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Monday

Semiconductor

- Semiconductor is a device whose resistivity and Conductivity lie b/w insulator and conductor
  - ρ(insulator) > ρ(semiconductor) > ρ(conductor) and σ(insulator) < σ(semiconductor) < σ(conductor)

e.g;- Si, Ge, GaAs etc.
(Gallium Arsenide)

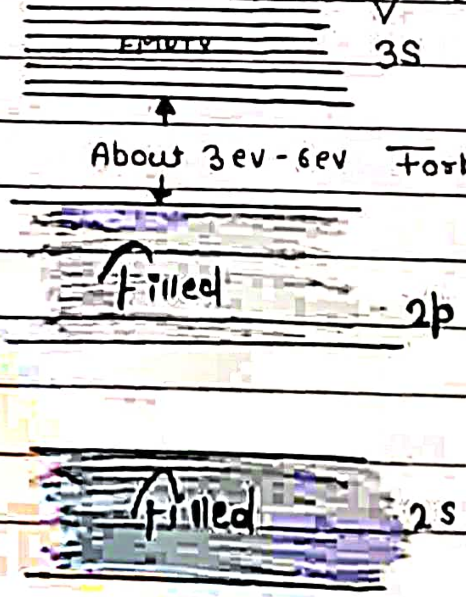
{ ∵ ρ = resistivity
σ = conductivity

Classification of material -

- on the basis of band theory, solids can be broadly.
- Classified into three Categories - insulator, Semiconductor and conductors.

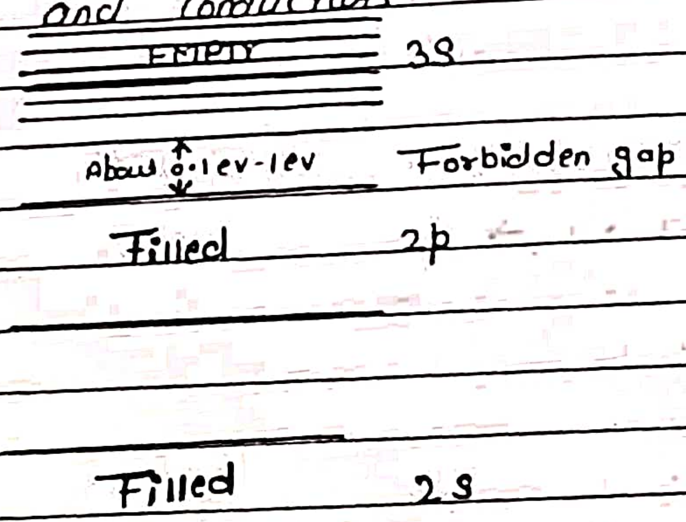
Insulator →

- In Case of insulator, the forbidden gap is very wide Due to this fact electron Cannot Jump from Valence band to Conduction band.
- They have Completely filled valence band and completely empty Conduction band.
- The resistivity of insulators is very high.
- Insulators are bad Conductors of electricity.



Semi-Conductor -

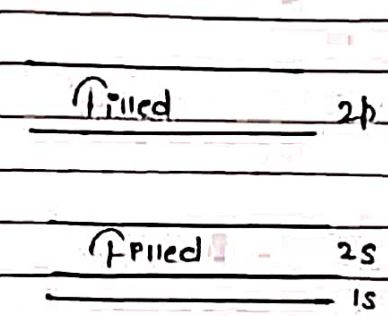
- In Semiconductors, the band gap is very small (0.7ev for ge and 1.1 ev for si)
- At 0k there are no electrons in the Conduction band and the Valence band is completely filled.
- As the temperature increase, electrons from the Valence band Jump into Conduction band.
- The resistivity Varies from 10^{-14} to 10^{7} Ω meter
- They have electrical properties b/w those of insulators and Conductors

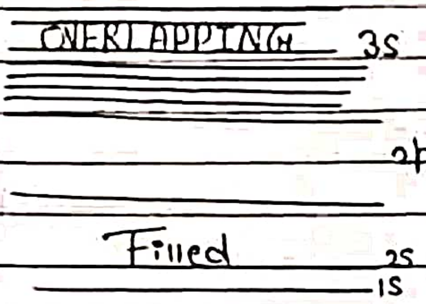


Valence and conduction bands of semi-conductor seperated by small band gap.

Conductors -

- In case of Conductors, there is no forbidden gap and the Valence band, conduction band overlaps each other.
- Plenty of Free e⁻ are available for electrical Conduction
- They posess very low resistivity and very high Conductivity values.
- Metals c like copper, iron etc are example of Conductors





Metals having
(a) Partially filled valence band (b) overlap of complete filled valence band.

○ Types of Semiconductor →

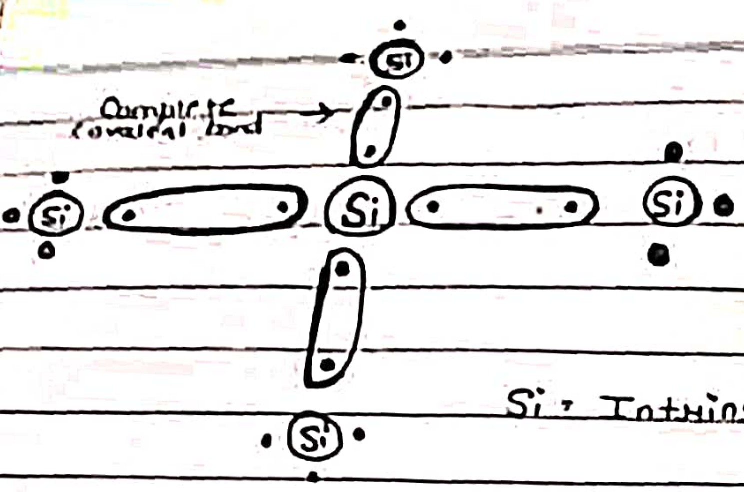
1. Intrinsic Semiconductor
2. Extrinsic Semiconductor

(1) Intrinsic Semiconductor -

- Pure germanium or silicon called an intrinsic Semiconductor Each atom possesses four valence electrons in the outermost orbitals.

- Crystalline Structure of instrinsic semiconductor at low temperature [0K].
- Silicon and germanium are tetravalent (having 4 valence electron
- Each atom forms a covalent bond or electron pair bond with the electrons of neighbouring atom.

