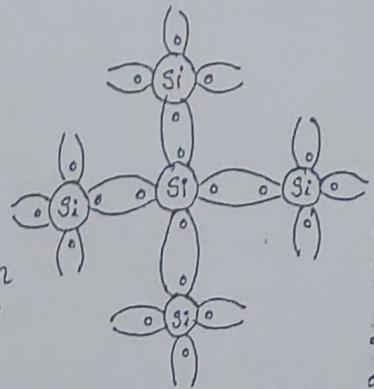


Intrinsic Semiconductor are one having no impurity but may have defects. The important Intrinsic Semiconductors are silicon, and Germanium.

If we consider pure silicon lattice, there are four nearest neighbour to each silicon atom and there are two electron bonds between each of the neighbours and the atom. In Intrinsic Semiconductor a forbidden gap exist between a filled valence band and the conduction band, but the width of the forbidden gap expressed in energy is much smaller than that of an Insulator.



In order to conduct, the electrons from top of the full valence band have to move into the conduction band by crossing the forbidden gap. The field that needs to be applied to do this work will be extremely large.

For example - Si - $E_g = 1.1 \text{ eV}$ Neighbouring ion core distance $\approx 1 \text{ \AA} = (10^{-10} \text{ m})^2$
Therefore field gradient of $1V/(10^{-10} \text{ m}) = 10^{10} \text{ V/m}$ is necessary to move an electron from the top of valence band to bottom of conduction band. Such high field gradient is not realizable in practice.

The other possibility by which this transition can be brought about is by thermal excitation. At room temperature, the thermal energy that is available can excite a limited number of electrons across the energy gap. This limited number account for Semiconduction.

The promotion of some electrons across the gap leaves some vacant sites in valence band called holes. An Intrinsic Semiconductor contains equal number of electrons in conduction band and equal number of holes in valence band. i.e. ($n_e = n_p$)

Under extremely applied field, the electrons which are excited into the conduction band by thermal means, can accelerate using the vacant sites available in the conduction band. At the same time, the holes in valence band also move but in direction opposite to that of electrons. Thus electrical conductivity is written as $\sigma_i = n_e e \mu_e + n_p e \mu_p$

Fermi Energy in Intrinsic Semiconductors

The number of free electrons per unit volume in Intrinsic Semiconductor

$$n = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2} \exp \left(\frac{E_F - E_C}{kT} \right)$$

The number of free holes per unit volume in Intrinsic Semiconductors

$$P = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2} \exp \left(\frac{E_V - E_F}{kT} \right)$$

In Intrinsic Semiconductor ($n = P$)

$$2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2} \exp \left(\frac{E_F - E_C}{kT} \right) = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2} \exp \left(\frac{E_V - E_F}{kT} \right)$$

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

$$e^{\frac{2E_F - E_C}{kT}} = \left[\frac{m_h^*}{m_e^*} \right]^{3/2} \exp \left(\frac{E_V - E_F}{kT} \right)$$

Taking log on both sides

$$\frac{2E_F}{kT} = \frac{3}{2} \log_e \left(\frac{m_h^*}{m_e^*} \right) + \log_e \left[\exp \left(\frac{E_V - E_F}{kT} \right) \right]$$

$$\frac{2E_F}{kT} = \frac{3}{2} \log_e \left(\frac{m_h^*}{m_e^*} \right) + \left(\frac{E_V - E_F}{kT} \right) \Rightarrow E_F = \frac{3kT}{4} \log_e \left(\frac{m_h^*}{m_e^*} \right) + \frac{E_V - E_F}{2}$$

If $m_p^* = m_e^*$ then

$$E_F = \frac{E_V + E_C}{2}$$

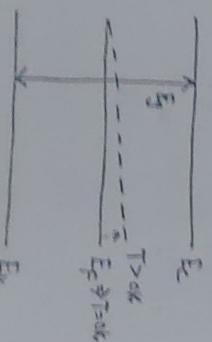
Variation of Fermi Level based on Temperature

$$\text{When } T=0K \Rightarrow E_F = \left(\frac{E_V + E_C}{2} \right)$$

Fermi level is located half way between Valence and Conduction band as its position is independent of temperature

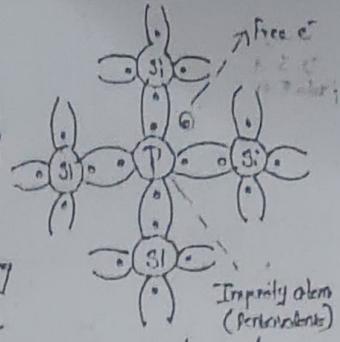
$$\text{When } T > 0K \Rightarrow E_F = \frac{3kT}{4} \log_e \left(\frac{m_h^*}{m_e^*} \right) + \left(\frac{E_V + E_C}{2} \right)$$

Fermi level rises slightly ($\because m_h^* > m_e^*$) upward with increase in temperature



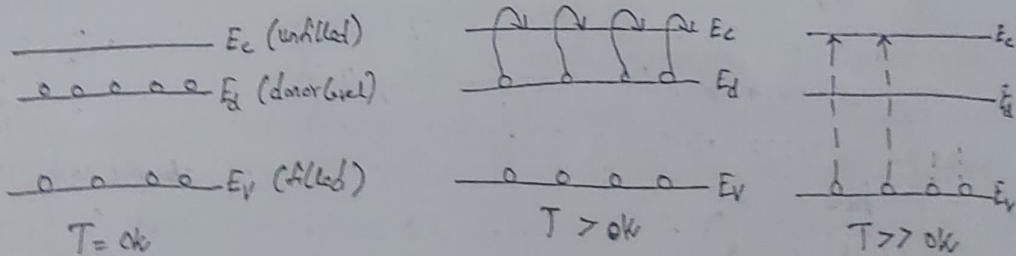
The Semiconductor, N-type Semiconductors are formed.

