's constant}$$

$$= 4 \times \pi \times \left[\frac{2 \times 1.602 \times 10^{-19} \times 9.107 \times 10^{-31}}{(6.626 \times 10^{-34})^2} \right]^{3/2}$$

$$= 6.82 \times 10^{27} \ m^{-3} (eV)^{-3/2}$$

Acc. to principle of Quantum Mechanics, the fermi-Dirac prob func^n is given by :-

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

K = Boltzmann's constant $(K = 8.62 \times 10^{-5} eV/K)$

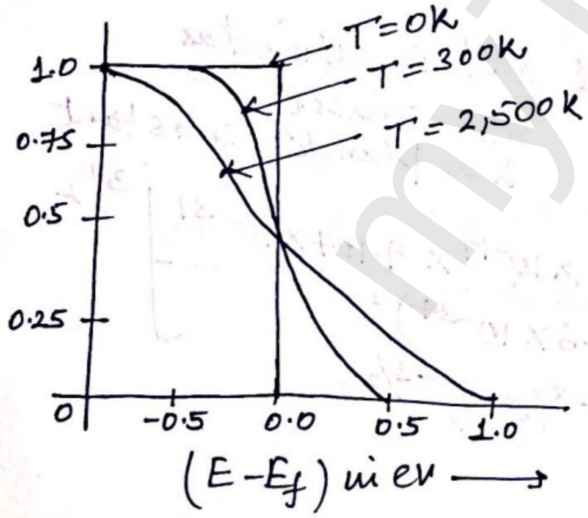
f(E), gives the prob. than an available energy state at E will be occupied by an electron at absolute temp. T

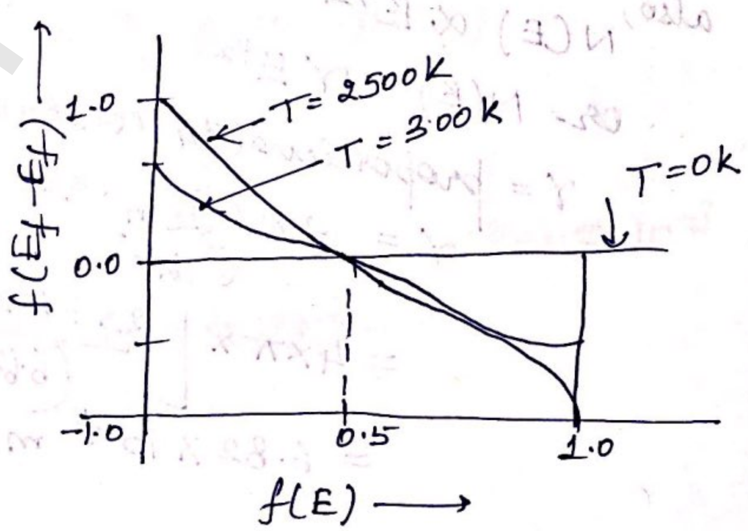
f(E) specifies the fraction of all states at energy E (electron volts) occupied under cond^{n}s of thermal equilibrium.

E_F = fermi Level, and it represents an important Quantity in the analysis of semiconductor behaviour

$$f(E_f) = \frac{1}{1+e^{(E_f-E_f)/KT}} = \frac{1}{1+1} = \frac{1}{2}$$

Thus, an energy state at the fermi level has a prob. of 50% of being occupied by an electron





at $T = 0K$, two possibilities are

(i) $E < E_f$

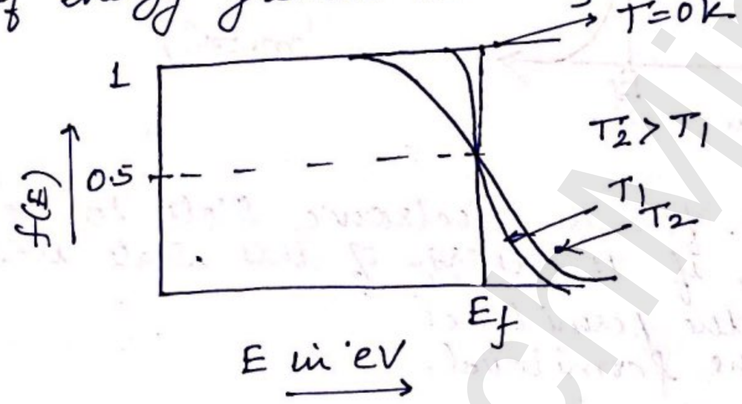
$$f(E) = \frac{1}{1+0} = 1$$

All the Quantum levels with energies less than E_f will be occupied at absolute zero.