- Atoms hence has no free electron available for Conduction (All the valence e⁻ are tightly bounded)
- The Semiconductor therefore behaves as an insulator at absolute zero temperature (0K)



Si : Intrinsic Semiconductor atom

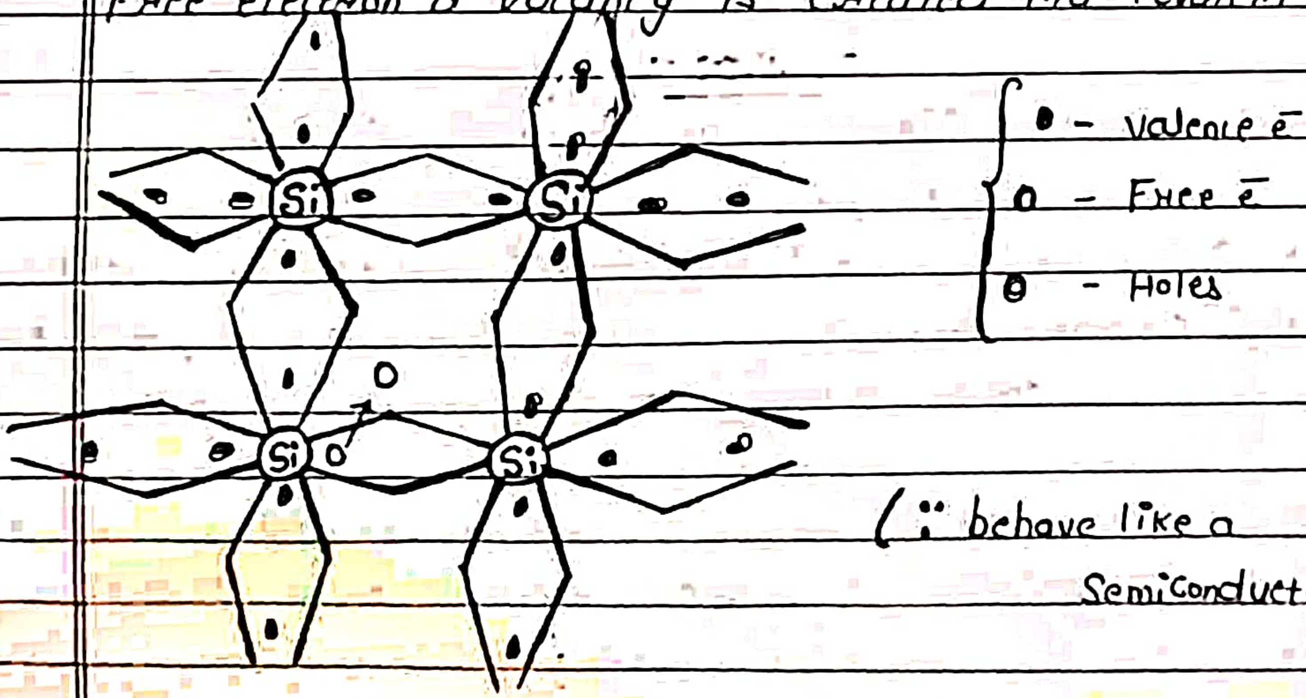
Crystalline structure of intrinsic semiconductor

- Crystalline Structure of intrinsic Semiconductor at Room temp. - [300K]

- At room temp., some of the valence electrons gain enough thermal energy to break up the covalent bonds.

- The breaking up of covalent bonds sets the electron free and is available for conduction.

- When an electron escapes from a covalent bond and becomes free electron a vacancy is created in a covalent bond



(∵ behave like a Semiconductor)

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- Such a Valency is called Holes and Carries opposite charge.
- It moves under the influence of an electric field in the direction of the electric field applied.

- The Semi-conductor Crystal is electrically neutral as

(2) Extrinsic SemiConductor-

- The Conductivity of an intrinsic semiconductor can be increased by adding small amounts of impurity atoms such as IIIrd or Vth group atoms The Conductivity of Silica is Increased by 1000 times on adding 10 parts of boron per million part of silicon.
- The process of adding impurities is called doping and the impurity is added is called dopant.

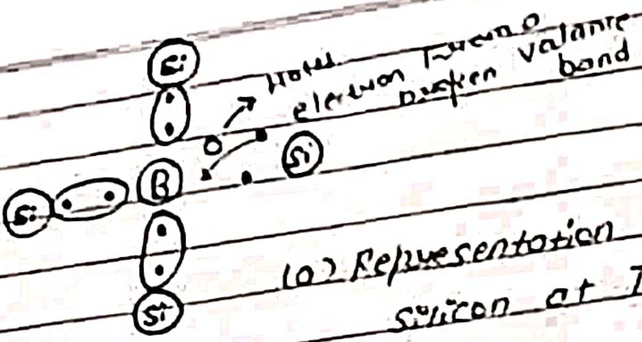
- Depending on the type of impurity added, extrinsic Semiconductors are further classified as-

(1) P-Type Semiconductor
(2) N-Type Semiconductor

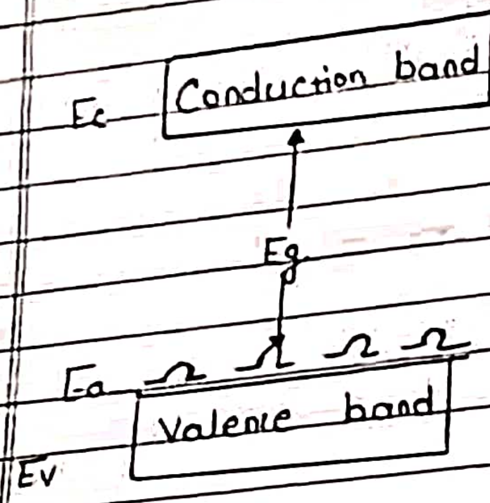
(1). P-Type SemiConductor-

- P-Type SemiConductor is formed by doping with trivalent Impurity atoms (acceptor) like III group atom. i.e Al, Ga, Indium etc to a pure semiconductor like Ge or Si, As the acceptor trivalent atoms has only three valence electron and Germanium. Silicon has four Valence electrons Holes and vacancy is Created for each acceptor donor atom.

- Hence holes are majority and electrons are minority.
- Also an acceptor energy levels "EA" is Formed near V.B Consisting of holes.



(a) Representation of P Type silicon at $T = 0K$



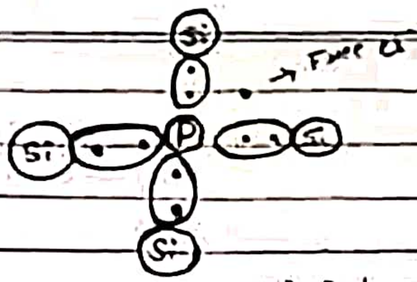
(b) Energy band diagram at $T=0K$

- As temp. inc. ($T>0K$) the electron in VB which are in Covalent bond break the bonds became free and move from VB to acceptor energy level Ea.

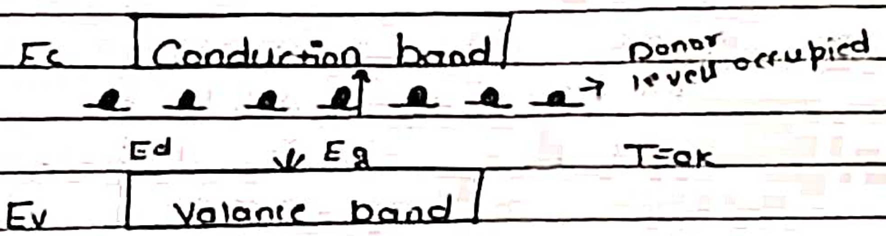
(2). N-Type Semiconductor :-

- In pure semiconductor, when pentavalent or impurity like phosphorus, atom consisting of Five Valen e^- is doped, and then concentration of e^- inc. than hol
- Hence the given semiconductor formed is called N-type semiconductor.