Consider a silicon crystal which is doped with pentavalent impurity such as P, As etc. In case of phosphorus, added as impurity to pure Si crystal, four of five electrons in outermost orbital of phosphorus atom take part in bonding with four silicon neighbours. The fifth electron cannot take part in the discrete covalent bonding and is loosely bound to parent atom (e^- orbit is $\approx 80\text{ \AA}$). Such large orbit evidently means that fifth electron is almost free and is at the energy level close to conduction band.



When $T=0\text{K}$, Valence band is filled and phosphorus atoms will be ionised. The energy levels of donor electrons are very close to bottom of conduction band.

At $T>0\text{K}$, donor electrons are excited to conduction band and becomes majority charge carriers. If thermal energy is sufficiently high, in addition to ionisation of donor impurity atoms, breaking of covalent bonds may also occur thereby giving rise to generation of electron-hole pairs.



Fermi Energy in N-type Semiconductor is given by

$$E_F = \left[\frac{E_d + E_c}{2} \right] + \frac{kT}{2} \ln \left(\frac{N_d}{N_z} \right)$$

where $N_z = 2 \left[\frac{2\pi m_e kT}{h^2} \right]^{3/2}$

When $T=0\text{K}$

$$E_F = \left[\frac{E_d + E_c}{2} \right]$$

When $T>0\text{K}$

$$E_F = \left[\frac{E_d + E_c}{2} \right] + \frac{kT}{2} \ln \left(\frac{N_d}{N_z} \right)^{-1}$$

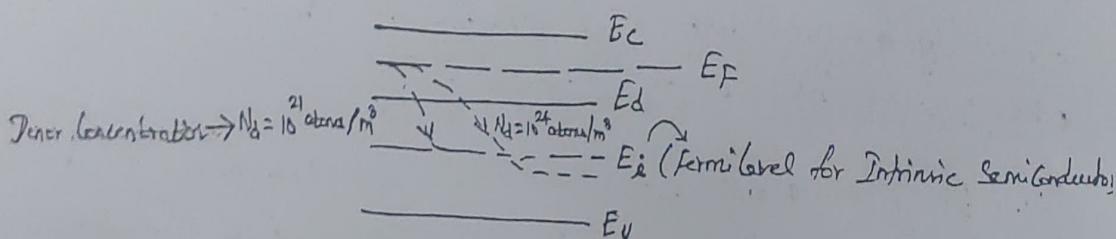
$$E_F = \left[\frac{E_d + E_c}{2} \right] - \frac{kT}{2} \ln \left(\frac{N_d}{N_z} \right)$$

Variation of Fermi level with Concentration (donor) & Temperature

$$\text{At } T=0K \quad E_F = \left[\frac{E_d + E_c}{2} \right] \longrightarrow$$

$$\text{At } T>0K \quad E_F = \left[\frac{E_d + E_c}{2} \right] - \frac{kT}{2} \ln \left(\frac{N_2}{N_d} \right)$$

(ie) when T increases, E_F decreases — Initially donor atoms are ionized and further increase in temperature leads to generation of electron-hole pair due to breaking of covalent bonds and material tends to behave in intrinsic manner.



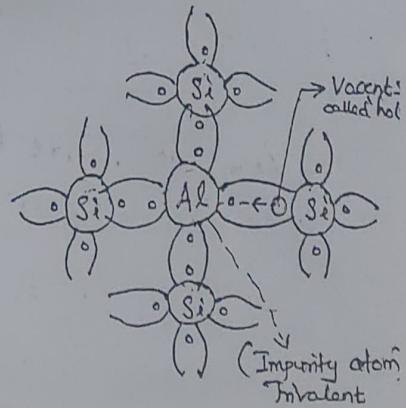
P-type Semiconductor — When trivalent impurity is added to pure Semiconductor, P-type Semiconductors are formed

Consider silicon crystal which is doped with trivalent impurity such as Al, B. In case of Al added as impurity to pure Si-crystal, three electrons bonds with three neighbouring silicon atoms and Al accepts one electron from fourth silicon atomic bond. Create Vacant site called hole on silicon.

This hole is considered to reside around the aluminium atom (Orbit $\approx 80\text{\AA}$) is free and is at the energy level close to top of Valence band.

When $T=0K$, Valence band is filled and Al atom is ready to accept electrons. Hence acceptor level is close to top of Valence band.

At $T>0K$, acceptor level takes electrons from Valence band and thus giving to holes in Valence band for conduction. If temperature $T>>0K$ electron-hole pairs are generated due to breaking of covalent bond.



$$E_F = \left(\frac{E_V + E_A}{2} \right) - \frac{kT}{2} \ln \left(\frac{N_A}{N_D} \right) \text{ where } N_D = 2 \left[\frac{2\pi m_p^* kT}{h^2} \right]^{3/2}$$

When $T=0K$

$$E_F = \left[\frac{E_V + E_A}{2} \right]$$

When $T > 0K$

$$E_F = \left(\frac{E_V + E_A}{2} \right) - \frac{kT}{2} \ln \left(\frac{N_A}{N_D} \right)$$