(ii) $E > E_f$

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

Hence, there is no prob. of finding an occupied Quantum state of energy greater than E_f at absolute zero



Therefore, fermi energy level is defined as the energy level in a solid below which all levels are filled and all the levels are empty above this at 0 K.

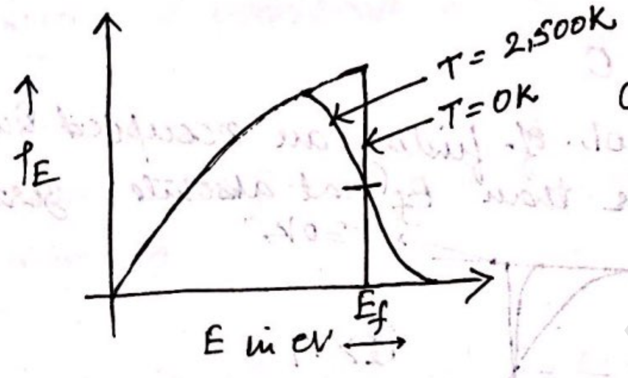
At absolute zero temp. f_E is defined as :-

$$f_E = \begin{cases} \gamma E^{1/2} & \text{for } E < E_f \\ 0 & \text{for } E > E_f. \end{cases}$$

THE FERMI LEVEL

E_f may be defined as the max. energy that any electron may possess at absolute zero.

Note:- At 0°K there is no electron having energies exceeding E_f.



The area under the curve represents the total no. of free electrons (per cubic meter of metal)

Ques. Find the prob. for an electronic state to be occupied at room temp, if the energy of this state lies

(a.) at 0.1eV above the fermi level

(b) 0.1eV below the fermi level.

Solⁿ:- $f(E) = \dfrac{1}{1+e^{(E-E_f)/KT}}$

k = Boltzmann constant in $eV/k = 8.61\times10^{-5} eV/K$

$T = 300K$

$KT = 300 \times 8.61\times10^{-5} = 0.0258 V$

(i) at 0.1eV above the fermi level

i.e. $E - E_f = 0.1eV$

$$f(E) = \frac{1}{1+e^{0.1/0.0258}} = 0.02 \text{ Ans.}$$

(ii) at 0.1 eV below the fermi level

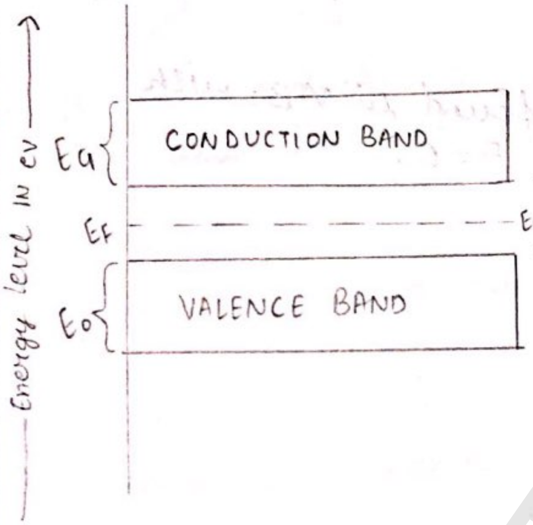
i.e. $E - E_f = -0.1eV$

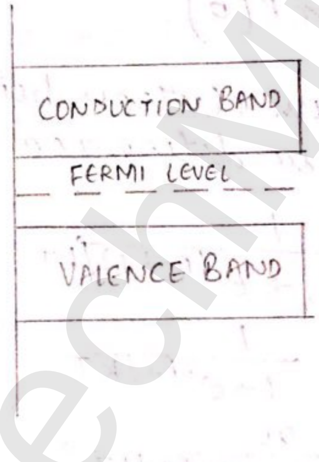
$$f(E) = \frac{1}{1+e^{-0.1/0.0258}} = 0.98 \text{ Ans}$$