- By adding donar impurities, the free e^- generated or don from an energy level called as "Donar energy level" i.e. E_D
- ∵ Example of pentavalent - (1) Arsenic (2) Antimony (3) phosphorus



(a) Representation of n-type silicon at T=0K

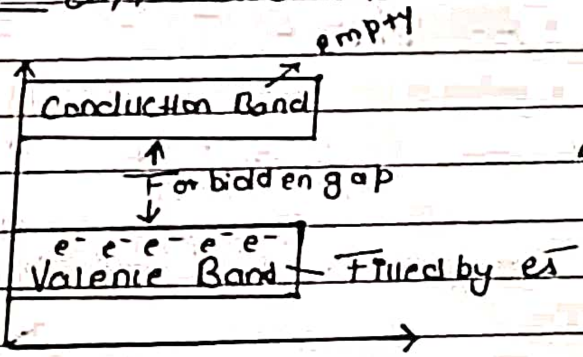


(b) Energy band diagram at T=0K

○ Energy Bands -

Range of energy possessed by electrons in a solid is known as energy band.

(1) Valance band - Range of energy possessed by valance $\bar{e}$.
(2) Conduction band - Range of energy possessed by Free $\bar{e}$
(3) Forbidden gap - diff. b/w V.B and C.B



$\Delta E_g = CB - VB$
eg - Si → 1.1eV

Carrier Concentration -

The Fermi distribution Function can be used to Calculate the Conc. of holes and electrons in the Semiconductor, if the density of available States in the Valence and Conduction bands is known the Concentration of electron in the Conduction band is given by -

$$n = \int_{E_c}^{\infty} F(E)\, N(E)\, dE \quad - ①$$

The no. of es per unit volume in the energy range dE is the product of density of states N(E) and the probability of occupancy F(E)

Thus total electron concentration is integral over the entire conduction band.

$$n = \int_{E_c}^{\infty} f(E)\, N(E)\, dE \quad - ①$$

Solving eq (1) we get the electron concentration in the conduction band

as $$\boxed{n = N_c\, e^{-(E_c - E_F)/kT}} \quad - ②$$

where

$$N_c = 2\left[\frac{2\pi m_n kT}{h^2}\right]^{3/2}$$

mn is the effective mass of electron.

Similarly, hole conc. in the valance band can be obtained as -

$$\boxed{p = N_v\, e^{-(E_F - E_V)/kT}} \quad - ③$$

where

$$N_v = 2\left[\frac{2\pi m_p kT}{h^2}\right]^{3/2}$$

∵ mp is the effective mass of the holes.

At thermal equilibrium, e^- and holes concentration given by equations (2) and (3) are valid for intrinsic as well as extrinsic semiconductor.

Intrinsic Carrier Concentration

$$n = \int_{E_c}^{\infty} f(E)\, N(E)\, dE \quad - ①$$

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$n = N_c e^{-(E_c - E_F)/KT}$ — (2)

$p = N_v e^{-(E_F - E_v)/KT}$ — (3)

$$\boxed{n \cdot p = (n_i)^2}$$

$n \cdot p = N_c e^{-(E_c - E_F)/KT} N_v e^{-(E_F - E_v)/KT}$

$n \cdot p = N_c N_v e^{-(E_c - E_v)/KT}$ — (4)

For intrinsic Semiconductor -

$n = n_i$ and $p = p_i$ and

$n_i p_i = N_c N_v e^{-(E_c - E_v)/KT}$

$n_i = p_i$

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

$\because n_i$ = Carrier Concentration

n = no. of electrons

p = no. of holes

Fermi level in Intrinsic SemiConductor lies at the middle of the Forbidden Gap -

The electron Concentration band of Semiconductor at temp. T is given by -

$n = N_c e^{-(E_c - E_F)/KT}$ —(1)

N_c is the effective density of states in Conduction band

The hole Concentration in Valence band of semiconductor at temp. T is given by -

$p = N_v e^{-(E_F - E_V)/KT}$ —(2)

N_v is the effective density of states in Valance band

For intrensic semiconductor -

$n = p$

$$\therefore N_c e^{-(E_c - E_F)/kT} \Rightarrow N_v e^{-(E_F - E_v)/kT}$$

$$\therefore \frac{e^{-(E_c - E_F)/kT}}{e^{-(E_F - E_v)/kT}} = \frac{N_c}{N_v}$$

$$\boxed{\text{At equilibrium } N_c = N_v}$$

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

$$e^{-(E_c - E_F - E_F + E_v)/kT} = e^0$$

$$\frac{E_c - E_F - E_F + E_v}{kT} = 0$$

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

Intrinsic Conductivity

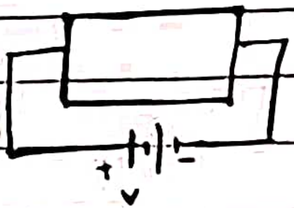
Consider a rectangular bar of intrinsic semiconductor connected to a battery is shown in Figure. when an electric field is applied along x-axis, the $\bar{e}$ move along negative x axis and holes along x-axis charge carrier attain some constant velocity called drift velocity

$v_d = \mu E$ —(i)

Let n be the conc. of e^-s, The current density

$J_e = n e v_d$ —(ii)

From (i) and (ii)



$J_e = n e \mu_e E$ —(iii)

Similarly,

$J_h = p e \mu_h E$ —(iv)

Total electric current density

$J_{total} = J_e + J_h$

$J_{total} = n e \mu_e E + p e \mu_h E$

$J_{total} = e(n \mu_e + p \mu_h)E$

Energy gap of a Semiconductor

The energy gap b/w valence band and conduction band

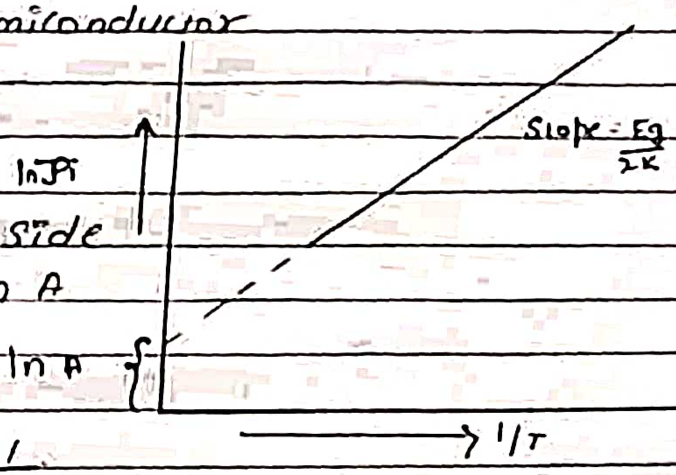
The resistivity of semiconductor

$$\rho_i = \frac{1}{\sigma} = \frac{1}{B \cdot e^{\left(\frac{-E_g}{2kT}\right)}}$$

$$\rho_i = A\, e^{\left(\frac{E_g}{2kT}\right)}$$

Taking ln on both side

$$\rho_i = \ln\left(\frac{E_g}{2kT}\right) + \ln A$$



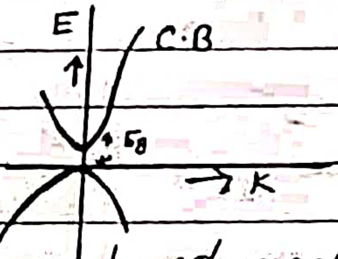
energy gap — $\ln \rho_i$ vs $\frac{1}{T}$

$$\frac{E_g}{2kT} = \frac{dy}{dx}$$

$$E_g = 2kT \frac{dy}{dx}$$

Direct band gap semiconductor

- In direct gap semiconductors the band diagram b/w energy and wave vector is shown