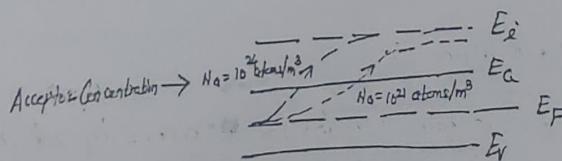
$$E_F = \left(\frac{E_V + E_A}{2} \right) + \frac{kT}{2} \ln \left(\frac{N_A}{N_D} \right)$$

Variation of Fermi level with concentration (acceptors) & temperature



$$\text{At } T > 0K \quad E_F = \left(\frac{E_V + E_A}{2} \right) + \frac{kT}{2} \ln \left(\frac{N_A}{N_D} \right)$$

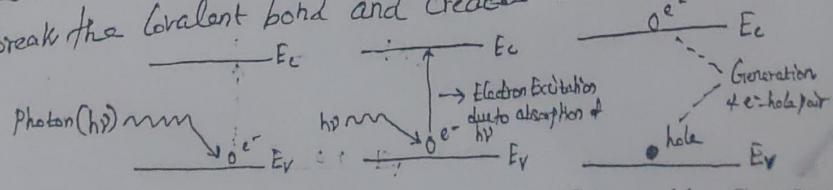
(i) When T increases, E_F increases — Initially acceptor atoms are ionized and further increase in temperature leads to generation of electron-hole pair due to breaking of covalent bonds and material tends to behave in intrinsic manner.



Explanation for Carrier Generation

Generation is a process in which free electrons & holes are generated in pair for semiconductor by absorbing light energy or raising temperature.

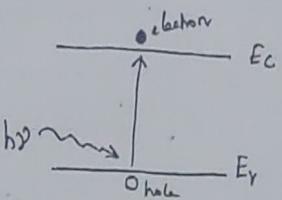
Consider the process of optical absorption in semiconductor. If light of energy ($h\nu$) is allowed to fall on the semiconductor. If the photon energy ($h\nu$) $\geq E_g$ (band gap of semiconductor) then photon energy is absorbed in the semiconductor because it has enough energy to break the covalent bond and creates electron-hole pair.



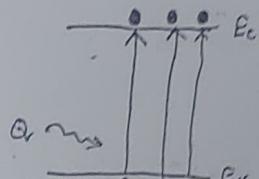
Generation due to light absorption - Occurs if photon energy is large enough to raise an electron from valence band into empty conduction band state, generating one electron-hole pair. For this photon energy $E \geq E_g + E_k$, where E_k is added to electron & the hole in the form of kinetic energy.

(ii) Generation due to High energy beam - Occurs if high energy beam whose available energy (E) is much larger than (E_g) so that multiple electron-hole pairs can be formed. This kind of generation mechanism are used in nuclear particle counter based on semiconductors.

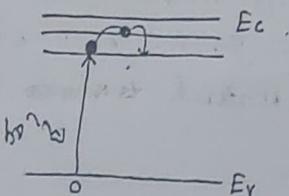
(iii) Generation due to Impact Ionization - Caused by an electron/hole with an energy, which is much larger / smaller than the conduction / valence band edge.



Generation - Due to Light absorption



Generation - Due to High energy beam

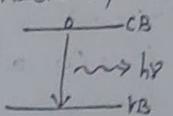


Generation - due to Impact Ionization

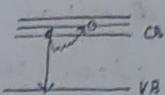
Explanation for Recombination Process

Recombination of electron & holes is a process by which both carriers annihilates each other - electron occupy through one or multiple steps - the empty state associated with hole. Both carriers eventually disappear in this process. This leads to one possible classification of the recombination processes.

1) Radiative Recombination



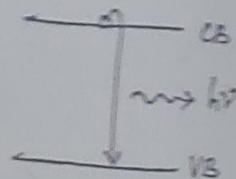
2) Non Radiative Recombination



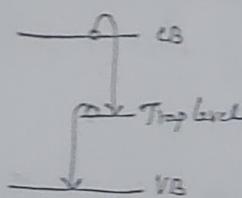
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Let us see different types of Recombination mechanisms

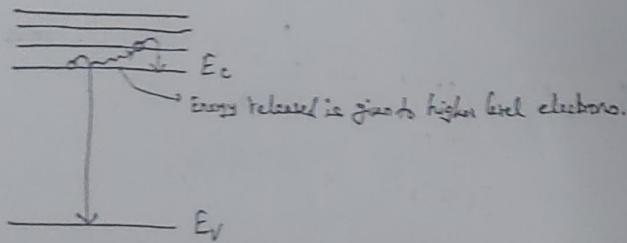
- D) Band to band Recombinations - Occur when electron moves from its conduction band state into empty Valence State associated with hole. This type of Recombination is mostly radiative.



- 2) Trap-assisted Recombination - Here Electron falls into a trap or energy level within the bandgap caused by the presence of Impurity atoms or structural defects. During Recombination, the electrons falls to trap from Conduction band & then to Valence band. This Recombination is also called Shockley - Read - Hall Recombination



- 3) Auger Recombination - Involves band to band transition but resultant energy is released either to hex level electrons in Conduction band or lower level in Valence band. This Recombination mostly results with phonon emission to stimulate other electrons (or holes) in Conduction / valence bands.



Carrier Transport - Drift & Diffusion Current

Current flow in a semiconductor can be either due to an applied electric field (drift current) or due to difference in the carrier concentrations (diffusion current)

Drift Current — When electric field is applied across a bar of semiconductor, electron & hole acquire a drift velocity (v_d) proportional to the magnitude of the electric field. While electron move in a direction opposite to that of applied field, holes move in the direction of the field. This directional movement of charge carriers constitutes a current, which is usually referred as "Drift Current".