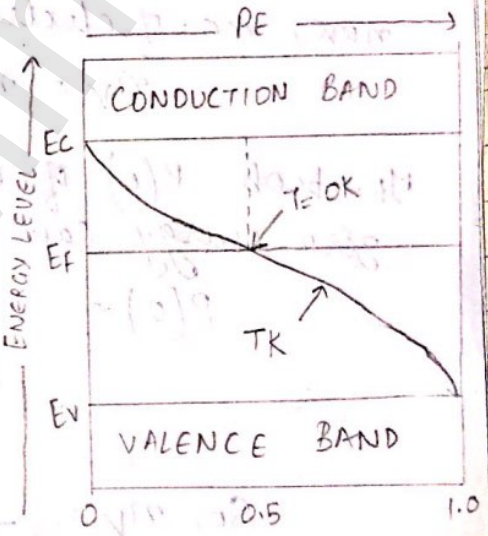
FERMI LEVEL IN AN INTRINSIC SEMICONDUCTOR

The fermi level is simply a refrence energy level. It is the energy level at which the prob. of finding an electron n energy units above it in the conduction band is equal to the prob. of finding a hole (electron absence) n energy units below it in the Valance band.

Let at any temp. TK,
no. of e^- in the C.B be n_C
no. of e^- in the V.B be n_V
total no. of electrons in both the bands, $n = n_C + n_V$







Let us assume that,

(i) widths of energy bands are small in compairision to forbidden energy gap b/w them

(ii) all levels in band have the same energy, B.W. being assumed to be small.

(iii) Energies of all the levels in valance band are Eo (as shown in fig. ⓐ)

(iv) energies of all levels in C.B. are E_G.

$\therefore$ no. of e^- in C.B.

$$n_C = n \cdot P(E_G)$$

$P(E_G)$ = prob. of an e^- having energy E_G.

$$P(E) = \frac{1}{1+e^{(E-E_f)/KT}}$$ (from Fermi-Dirac prob. distribution)

So, $$P(E_G) = \frac{1}{1+e^{(E_G-E_f)/KT}}$$

where E_f = fermi level.

$$\Rightarrow n_C = \frac{n}{1+e^{(E_G-E_f)/KT}}$$

now, no. of electrons in V.B,

$$n_V = n\,P(0)$$

The prob. $P(0)$ of an electron being found in V.B. with zero energy can be determined by $E=0$.

$$P(0) = \frac{1}{1+e^{(0-E_f)/KT}}$$

$$= \frac{1}{1+e^{-E_f/KT}}$$

So, $$n_V = \frac{n}{1+e^{-E_f/KT}}$$

$$\Rightarrow n = n_C + n_V$$

$$= \frac{n}{1+e^{(E_G-E_f)/KT}} + \frac{n}{1+e^{-E_f/KT}}$$

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

or $$\boxed{E_F = \frac{1}{2}E_G}$$

In an intrinsic semiconductor, the fermi level lies midway b/w the C.B. and V.B.

CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTOR

Number of Electrons in conduction Band

The electron population (the no. of conduction e⁻ dn per cubic metre) at any energy level is defined as:-

$$dn = N(E)\,f(E)\,dE \quad \text{——— (1)}$$

where $N(E)$ is the dencity of states and $f(E)$ is the fermi funcⁿ

also $N(E) = \gamma E^{1/2}$ ——— (2)

in semiconductor lowest energy in conduction band is E_c and therefore, eqⁿ (2) is modified as:-