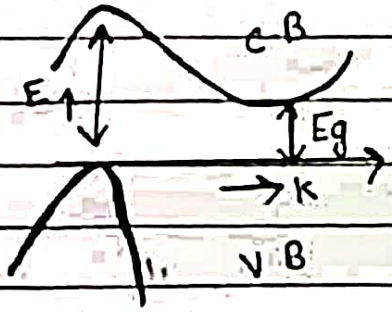
- In direct band gap the maximum of valence band and minimum of the conduction band present at same of K
- when an e^- recombines with hole, it emits their energy

in terms of light

- Life time of charge Carriers is Very less
- These are mostly form the Compound Semiconductor
- Examples : InP, GaAs
- Band gap of InP-1.35eV and GaAs-1.42eV
- used to fabricate LEDs and laser diodes

Indirect gap Semiconductors

- The band diagram b/w energy and wave Vector is shown in figure



- The max V.B and mini C.B present at diff. values of K

- when an e⁻ recombines with holes, it emits their energy in term of heat.

- Life time charge Carrier is more
- These are mostly form the elemental semiconductor
- Examples: Ge and Silicon.
- Band gap of Ge = 0.7eV and Si = 1.12eV
- used to fabricate diodes and transistors.

Drift Current and diffusion Currents

Drift Current :- The Flow of electric current due to the motion of charge Carrier under free influence of external electric field.

when an electric field E is applied across a semicond material, the charge carriers attain a drift velocity.

$V_d = \mu E$ — (i)

relation b/w current density J and V_d is

$J = Nq V_d$ — (ii)

where N is carrier concentration.

q is charge of e^- or hole

From eq (i) and (ii)

$J_{drift} = Nq\mu E$

μ is mobility of charge carrier

drift current density due to e^- is $J_e = ne\mu_e E$

n is e^- carrier conc.

drift density due to holes is $J_h^{drift} = pe\mu_n E$

Total drift current density

$$J^{drift}(total) = J_e^{drift} + J_h^{drift}$$

$$= ne\mu_n E + pe\mu_n E$$

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

Diffusion Current :-

The flow of electric current due to the motion of charge carriers under concentration gradient is called diffusion current.

∵ Rate of diffusion of charge $\propto -\frac{\partial(\Delta N)}{\partial x}$

$$= -D\frac{\partial(\Delta N)}{\partial x}$$

D is the diffusion coefficient of charge carrier.

-ive sign indicates decrease of N with inc. of x

So

$$J^{diffu} = q\left[-D\frac{\partial(\Delta N)}{\partial N}\right] = -qD\frac{\partial(\Delta N)}{\partial x}$$

q is the charge of charge carrier.

diffusion current due to holes

$$J_h = -e.D_h\frac{\partial(\Delta P)}{\partial x}$$

due to electrons

$$J_e = e.D_e\frac{\partial(\Delta n)}{\partial x}$$

$$J^{diff}(total) = J_h^{diff} + J_e^{diff}$$

$$= -e.D_h\frac{\partial(\Delta P)}{\partial x} + e.D_e\frac{\partial(\Delta n)}{\partial x}$$

The expression for total current density due to holes

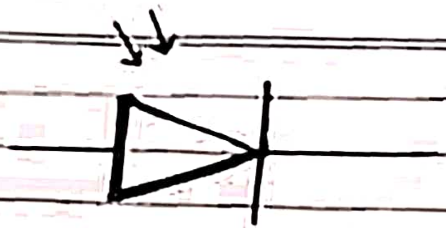
$$J_h(total) = pe\mu_h E - e.D_h\frac{\partial(\Delta P)}{\partial x}$$

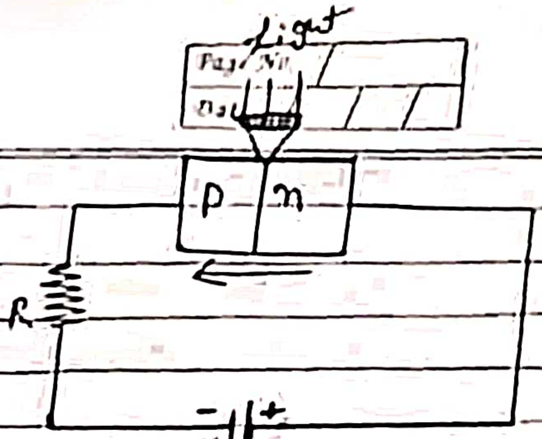
due to electron

$$J_e(total) = ne\mu_e E + e.D_e\frac{\partial(\Delta n)}{\partial x}$$

Photo Diode

Silicon photo diode is a light sensitive devices. It is also called as photo detector. Photo diode converts light signals into electrical signals. It is always operated in reverse biased condition.





Construction

The diode is made of semiconductor pn junction kept in a sealed plastic casing. The cover is so designed that the light rays are allowed to fall on one surface of junction and the remaining sides of the casing are painted to restrict the penetration of light rays. A lens permits light to fall on the junction.

Working

When light falls on the reverse biased p-n photo diode junction, hole-electron pairs created by breaking of covalent bondings. The magnitude of photo current depends on the number of charge carriers generated and on the light falling of diode element. The current is also affected by the Frequeny of light falling on the diode element. The magnitude of current under large reversed bias is given by

$$I = I_s + I_o\left(1 - e^{V/nV_T}\right)$$

where, I_s = Short Circuit current prop to light intensity

I_o • Reverse saturation current

V = Voltage across diode

V_T = Volt equilent of temp.