Consider ' J ' be the current density in semiconductor having ' n ' electrons per unit volume travelling at a velocity ' v_d ' is given by

$$J = nev_d$$

But $v_d \propto E \Rightarrow v_d = \mu E$ where μ is mobility of charge carrier

$$\therefore J = n\mu E$$

If the material is semiconductor, the current flow would be due to electron & hole motion, correspondingly the current densities due to electron drift & hole drift are

$$J_n(\text{drift}) = n\mu_n E$$

$$J_p(\text{drift}) = p\mu_p E$$

Thus total drift current is the sum of the two components

$$J(\text{drift}) = J_n(\text{drift}) + J_p(\text{drift})$$

$$J(\text{drift}) = n\mu_n E + p\mu_p E$$

Diffusion Current — If there is non-uniform concentration of charge carriers in semiconductor, in addition to drift current, there exists another important current component due to this concentration gradient. When there is a concentration gradient, the carrier tends to diffuse from region of higher concentration to region of lower concentration thereby constituting a current flow called diffusion current.

Let us consider Δn be the electron concentration with distance x in semiconductor.

The rate of electron flow = $\frac{\partial}{\partial x} (\Delta n)$ concentration gradient

Then rate flow of electron across unit area = $D_n \frac{\partial (\Delta n)}{\partial x}$ (D_n - Diffusion coefficient)

$$J = -\text{charge} \times \text{flux}$$

Then current density due to electric drift is $J_n = eD_n \frac{dN}{dx} (\text{A/m}^2)$

Similarly current density due to hole diffusion is $J_p = eD_p \frac{dP}{dx} (\text{A/m}^2)$

$-ve$ sign signifies that direction of hole current is opposite to the direction of the increasing concentration gradient.

Current density Equations

When electric field and concentration gradient is present across the Semiconductor sample, both drift and diffusion currents are and the total current density for electron and hole is given by

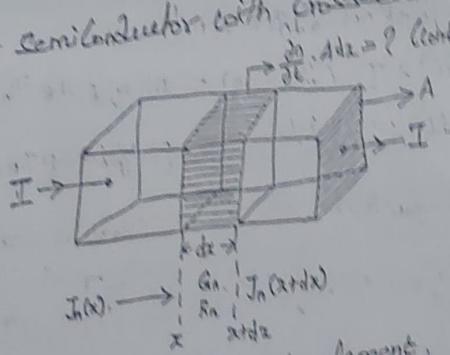
$$J_n = J_n(\text{drift}) + J_n(\text{diffusion}) = ne\gamma_n E + eD_n \frac{dN}{dx} (\text{A/m}^2)$$

$$J_p = J_p(\text{drift}) + J_p(\text{diffusion}) = pe\gamma_p E - eD_p \frac{dP}{dx} (\text{A/m}^2)$$

Continuity Equation

The overall effect when drift, diffusion, generation as well as recombination of carriers in a Semiconductor is expressed by the continuity equation.

Consider a bar semiconductor with cross-sectional area (A) as shown



(dx) be the infinitesimal thickness of element. Then volume of infinitesimal element is $(A \cdot dx)$.

The essence of continuity equation is that the overall rate of increase in number of electrons $\left(\frac{dn}{dt}\right)$ at a given volume $(A \cdot dx)$ is given by a algebraic sum of four components:

- 1) Rate of flow of electrons into the infinitesimal element at (x)
- 2) Rate of flow of electrons out of it at $(x+dx)$
- 3) Rate at which electrons generated in the element (G_n)
- 4) Rate of recombination in the element (R_n)

$$\text{Then } \frac{dn}{dt} \cdot A \cdot dx = J_n(x+dx) \frac{A}{2} - J_n(x) \frac{A}{2} + (G_n - R_n)$$

We know $J = -nA\frac{dV}{dx}$

$$J_{nA} = I$$

Electron flow (I_n) Rate of electron flow = $\frac{I_n A}{q} \cdot dx = \frac{dn}{dt} \left[\because \frac{dn}{dx} = I_n \right]$
in terms of $(A \cdot dx)$

Now,

$$\text{Rate of electron flow at } (x) = \frac{I_n A}{q} \cdot A \cdot dx \rightarrow (\text{into the element})$$

$$\text{Rate of electron flow at } (x+dx) = \frac{I_n(x+dx)}{q} \cdot A \cdot dx \rightarrow (\text{out of the element})$$

Increase in electron flow at given volume $A \cdot dx$

$$\text{Then, } \frac{dn}{dt} A \cdot dx = \left[\frac{I_n(x+dx)}{q} - \frac{I_n(x)}{q} \right] A \cdot dx + G_n - R_n$$

Since dx is extremely small, we can express

$$I_n(x+dx) = I_n(x) + \frac{dI_n}{dx} \cdot dx$$

$$\text{Then, } \frac{dn}{dt} = + \frac{dI_n}{dx} \left(\frac{1}{q} \right) + G_n - R_n \quad (\text{for electrons})$$

$$\text{Also, } \frac{dp}{dt} = - \frac{dI_p}{dx} \left(\frac{1}{q} \right) + G_p - R_p \quad (\text{for holes})$$

In the above equation $I_n A \frac{dV}{dx}$ depends on

$$I_n = I_n(\text{drift}) + I_n(\text{diffusion}) = n e \gamma_e E + e D_n \frac{d}{dx}(dn)$$

$$I_p = I_p(\text{drift}) + I_p(\text{diffusion}) = p e \gamma_p E - p D_p \frac{d}{dx}(dp)$$