$$N(E) = \gamma\,(E - E_c)^{1/2} \text{ for } E > E_c \quad \text{——— ③}$$

fermi-dirac prob. funcⁿ is:-

$$f(E) = \frac{1}{1 + e^{(E-E_f)/kT}} \quad \text{——— ④}$$

where E_f = fermi level

The conc. of e⁻ in the Conduction Band is

$$n = \int_{E_c}^{\infty} N(E)\,f(E)\,dE$$

for $E \geq E_c$, i.e. in conduction Band $E - E_f >> KT$

so, $f(E) = e^{-(E-E_f)/KT}$

$$\therefore\ n = \int_{E_c}^{\infty} \gamma\,(E-E_c)^{1/2}\,e^{-(E-E_f)/kT}\,dE$$

$$n = \gamma\,kT^{1/2} \int_{E_c}^{\infty} \left(\frac{E-E_c}{kT}\right)^{1/2} e^{-(E-E_c-E_f+E_c)/kT}\,dE$$

$$= \gamma\,kT^{1/2} \int_{E_c}^{\infty} \left(\frac{E-E_c}{kT}\right)^{1/2} e^{-(E-E_c)/kT} \cdot e^{-(E_c-E_f)/kT}\,dE$$

$$\Rightarrow \quad n = \gamma kT^{1/2} e^{-(E_c-E_f)/kT} \int_{E_c}^{\infty} \left(\frac{E-E_c}{kT}\right)^{1/2} \times e^{-(E-E_c)/kT} dE$$

Assume $\frac{E-E_c}{kT} = x$

$dE = kT\,dx$

Also $E = E_c$ for $x = 0$

$E = \infty$ for $x = \infty$

$$\Rightarrow \quad n = \gamma (kT)^{3/2} e^{-(E_c-E_f)/kT} \int_0^{\infty} x^{1/2} e^{-x} dx$$

$$\int_0^{\infty} x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2} \quad \text{and} \quad \gamma = \frac{4}{\sqrt{\pi}}\left(\frac{2\pi m_e}{h^2}\right)^{3/2} \times (1.602\times10^{-19})^{3/2}$$

$$n = \frac{4}{\sqrt{\pi}}\left(\frac{2\pi m_e}{h^2}\right)^{3/2}(1.602\times10^{-19})^{3/2}(kT)^{3/2}\frac{\sqrt{\pi}}{2} \times e^{-(E_c-E_F)/kT}$$

$$= 2\left[\frac{2\pi m_e kT}{h^2}\right] \times (1.602\times10^{-19})^{3/2} e^{(-E_c-E_f)/kT}$$

$$\Rightarrow \boxed{n = n_c\, e^{-(E_c-E_f)/kT}}$$

where n_c = effective density of states func^n in conduction band.

$$n_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \times (1.602\times10^{-19})^{3/2}$$

$$= 2\left(\frac{2\pi m_e k'T}{h^2}\right)^{3/2}$$

where $m_e = 9.107\times10^{-31}\frac{m_e}{m}$ kg (m_e = effective mass of e^- in kg)

$h = 6.625\times10^{-34}$ J-S

k = Boltzmann constant in eV/K = 8.62×10^{-5} eV/K as energy can neither

K' = Boltzmann Constant in J/K

$= 1.602 \times 10^{-19} \times 8.62 \times 10^{-5}$

$= 1.38 \times 10^{-23}$ J/K.

Number of Holes in the Valance Band

The density of states is given by

$$N(E) = \gamma (E_V - E)^{1/2}$$

E_V = max. energy in the Valance band.

The prob. func^n^ of a hole is given by :-

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

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

$$1 - f(E) \simeq e^{-(E - E_f)/KT}$$

(if $E_F - E >> KT$ for $E \leq E_V$)

The conc. of holes is :-

$$p = \int_{-\infty}^{E_V} \gamma (E_V - E)^{1/2} e^{-(E - E_f)/KT} dE$$

$$p = n_V e^{-(E_F - E_V)/KT}$$

where $n_V = 2\left(\frac{2\pi m_h KT}{h^2}\right)^{3/2} (1.602 \times 10^{-19})^{3/2}$

$$= 2\left(\frac{2\pi m_h k' T}{h^2}\right)^{3/2}$$

where m_h = effective mass of a hole.