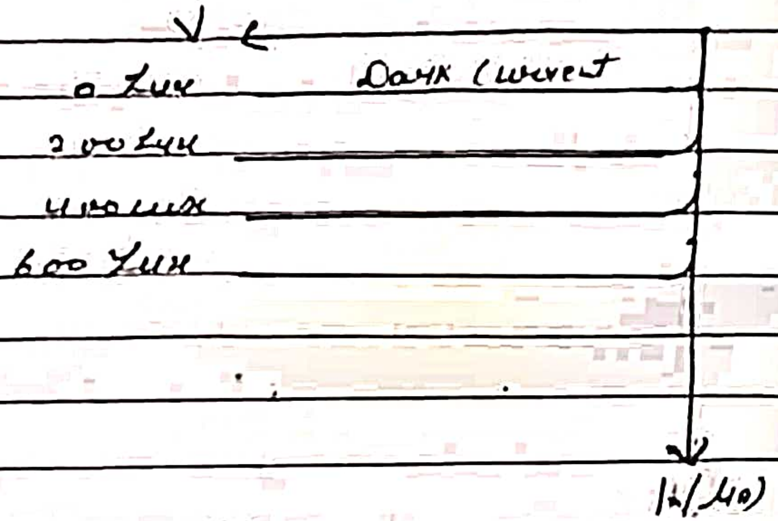
n = Parameter, 1 for Ge, 2 for Si

Characteristics

The characteristics of photo diode are show in Fig. The reverse current increases in direct proportion to the level of light. Even no light is applied there is minimum reverse leakage current called dark current flowing through the diode. Ge has higher dark current than silicon.

Applications

- Light detectors
- Demodulators
- Encoders



LED (Light emitting diode)

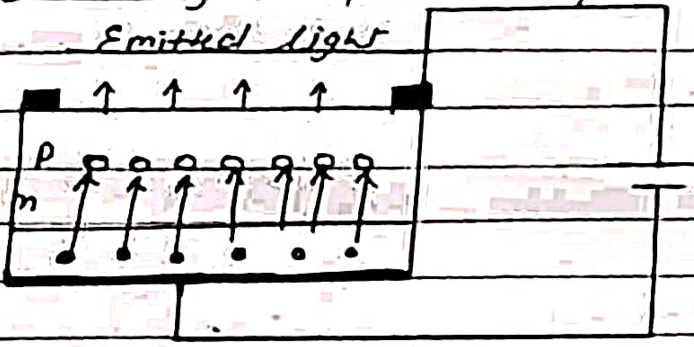
Light emitting diode is a pn junction device. It is always operated in forward biased condition. LED converts electrical energy into light energy. In the fabrication of LED's direct band gap semiconductors like GaP, GaAsP are used. In direct band gap semiconductors most of the energy is emitted in the form of light when hole and electron recombination takes place.

Symbol

LED Symbol

Construction :-

The basic structure and of an LED is shown in fig. In LED, an N-type layer is grown on a substrate and a p-type is deposited on it by diffusion. A metal (gold) coating is applied to the bottom of the substrate for the reflection of light and also to provide cathode connection. The metal anode connections are mode at the outer edges of the p-layer.



Working

When an LED is forward biased the electrons and holes move in towards the junction and recombination takes place. As a result of recombination the e^{-}s lying in the conduction band of an n-region fall into the hole lying in the valence band of a p-region. The difference of energy in the valence bands and conduction band is radiated in the form of light energy. Here their excess energy is transferred to the emitted photon. The brightness of emitted light is directly proportional to the forward bias current.

Applications

For instrument display
In Calculators
Digital clocks
optical Communication system

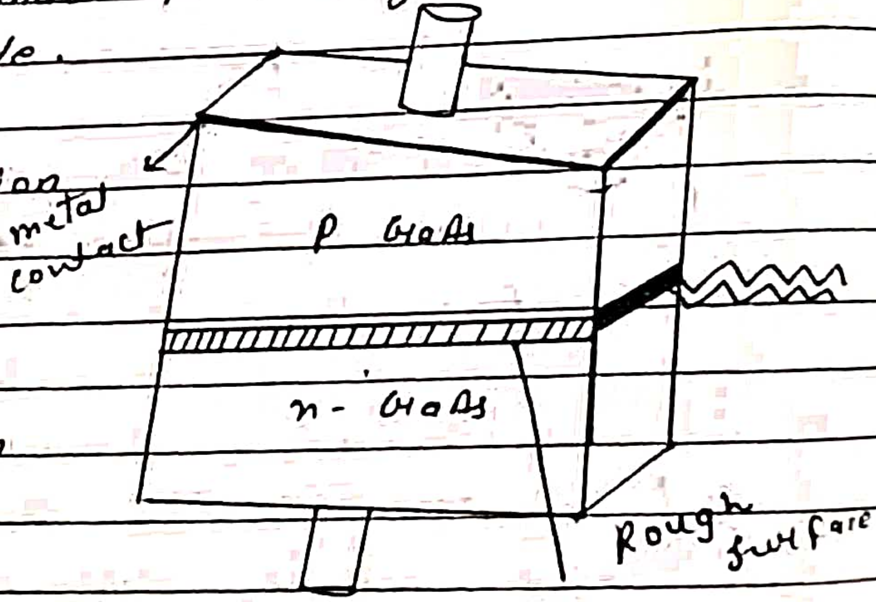
Laser Diode :-

Direct band gap semiconductors are preferred in the fabrication of laser diodes because they emit energy in terms of light when an electron and hole recombination takes place. These are operated at forward biased condition. Compound semiconductors like GaAs and InP and etc. are example of direct band gap semicon.

Constructions

In this laser system, the active is a p-n junction diode made from crystalline gallium arsenide.

The p and n-region in the diode are obtained by heavily doping ge and tellurium in GaAs.



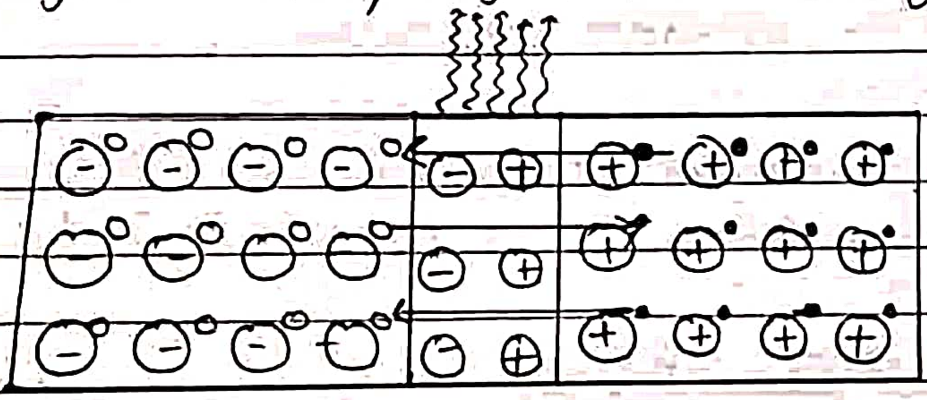
The thickness of the p-n junction is very narrow so that the emitted radiation has large divergence and poor coherence.

At the junction two sides are roughed to avoid laser emission and remaining two faces one is partially polished and other is fully polished. The laser emission takes place from the partially polished face. To provide bias two metal contacts are provided in the top and bottom of the diode as shown in figure.