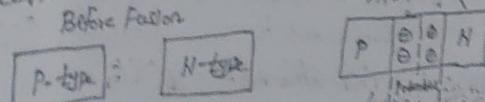
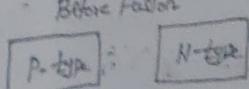
so continuity equation for charge carriers becomes

$$\frac{dn}{dt} = \frac{1}{q} \frac{\partial}{\partial x} \left[n e \gamma_e E + e D_n \frac{d}{dx}(dn) \right] + G_n - R_n \quad (\text{for electrons})$$

$$\frac{dp}{dt} = - \frac{1}{q} \frac{\partial}{\partial x} \left[p e \gamma_p E - p D_p \frac{d}{dx}(dp) \right] + G_p - R_p \quad (\text{for holes})$$

p-n Junction

p-n Junction is one of the basic building blocks of integrated circuits.
Such a Junction can be formed by selective diffusion (or) Ion implantation of N-type (p-type dopant) to P-type (N-type) Semiconductor
Before Fusion

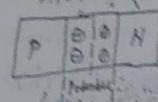


$$\downarrow \text{Annealing} \downarrow$$

$$E_F$$

$$E_F$$

$$E_F$$



$$E_F$$

$$E_F$$

(After annealing)

Conduction Band

When P-region and N-region are brought in close contact, a PN-junction due to difference of charge carrier. The hole difference from p-region to n-region, electrons diffuse from n-region to the p-region. Under thermal equilibrium, a built-in electric field directed from positive to negative charge with force which drives and the net transport of carriers. (carrier distribution is changed across the potential barrier. (also called depletion layer))

At thermal equilibrium, there is diffusion component of current that cancel each other, $I_P + I_N = 0$. Therefore built-in field must be limited throughout the electric field concentration on both sides same.

Final level in p-region & N-region is given by

$$E_F = E_{F0} - kT \ln\left(\frac{N_D}{N_A}\right) \text{ for p-region}$$

$$E_F = E_{F0} - kT \ln\left(\frac{N_A}{N_D}\right) \text{ for N-region}$$

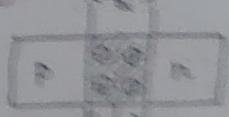
$$(E_F) \text{ p-region} = (E_F) \text{ N-region} \text{ since } E_{F0} - E_{F0} = kT \ln\left(\frac{N_A}{N_D}\right)$$

$$E_{F0} - E_{F0} \rightarrow \text{Therefore built-in potential } V_B = kT \ln\left(\frac{N_A}{N_D}\right)$$

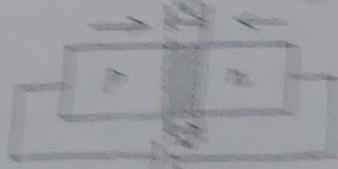
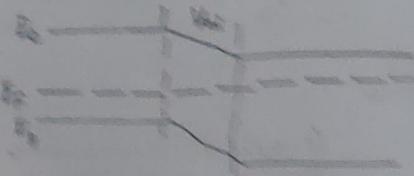
PN-Junction under forward biasing

When PN-junction is applied with external voltage, the electron and hole concentration deviates from their equilibrium values. Also, potential difference across depletion region increases from its equilibrium value (V_{bi}) by an amount of applied bias.

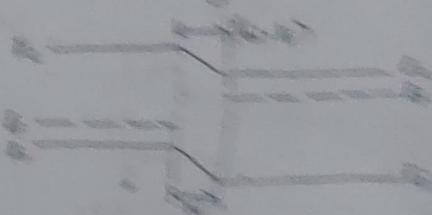
When PN-junction is forward biased by (V_f) , that is, the terminal of battery is connected to p-region and -ve terminal to N-region. As potential difference across depletion region becomes by $(V_{bi} + V_f)$, the width of depletion region with decreases. Thus more charge from n-region moves to p-region and maximum distance went ΔV_f .



at equilibrium



forward biased



When P-region and an n-region are brought in close contact, a pn-junction forms due to diffusion of charge carriers. While holes diffuse from p-region to n-region, electrons diffuse from n-region to the p-region. Under thermal equilibrium, a built-in electric field directed from positive to negative charge which gives rise to drift current and no net transport of carriers due to diffusion is observed across the potential barrier. (also called depletion region)

At thermal equilibrium, drift & diffusion component of current must cancel each other, $I_p = I_n$ is zero. Therefore Fermi level must be constant throughout & electron, hole concentrations on both sides remain same.

Fermi level on p-region & N-region is given by

$$E_F = E_{ip} - kT \ln\left(\frac{N_d}{n_i}\right) \text{ for p-region}$$

$$E_F = E_{in} - kT \ln\left(\frac{N_d}{n_i}\right) \text{ for N-region}$$

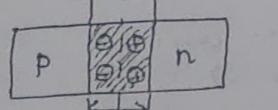
$$(E_F) P\text{-region} = (E_F) N\text{-region} \text{ then } E_{ip} - E_{in} = kT \ln\left(\frac{N_d N_d}{n_i^2}\right)$$

$$\text{If } E_{ip} - E_{in} = V_{bi} \rightarrow \text{Therefore built-in potential } V_{bi} = kT \ln\left(\frac{N_d N_d}{n_i^2}\right)$$

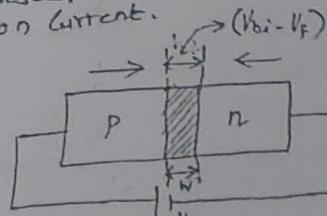
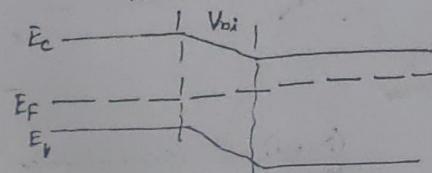
pn-Junction under forward biasing

When pn-Junction is applied with external voltage, the electron and hole concentration deviates from their equilibrium values. Also potential difference across depletion region decreases from its equilibrium value (V_{bi}) by an amount of applied bias.