Fermi-Level in an Intrinsic Semiconductor

Since the semiconductor crystal is electrically neutral,

$$n_i = p_i$$

Thus $n_c e^{-(E_c-E_F)/kT} = n_V e^{-(E_F-E_V)/kT}$

or $\frac{n_c}{n_V} = \frac{e^{-(E_F-E_V)/kT}}{e^{-(E_c-E_F)/kT}} = e^{(E_c+E_V-2E_F)/kT}$

or $E_c + E_V - 2E_F = kT \log_e \frac{n_c}{n_V}$

$$E_F = \frac{E_c+E_V}{2} - \frac{kT}{2}\log_e\frac{n_c}{n_V}$$

if $n_c = n_V$

$$\boxed{E_F = \frac{E_c+E_V}{2}}$$

Hence fermi-level lies in the centre of the forbidden energy band.

Intrinsic Concentration

The product of conc of e^- and holes is:

$$np = n_c n_V e^{-(E_c-E_V)/kT}$$

$$= n_c n_V e^{-E_G/kT} \text{ —— ① } \quad (E_G \equiv E_c - E_V)$$

eqn ① is valid for both intrinsic as well as extrinsic semiconductors.

For intrinsic semiconductor,

$$np = n_i^2$$

$$n_c = 2\left(\frac{2\pi m_e k'T}{h^2}\right)^{3/2} = 4.82\times 10^{21}\left(\frac{m_e}{m}\right)^{3/2} T^{3/2}$$

$$n_v = 2\left(\frac{2\pi m_h k'T}{h^2}\right)^{3/2} = 4.82\times 10^{21}\left(\frac{m_h}{m}\right)^{3/2} T^{3/2}$$

$$np = n_i^2 = (2.33\times 10^{43})\left(\frac{m_e m_h}{m^2}\right)^{3/2} T^3 e^{E_G/kT} \quad \text{——} ②$$

Variation of E_G with temp. is

$$E_G = E_{G0} - \beta T \quad \text{——} ③$$

where E_{G0} is the amplitude of energy gap at 0K

$$n_i^2 = A_0 T^3 e^{-E_{G0}/KT} \quad \text{——} ④$$

(using ② and ③)

where $A_0 = 2.33\times 10^{43}\left(\frac{m_e m_h}{m^2}\right)^{3/2} e^{-\beta/k}$

FERMI LEVEL IN AN EXTRINSIC SEMICONDUCTOR

We know that,

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

where k is the Boltzmann constant in eV/K
T is temp. in K
E_F is fermi level

also, $n = n_c\, e^{-(E_C-E_F)/KT}$
$p = n_v\, e^{-(E_F-E_V)/KT}$

Fermi level in N-type semiconductor :-

N-type semiconductor is entirely due to extrinsically supplied electrons from the donors and hence,

$n = N_D$. so,

$$n = N_D = N_c e^{-(E_c - E_F)/KT}$$

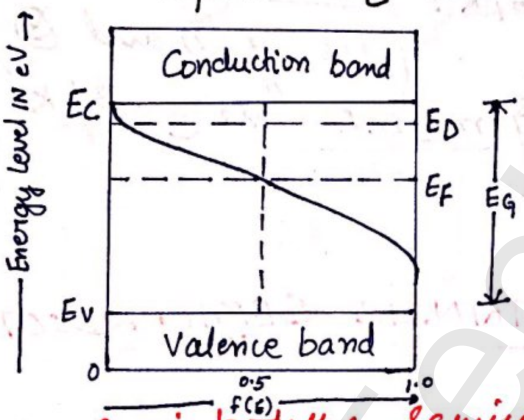
Taking log on both sides

$$\log n_D = \log n_c - \frac{(E_c - E_F)}{KT}$$

$$\frac{E_c - E_F}{K T} = \log \frac{n_c}{n_D}$$

$$\boxed{E_C - E_F = KT \log \frac{n_c}{n_D}}$$

$$E_F = E_C - KT \log_e \frac{n_c}{N_D}$$



Position of Fermi level in an N-Type Semiconductor.