Working

The semiconductor laser device is always operated in forward bias condition. Electron and holes are the minority charge carriers in p-region and p-region semiconductors.

When a huge current (10^4 amp) is passing through the p-n junction. p-region is positively biased. holes are injected into n-region from p-region and n-region is negatively biased electrons are injected into p-region from n-region.



For GaAs semiconductor $E_g = 1.4\,eV$

From planck's law

$$E_g = h\nu = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g} = \frac{6.63\times10^{-34}\times3\times10^{8}}{1.4\times1.6\times10^{-19}} = 8874\,A^{\circ}$$

The wave length of emitted radiation depends up on the conc of donor and acceptor atoms in GaAs. In case of GaAs homo junction which has an energy gap of 1.4eV gives a laser beam of wave length around 8874A°

The efficiency of the laser emission is inc. when we cool the GaAs diode.

Carrier Generation

Is a process where e - hole pairs are created by exciting an e^- from the VB of the semiconductor to the CB, there by creating a hole in the VB.

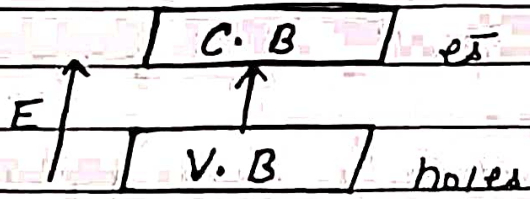
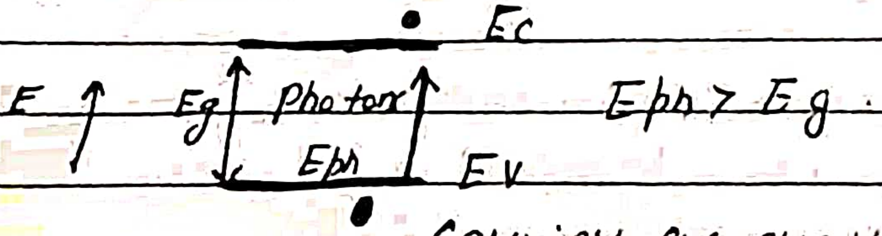


Fig. e^-s - holes generation.

Ways -

Light absorption.
High energy particle beam bombardment

1 By light Absorption



Carrier generation by photon generation.

If each absorbed photon creates one e^- - hole pair, the e^- and hole generation rates are given by

$$G_n = G_p = \alpha \frac{P_{opt}(x)}{E_{ph}\, A}$$

where α is absorption coefficient of the material for a particular photon energy and A is exposed are

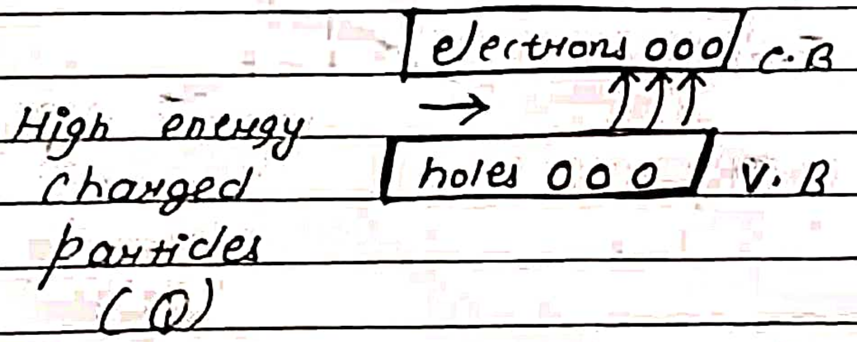
The absorption of light in semiconductor cause the optical power to decrease with distance. This effect is expressed mathematically by

$$\frac{d}{dt} P_{opt}(x) = -\alpha P_{opt}(x)$$

(2) By high energy particle beam bombardment

Thus e^- hole pair can be generated by high energy beams consisting of charged particles. If the available energy of particle is much larger than that band gap energy so multiple e^--hole pair can be produced.

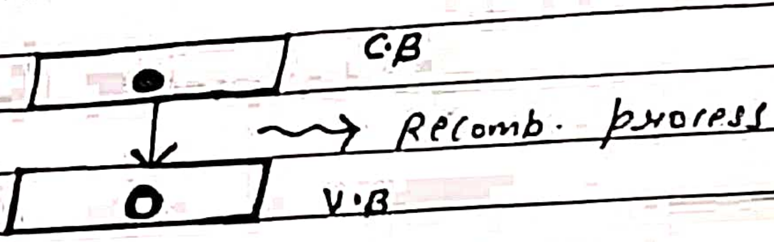
The H·E particle gradually loses it's energy and eventually stops. This generation mechanism is used in semiconductor based nuclear particle counter.



Recombination:-

Recombination of e^- and holes is a process by which both carriers 'annihilate' each other. This means e^-s occupy the empty states available with a hole. Both carriers eventually disappear in the process.

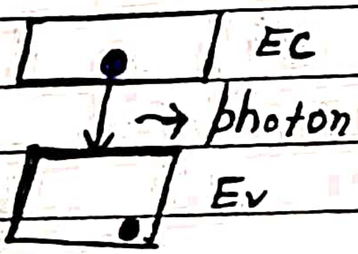
The energy released during recom. process can be radioactive or non radioactive

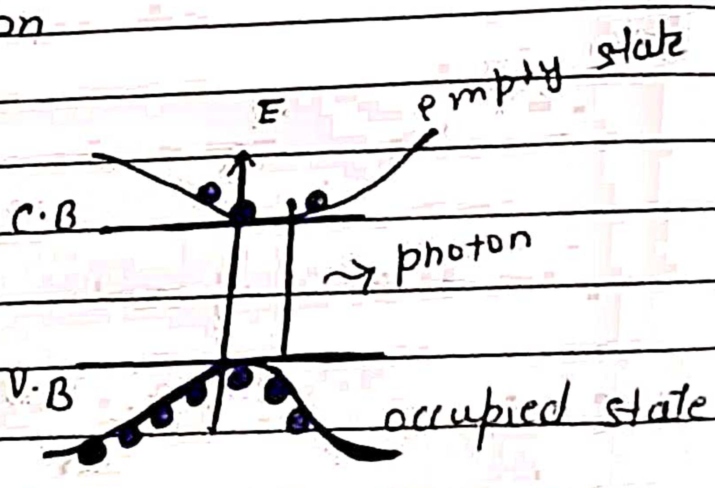


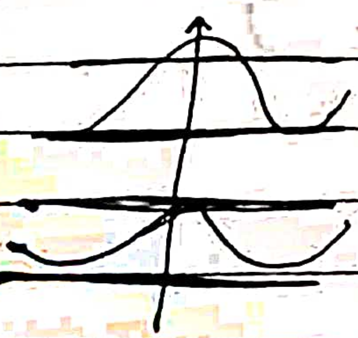
Types of Recombinations mechanism

- Band to band recombination
- Trap assisted recombination
- Auger recombination

(1) Band to Band







Band to band recombination depends upon the density of available e^-s and hole. Both Carrier type need to be available in the recombination process. Therefore recombination rate is expected to be proportional to product of 'n and p'.