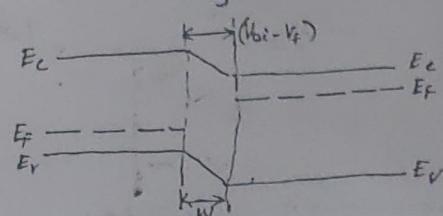
When pn-Junction is forward biased by (V_f), that is, the terminal of battery is connected to p-region and -ve terminal to N-region, the potential difference across depletion region decreases by ($V_{bi} - V_f$). Thus width of depletion region will decrease. Thus more electrons from n-region moves to p-region and increases diffusion current.



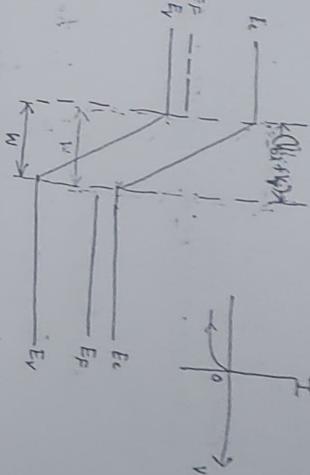
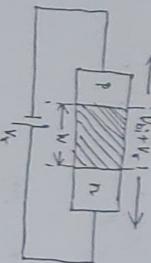
At equilibrium



Under forward bias



When a pN -Junction is reverse biased by (V_R), that is, terminal of battery is connected to n -region and the terminal to p -region, the potential difference across depletion layer increases by ($V_R + V_b$). Thus width of depletion layer increases and hence no recombination in n -region and no holes from p -region diffuse across the junction. Now current is due to diffusion of minority charge carriers in pN region which is extremely small.



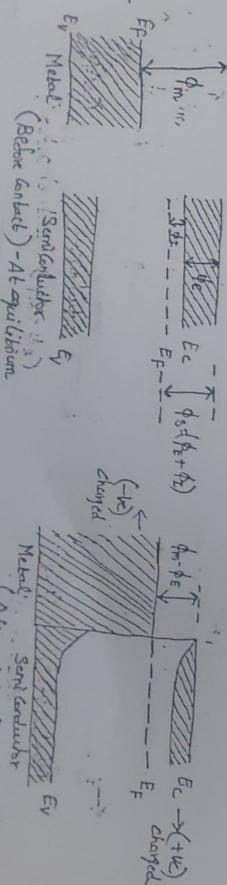
Metal-Semiconductor Junction

The metal - semiconductor junction is the oldest practical semiconductor device. This can either be rectifying or non-rectifying. The rectifying semiconductor junction is also known as Schottky diode, while the non-rectifying junction is called an Ohmic contact.

D) Rectifying Junction (or) Schottky Junction - [Non ohmic]

whenever a workfunction of n -type semiconductor is smaller than that of the metal (or) workfunction of p -type semiconductor is greater than that of metal, it forms Rectifying (or) Schottky Junctions.

Let ϕ_m and ϕ_s be the workfunction of metal & n -type semiconductor respectively, when $\phi_m > \phi_s$, when the metal - Semiconductor contact is made, the conduction electrons begin to flow from semiconductor into the metal until Fermi energies on both sides of junction are equal. Therefore metal becomes $+ve$ charged and n -type semiconductor (depleted) becomes $-ve$ charged. As a result, potential barrier is formed at the metal - semiconductor junction equal to $(\phi_m - \phi_s) = eV$.



When potential is applied to system such that metal to -ve charge and semiconductor to +ve charge.

N-type is connected to the charge & metal to -ve charge, then height of barrier on Semiconductor side increases by $(V_s + V)$ and metal remains uncharged. Therefore junction is said to reverse biased & current flows from metal to semiconductor.

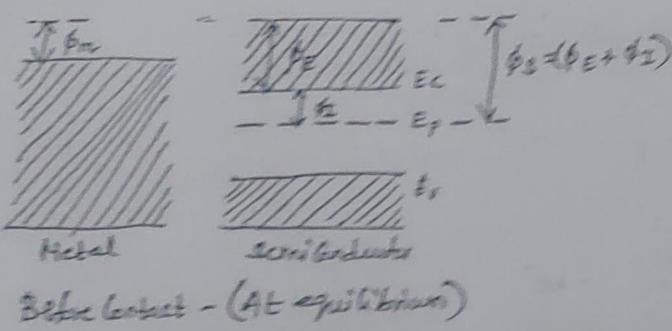
Conversely if the voltage is reversed so as to make semiconductor with +ve charge and metal to -ve charge, the height of barrier on Semiconductor side decreases by $(V_s - V)$ and metal remains uncharged. Therefore junction is said to forward biased & current flows from n-type to metal.

For forward bias, net current increases exponentially with applied voltage and for reverse bias - net current is constant. The metal - Semiconductor contact acts like rectifier and hence called rectifying contact.