Fermi-level in p-type semiconductor:-

In this case

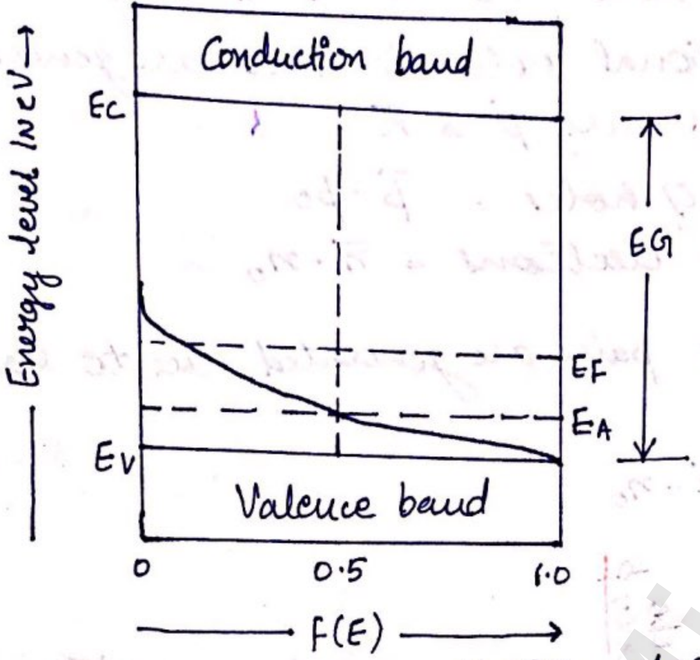
$$n = n_A$$

$$n \simeq n_A = n_V e^{-(E_F - E_v)/KT}$$

Solving we get

$$E_F = E_V + KT \log_e \frac{n_V}{N_A}$$

* As temp. of either N-type or p-type material increases, the fermi level moves towards the centre of energy gap.



Position of Fermi level in an P-Type semiconductor

CARRIER LIFETIME

In pure semiconductor no. of electrons is equal to the no. of holes because hole is created only by removing an electron from Covalent bond. Thus electrons and holes are generated in pairs.

In random motion of carriers a free electron may have an encounter hith the hole, they recombine and reestablish. This process is called recombination

In this process energy is released. This energy is absorbed by another electron to break its covalent bond & new electron hole pair is created.

Let $e^- - h^+$ pairs generation be g/unit volume/sec. A hole exists for τ_p seconds- called mean lifetime of holes & electrons exists for τ_n second - Called mean life time of electron.

Consider a bar of n-type-silicon. thermal eqm Concentrations of holes and e^- be n_0 resp.

At $t=t'$ additional holes electrons are generated

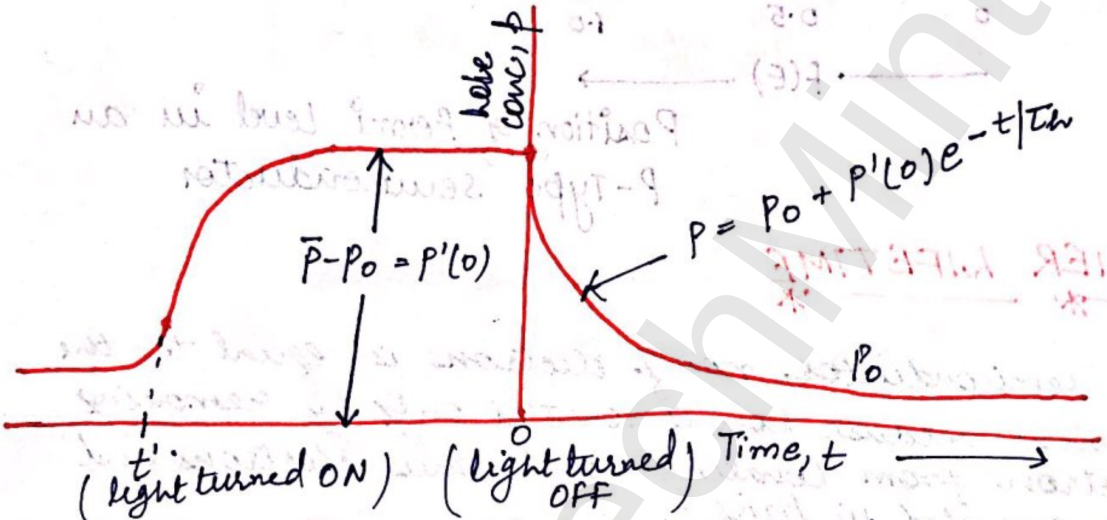
At eqm new conc. are $\overline{p}$ & $\overline{n}$