Also, in thermal equilibrium the recombination rate must be equal to the generation rate

As the product of n and p equal in thermal equi:

$$u = b(np - n_i^2)$$

b is recombination Coeff

2 Trap assisted recombination

It occur when e^- falls into a trap (an energy level within band gap caused by the presence of a foreign atom

The e^- occuping the trap, in a second trap step, moves into empty V B state, thereby completing the recombination process.

3. Auger recombination

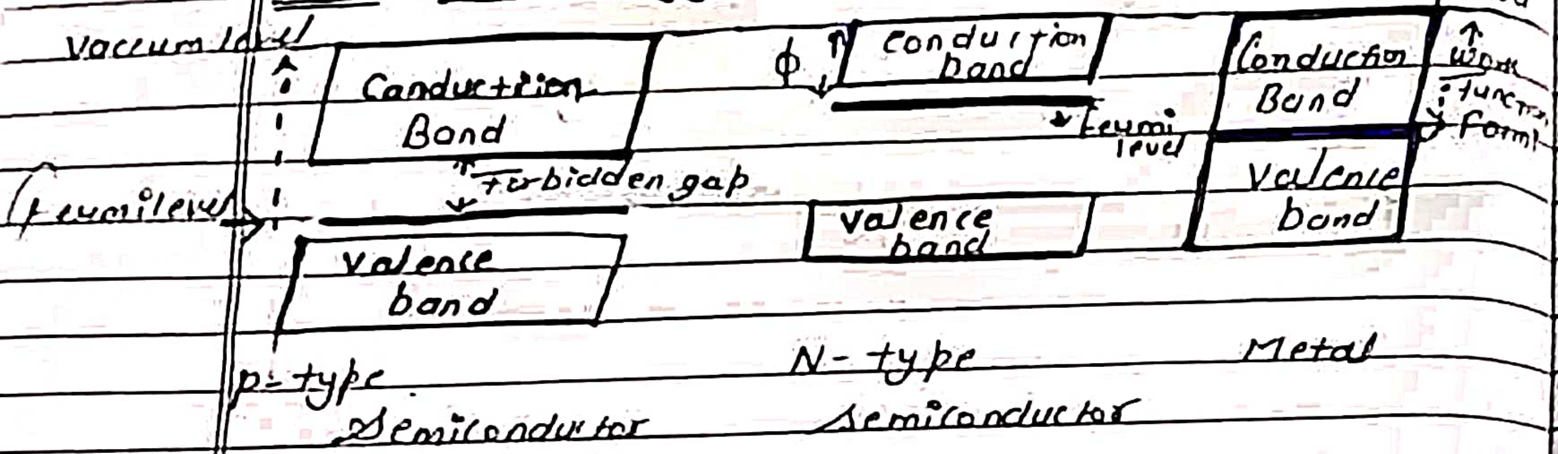
It is a process in which an e^- and a hole recombin in a band transition, but now the resulting energy is given -

off to another e (or hole) which gives up this energy by Collision with lattice

Metal- Semiconductor Junction-

02/02/24

Basic Terminology



1. Vaccum level :- Energy of electron when it is in vaccum with which kinetic energy is zero.

2. Work Function (ϕ) → Energy released when an e⁻ added to atom or molecule or diff. b/w vaccum and fermi level in semicondu

Metal Semiconductor Junction.

★ Junction:- when a metal and semiconductor are brought into contact, there are two type of Junction formed depending on the work function of semiconductor and its relation with the metal.

(i) Schottky Junction → $\phi_m > \phi_{semi}$

(ii) ohmic Junction → $\phi_m < \phi_{semi}$

(1) **Schottky Junction** :- we considered a junction formed b/w metal and n-type semi-conductor as shown in figure.

Fig. (a) (Before contact)

The fermi level of semiconductor is higher (since its work function is lower) than the metal. There are e⁻s in the conduction band of the semiconductor which can move to empty energy state above the empty energy state above the fermi level of the metal (E_F).

This leaves a positive charge on the semiconductor side and due to the excess electron on negative charge on the metal side as shown in fig.

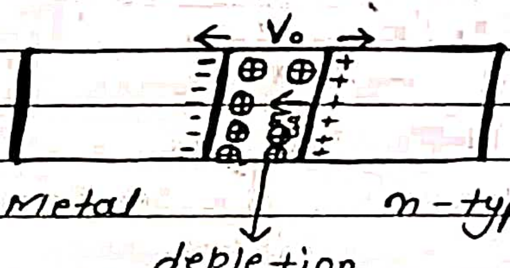


Fig (b)

The electrons are removed not only from the surface but also from a certain dept within the semiconductor.

This leads to the formation of the deplation region within the semiconductor as shown in fig (b).

Thus when a Schottky junction is formed the fermi-level lines up and also a positive potential is formed on the semiconductor side, because the depition region extends within a certain dept in the semiconductor, there is bending of of energy band on the semiconductor side

Bands bend up in the direction of the electric field (positive to negative), opposite to potential). This means the energy bands bend up going from n-type semiconductor to metal as shown in fig.(C)

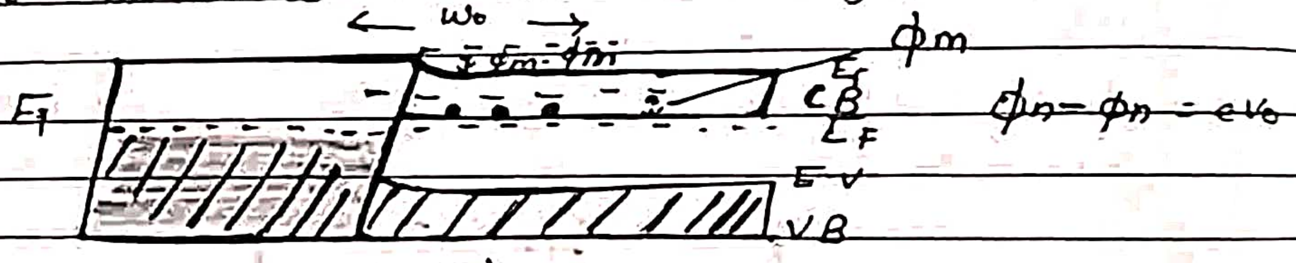


Fig (C)

The fermi level line up and there is a certain region in the semiconductor (Wo) where the bands bend called depletion region or space charge layer

A potential (eV_0) is developed in the Schottky junction given by eV_0 = work function of metal − work function of semiconductor

$$\phi_n - \phi_m = eV_0 \quad - ①$$

This contact potential act as barrier for the e^-s to move further from semiconductor to metal.

There is also a barrier for e^-s to move from move metal to semiconductor called Schottky barrier and is given by

$$\phi_B = (\phi_m - \phi_n) + (E_c - E_{Fn}) = \phi_m - \chi_n \quad - ②$$

where χ_n is the e^- atknitity for the n-type semiconductor.