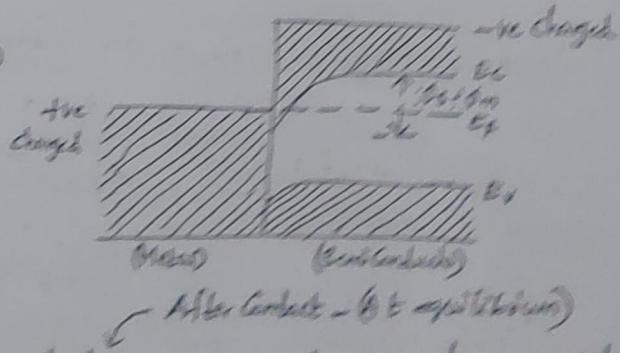
2) Non Rectifying Junction - [Ohmic]

When ever the workfunction of metal is less than n-type Semiconductor ($\phi_m < \phi_s$) it forms non rectifying (or) Ohmic Junction.

Let $\phi_m & \phi_s$ are workfunctions of metal & Semiconductor considered. When metal - Semiconductor contact is made, the conducting electrons begin to flow from metal to semiconductor until Fermi energies on both sides of junction are equal. Therefore metal becomes +ve charged and n-type semiconductor becomes -ve charged. As a result bi-potential barrier is created between metal - Semiconductor equal to $(\phi_s - \phi_m) = eV$



Before Contact - (At equilibrium)



After Contact - (At equilibrium)

When potential is applied to system such that metal to -ve charge and semiconductor to +ve charge, the electron flows from Semiconductor to metal without encountering an appreciable barrier. When semiconductor is applied with -ve charge and metal with +ve charge, the electron flows from metal to semiconductor without any charge in barrier. Thus in both cases current is directly proportional to applied voltage in accordance to Ohm's law. Such contacts are called Ohmic contacts.

Semiconducting materials for optoelectronic applications

Major Semiconducting materials used for optoelectronic applications,
II-V and II-VI Group

Among the two Groups semiconductors - II-V are more suitable,
as they are direct bandgap materials which in necessary condition needs
for optoelectronic devices to convert electrical light energy conversion.

II-V materials = column III & IV in periodic table.

III column = Al, Ga, In

IV column = Si, P, As, Sb

Important applications for some II-V Semiconducting materials.

AlGaAs = Light emitter & detector

GaInP = Optoelectronics

AlGaInP = Red Emitter LED

GaAsP = Visible LED

AlGaAsSb = Light emitter & detector

The suitable choice of such materials depends on their size, i.e.,
quantum dimension (1D, 2D or 3D) for optoelectronic applications.

II-VI Semiconducting materials = column II & VI in periodic table

They are having wide range of optoelectronic properties ranging from
for IR to UV region. Easily tuned in different (Eg), by incorporating
metallike ions. They have strong polarity due to ionic bonding

Important applications for some II-VI Semiconductors

ZnSe = Blue-Green LED's

ZnS = UV emitters, display

ZnO = UV emitters

CdS = Visible light LED's

CdSe = Colour LED's (short wave)

Phot Current in P-n Junction diode

In a photodiode, the incident optical signal generates electron-hole pairs that gives rise to a photocurrent across p-n junction.

When p-n junction is illuminated with light of photon energy (E_0) (i), photons are absorbed in semiconductor & electron-hole pairs are generated both in n-region and p-region of the junction. For the electron-hole pair to contribute towards current in external circuit, the generated electron and holes must be separated before they recombine. This is achieved if electron-hole pairs are generated in the depletion layer, where the electric field sweeps away the electron & holes in opposite directions.

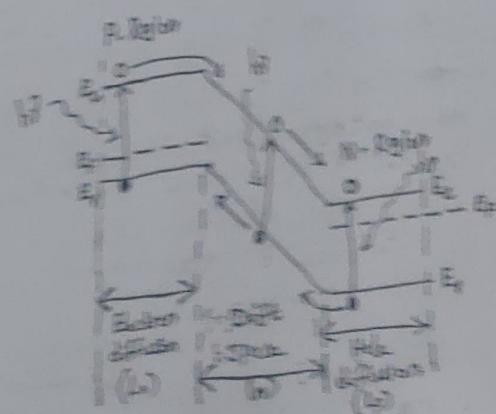
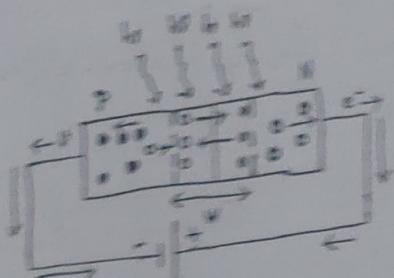
The photo-generated minority carrier, which are generated with one diffusion length from the depletion layer edge, can also diffuse in the depletion region without recombining. They are then swept away by the junction due to the electric field present in the depletion region. Due to the direction of electric field being from the n-region to p-region, the holes flow towards the p-region and electrons to the n-region. Since the direction of this photo-generated current I is opposite to that in a forward-biased diode, the total current in illuminated p-n junction diode is

$$I = I_{ph} + I_s + I_d$$

If G is generation rate, A is area over which photo current flows.

$$(I) = eG(L_p + L_n)A$$

Where L_p & L_n are distance of the depletion region edge where electron-holes are generated
W - width of depletion Region



Types of OLED

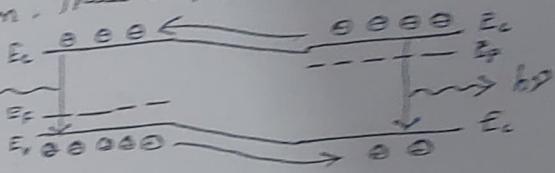
Light emitting Diodes (LED)

LED are PN-Junctions that can emit spontaneous radiation in Ultraviolet, visible (0-700 nm) & regions. These device converts electrical energy to optical energy under forward bias mode.