Excess conc. of holes = $\overline{p}-p_0$

" " " electrons = $\overline{n}-n_0$

As electron-holes pairs are generated due to radiation then, clearly,

$$\overline{p}-p_0 = \overline{n}-n_0$$



Although the increase in hole conc. and electron density are equal, the % increase for e^- in an N-type semiconductor is very small while % increase in holes may be tremendeous.

at steady state cond^n, time $t=0$, the radition is removed

Assuming that τ_h (mean life time of holes) is independent of magnitude of the hole conc.

$\frac{p}{\tau_h}$ = Decrease in hole conc. per second due to recombination

from defination of generation rate,

g = increase in hole conc. per second due to thermal generation.

as energy can neither be created nor destroyed

$$\frac{dp}{dt} = g - \frac{p}{\tau_h} \quad \text{———} \quad ①$$

under steady state cond^n's $\frac{dp}{dt} = 0$ and $p = p_0$

$$\text{so, } g = \frac{p_0}{\tau_h}$$

and eq^n ① can also be written as

$$\frac{dp}{dt} = \frac{p_0 - p}{\tau_h} \quad \text{———} \quad ②$$

The excess, or injected, carrier density p' may be defined as the increase in minority conc. above eq^m magnitude

$$p' = p - p_0 = p'(t) \quad \text{———} \quad ③$$

using ② and ③:-

$$\frac{dp'}{dt} = \frac{-p'}{\tau_h} \quad \text{———} \quad ④$$

The rate of change of excess conc. is proportional to this conc. The -ve sign indicates that the change is a decrease in the case of recombination and an increase when the conc. is recovering from a temporary depletion.

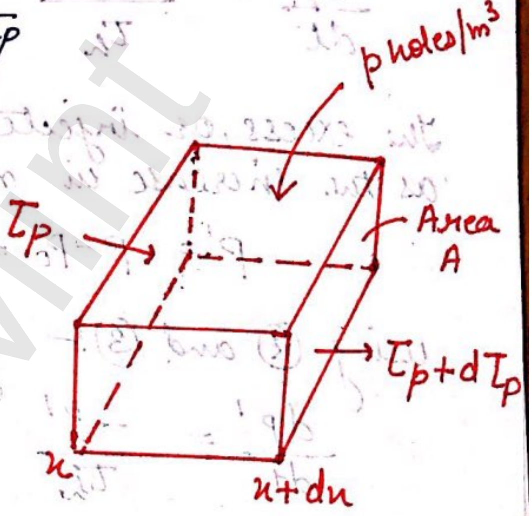
Since radiation causes an initial ($t<0$) excess conc.

$p'(0) = \bar{P} - p_0$ than this excitation is removed

$$p'(t) = p'(0)\, e^{-t/\tau_h} = (\bar{P} - p_0)\, e^{-t/\tau_h} = p - p_0.$$

CONTINUITY EQUATION

This eqⁿ is based on the fact charge can neither be created nor be destroyed. Consider the element of volume of area A and length dx in which avg. hole conc is p. current entering in volume at x is Ip at time t and leaving at x+dx is Ip+dIp at the same time t, There must be dIp more coulombs/sec leaving the vol than entering it.