There are two type of bias

① Forward bias

② Reversed bias

① Forward bias

Metal is connected to positive terminal and semiconductor is connected to negative terminal.

→ In forward bias the applied external potential opposes developed potential. So voltage is develo drop across the depletion region.

Fermi level no longer line up. In forward bias fermi level of semiconductor (E_{F_n}) shift upward

Thus. electrons injected from the external circuit have lower barrier to reaching from semiconductor to metal. Hence current increase

The current in a schottky diode in forward bias is given by

$$J = J_0\left[\exp\left(\frac{eV}{k_BT}\right)-1\right] - ③$$

J is current density and J₀ is the constant expressed as

$$J_0 = AT^2\exp\left(\frac{-\phi_B}{k_BT}\right) - ④$$

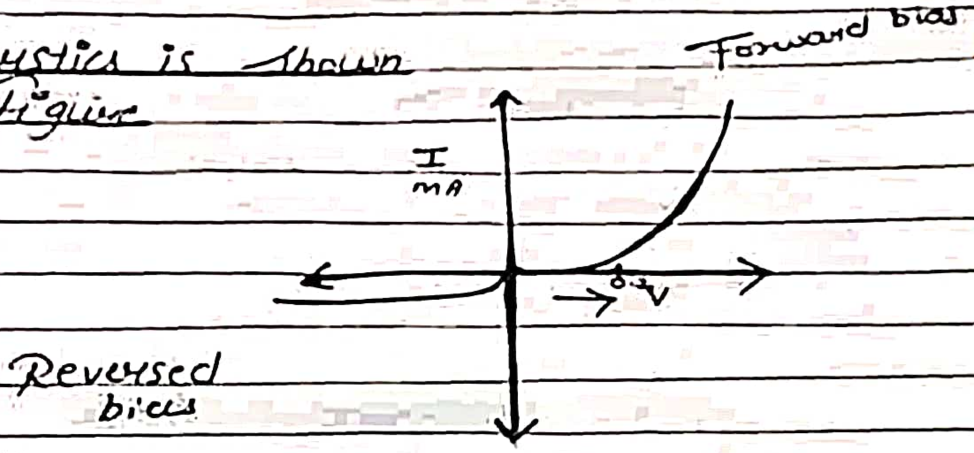
Where A is constant

Reversed bias :- Metal is connected to negative terminal and semiconductor is connected to positive terminal of the battery.

The applied external potential is the direction of developed potential so voltage across depletion region increase

Termilevel no longer line up. (E_{Fn}) Shift downward. So barrier became higher the current decreases and is given by same equation for (4) so a schottky junction act as rectifier that is it conduct in forward bias not in reversed bias its mean in Schottky junction current flow only in one direction

IV characteristics is shown in figure



Ohmic Junction

when the semiconductor has a higher work function than metal ($\phi m < \phi sem.$) the junction formed is called ohmic junction.

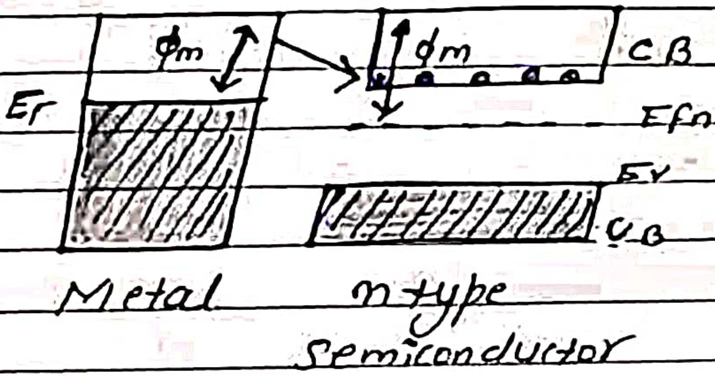
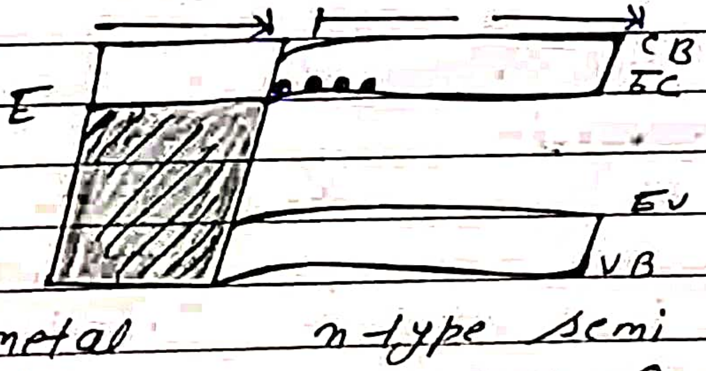


Fig (a) Before Contact



(b) After Contact

Fermi level line up as shown as figure in equilibrium, e⁻ moves metal to empty state in the conduction band(CB) so that there is an accumulation region near the interface (all the semiconductor side). This region has a higher conductivity due to electrons (due to e⁻) than the bulk of Semiconductor

Thus, a ohmic junction behave as a resistor, conducting in both forward and reversed bias.

I.e. that in ohmic current flow in both direction.

One of the interesting application of ohmic junction is in thermoelastic junction whereas some volume can be cooled by application of direct current.

For ohmic junction, heat can be generated or absorbed as shown in figure. This is called peltiar effect.

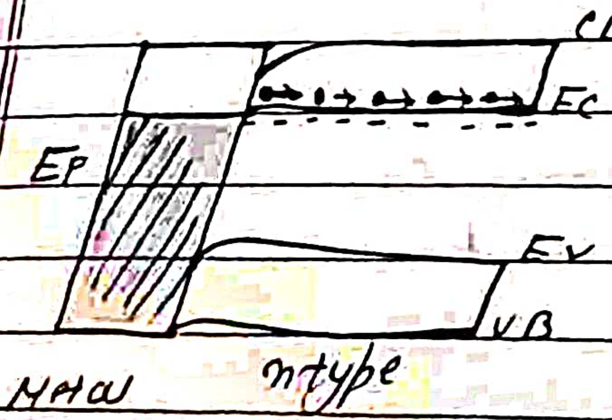


Fig:- Heat absorption

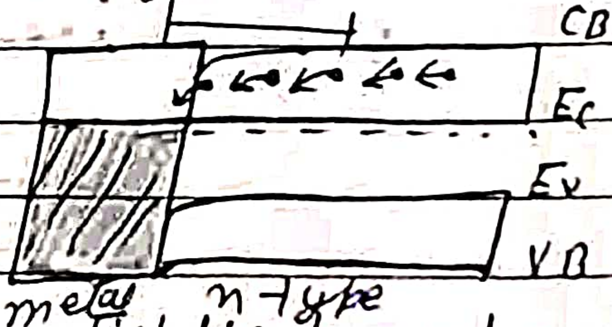


Fig:- Heat released

P+ this applicable to funition between any two the ~~dssi~~ dissimilar material

In p- type cooling and heating are reversed.