Principle

Under forward bias, the majority carries from N & P regions cross the junction and becomes minority carrier in the other regions.
 (i) Electrons from N-region Crosses Junction & becomes Minority Carrier in P-region
 Also holes from P-region Crosses Junction & becomes Minority Carrier in N-region
 The above process is called "minority carrier injection". If biasing voltage is further increased, the excess minority carriers diffuse away from Junction and recombine with majority carriers as shown in diagram. Thus a radiative recombination event leads to photon emission with energy equal to ($h\nu$) and is equal to E_g .

$$(ii) h\nu = E_g \\ \frac{hc}{\lambda} = E_g \Rightarrow \boxed{\frac{hc}{E_g} = \lambda} \Rightarrow \text{photo wavelength}$$



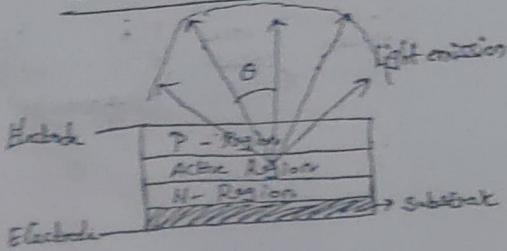
Types of LED's

LED must be constructed such that light emitted by radiative recombination event can escape the structure.

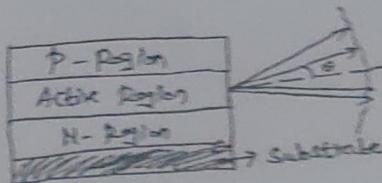
Designed as either Surface / Edge emitter

- 1) Surface Emitters - designed to reflect light from bottom edge to top surface to enhance output Intensity.
- 2) Edge emitter - here light emission is relatively direct from the active region (0-1 depletion region). Edge emitters have higher efficiency in coupling to an optical fibre whereas surface emitters are emitting light in wide angle and is highly incoherent and so used in signalling device and as indicators.

Surface Emitter LED



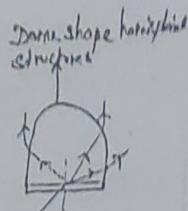
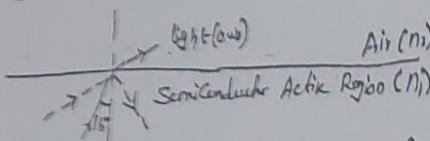
Edge emitter LED



internal quantum efficiency in LED
 Internal quantum efficiency is 100%. But external quantum efficiency decreases. The main reason is that most of emitting light radiation comes off material interface at greater than critical angle and hence dropped off the device.

(i) Critical angle at semiconductor-air boundary is given by $\theta_c = \sin^{-1} \left(\frac{n_1}{n_2} \right)$
 For example if $n_1 = 3.5$ (Noble) & $n_2 = 1.0$ (air)

$$\theta_c = \sin^{-1} \left(\frac{1}{3.5} \right) = 16^\circ \text{ then}$$



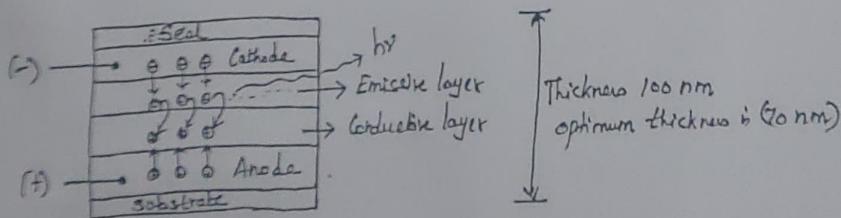
In the above diagram all the rays striking surface above 16° undergo total internal reflection and reflected back inside. Hence to improve external efficiency loss caused by bulk absorption and for improved surface transmission - Hemispherical lenses made of plastics are used at surface

Choice of materials for device fabrication - GaP, GaAs, GaAsP etc.

Organic Light Emitting Diode (OLED)

A type of LED where emissive electroluminescent layer is a film of organic compound which emit light in response to an electric current.

Structure of OLED - A simple OLED is made of six different layers. On the top and bottom there are layers of protective glass or plastic. The top layer is called seal and bottom layer is substrate. In between - a negative terminal (cathode) and positive terminal (anode) and finally between cathode and anode - two layers made of organic molecules called emissive layer (produces light) and the conductive layer



- 1) Substrate - clear glass / plastic
- 2) Anode - positive charged (Indium Tin Oxide) - inject holes
- 3) Organic layer - (Emissive + Conductive layers) - poly aniline + poly fluoresce
- 4) Cathode - Negative charged & inject electrons

Conjugated Polymers are having characteristics of LED and having (Eg) same like semiconductor, by doping with P-type/N-type materials used for light emission

Types of OLED

- 1) Passive Matrix OLED - The organic layer is between strips of cathode and anode that run perpendicular Advantages - easy fabrication, useful for small screen display
- 2) Active Matrix OLED - organic layer is between layer of cathode and anode Advantages - less power requirements, suitable for large screen

Advantages of using OLED - much thinner compared to LCD, less in weight, flexible, consumes less power, suitable for display in cellphones and MP3 players. Response time is 200 times faster than LCD, bigger viewing angle, less expensive

Disadvantages - OLED display do not last as long, organic molecules are sensitive to water

Applications - Animated bill boards, display in cellphone, MP3 players, Tablet computers with folding display, wrist watches, head sets, TV, Camera etc.