Dec. in no. of c/sec within vol. = dIp

" " " " holes/sec = $\frac{dI_p}{e}$

So, decrease in hole conc./ unit vol.

$$\frac{dI_p}{e} / A \cdot dx = \frac{1}{eA}\frac{dI_p}{dx}$$

$$= \frac{1}{e}\frac{dJ_p}{dx} \quad \because \left(\frac{I_p}{A} = J_p\right)$$

Inc. in hole conc. $g = \frac{p_0}{\tau_p}$

dec. in hole conc. $\frac{p}{\tau_p}$

Total increment $= \frac{p_0 - p}{\tau_p}$

Since charge can neither be created nor be destroyed hence increase in holes/ unit volume/sec $\left(\frac{dp}{dt}\right)$ must be equal to algebric sum of all the inc in hole conc.

$$\boxed{\frac{dp}{dt} = \frac{p_0 - p}{\tau_p} - \frac{1}{e}\frac{dJ_p}{dx}}$$

This eqⁿ is known as continuity eqⁿ for charges

This eqⁿ is also applicable for the case of electrons corresponding eqⁿ for electron is :-

$$\boxed{\frac{dn}{dt} = \frac{n_0 - n}{\tau_n} - \frac{1}{e}\frac{dJ_n}{dx}}$$

Ques. The energy band gap of germanium is 0.72eV at 300K. Determine the fraction of total no. of electrons (C.B. as well as V.B.) in the C.B at 300K, Boltzmann constant is 8.61×10^{-5} eV/K

$$\frac{\text{no. of } e^- \text{ in C.B } (n_c)}{\text{Total no. of electrons in both bands } (n)} = \frac{1}{1 + e^{(E_G - E_F)/KT}}$$

$$E_F = \frac{1}{2} E_G = \frac{1}{2} \times 0.72 = 0.36 \text{eV}$$

$$k = 8.61 \times 10^{-5} \text{eV/K}$$

$$T = 300K$$

$$\frac{n_c}{n} = \frac{1}{1 + e^{0.36/300 \times 8.61 \times 10^{-5}}} = 8.85 \times 10^{-7} \text{ Ans.}$$

Ques In an N-type semiconductor, the fermi level is 0.24eV below the C.B at a room temp. of 300K. If the temp is increased to 350K, determine the new position of the fermi level.

The fermi level in an N-type material is

$$E_F = E_C - KT \log \frac{n_c}{N_D}$$

$$E_C - E_F = KT \log \frac{n_c}{N_D}$$

at room temp. T = 300K

$$0.24 = 300K \log \frac{n_c}{n_D} \quad \text{——— (1)}$$

at temp. of 350K $\quad E_C - E_{F_1} = 350K \log \frac{n_c}{n_D}$ ——— (2)

Divide (2) by (1)

$$\frac{E_C - E_{F_1}}{0.24} = \frac{350}{300}$$

$$E_C - E_{F_1} = \frac{350}{300} \times 0.24 = 0.28 \text{eV}$$

i.e. the new position of the fermi level lies 0.28 eV below the C.B.

Ques In a p-type semiconductor, the fermi level lies 0.39 eV above the Valance band. Determine the new pos. of fermi level if the conc of acceptor atoms is trippled. Assume $kT = 0.026\,eV$

In p-type semiconductor material,

$$N_A = n_V\, e^{-(E_F - E_V)/KT}$$

Let initial acceptor atom conc. and fermi level be denoted by N_{A1} and E_{F1}. Then

$$N_{A1} = n_V\, e^{-0.39/0.026} = n_V e^{-15} \text{ ——— (1)}$$

$$(\because E_F - E_V = 0.39\ eV)$$

also when $N_{A2} = 3N_{A1}$ and fermi level is E_{F2}

$$N_{A2} = n_V\, e^{-(E_{F2} - E_V)/0.026}$$

$$\text{or } 3N_{A1} = n_V\, e^{-(E_{F2} - E_V)/0.026} \text{ ——— (II)}$$

comparing eqn (1) and (II)

$$n_V\, e^{-(E_{F2} - E_V)/0.026} = 3n_V e^{-15}$$

$$e^{-(E_{F2} - E_V)/0.026 + 15} = 3$$

$$-\frac{(E_{F2} - E_V)}{0.026} + 15 = \log_e 3$$

$$\boxed{E_{F2} - E_V = 0.36\ eV} \text{ Ans.}$$