Variation of Fermi level of Intrinsic semiconductors with temperature

Intrinsic semiconductor requires a thermal excitation or application of voltage/electric field for conduction to take place. In a pure intrinsic semiconductor like Si or Ge, an electron is excited from top of valence band to bottom of conduction band. These created hole-electron pairs are responsible for conduction. The Fermi-Dirac distribution of these electrons for conduction are:

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

The Fermi level of E_F for an intrinsic semiconductor lies midway in the forbidden gap such that,

$$E - E_F = \frac{E_g}{2}$$

Then,

$$f(E) = exp\left(\frac{-E_g}{2kT}\right)$$

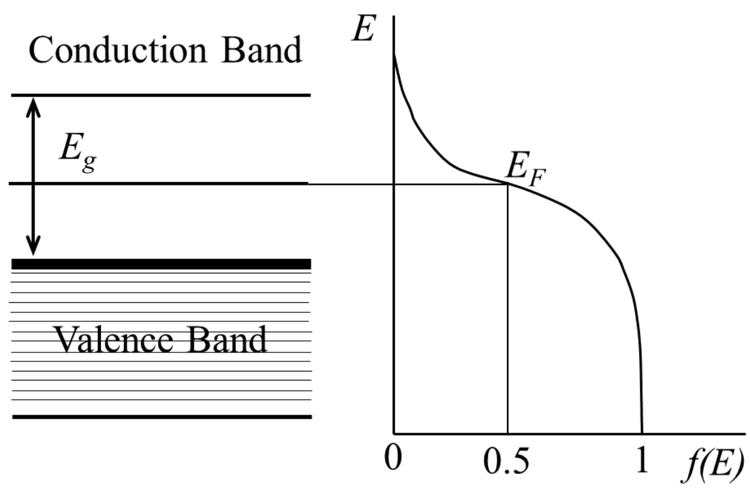


Figure 1: Fermi level of intrinsic semiconductor

Number of electrons promoted across the gap is given by,

$$n = N\ exp\left(\frac{-E_g}{2kT}\right)$$

where, N is the number of electrons available for excitation from top of the valence band.

For intrinsic semiconductor, number of holes in the valence band is equal to the number of electrons in the conduction band.

$$n_e = n_h$$

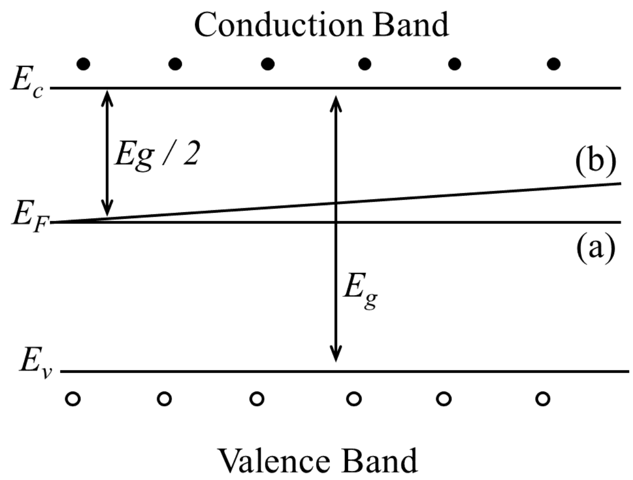


Figure 2: Fermi level of intrinsic semiconductor. (a) E_F at $T = 0$ K, and (b) E_F at $T > 0$ K

When energy is provided, these electrons and holes move with mobility μ_e and μ_h, respectively in opposite directions. The energy can be provided by external field or thermal excitation. Now total conductivity of intrinsic semiconductor is given by,

$$\sigma_i = n_e e \mu_e + n_h e \mu_h$$

e is the electronic charge, n_e is the concentration of electrons per unit volume, n_h is the concentration of holes per unit volume. Then,

$$n_e = \int_{E_C}^{\infty} Z(E)F(E)dE, \text{ concentration of electrons in conduction band}$$

where, $Z(E)$ is the density of states, $F(E)$ is the Fermi Dirac distribution.

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

Also,

$$n_h = \int_{-\infty}^{E_V} Z(E)F(E)dE, \text{ concentration of holes in valence band}$$

where, $Z(E)$ is the density of states, $F(E)$ is the Fermi Dirac distribution.

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

For intrinsic semiconductor, $n_e = n_h$

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

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

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

Taking log on both sides,

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

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

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

For, $m_h^* = m_e^*$, $log_e 1 = 0$.

$$E_F = \left(\frac{E_V + E_C}{2}\right)$$

The position of E_F is half-way between E_V and E_C changes slightly with temperature by rising above.

Photo Current in a p-n Diode

→ When light falls on a semiconductor to generate $e^- - h^+$ pairs, some of the carriers are collected at contact and leads to photo current.

→ The current flowing through a p-n diode due to the absorption of light, in the presence of an bias voltage is called as photo current.

→ Let us consider a long p-n diode in which excess charge carriers are generated uniformly at a rate G_L.

→ The p-n diode has a depletion region of width W.

→ The electron-hole pairs generated in the depletion region start moving or become mobile ~~ring~~ rapidly by the electric field existing in the region.

→ Hence, the electrons ~~are sto~~ start moving into the n-region while the holes start moving into p-region.

→ The photocurrent arising from the photons ~~absorp~~. absorbed in the depletion is thus given by;

$$I_{L1} = A \cdot e \int_0^x G_L \cdot dx = A \cdot e G_L W$$

where, I_{L1} → photocurrent

A → Area of the diode (Uniform generation rate in the diode is assumed.

W → width of depletion region.

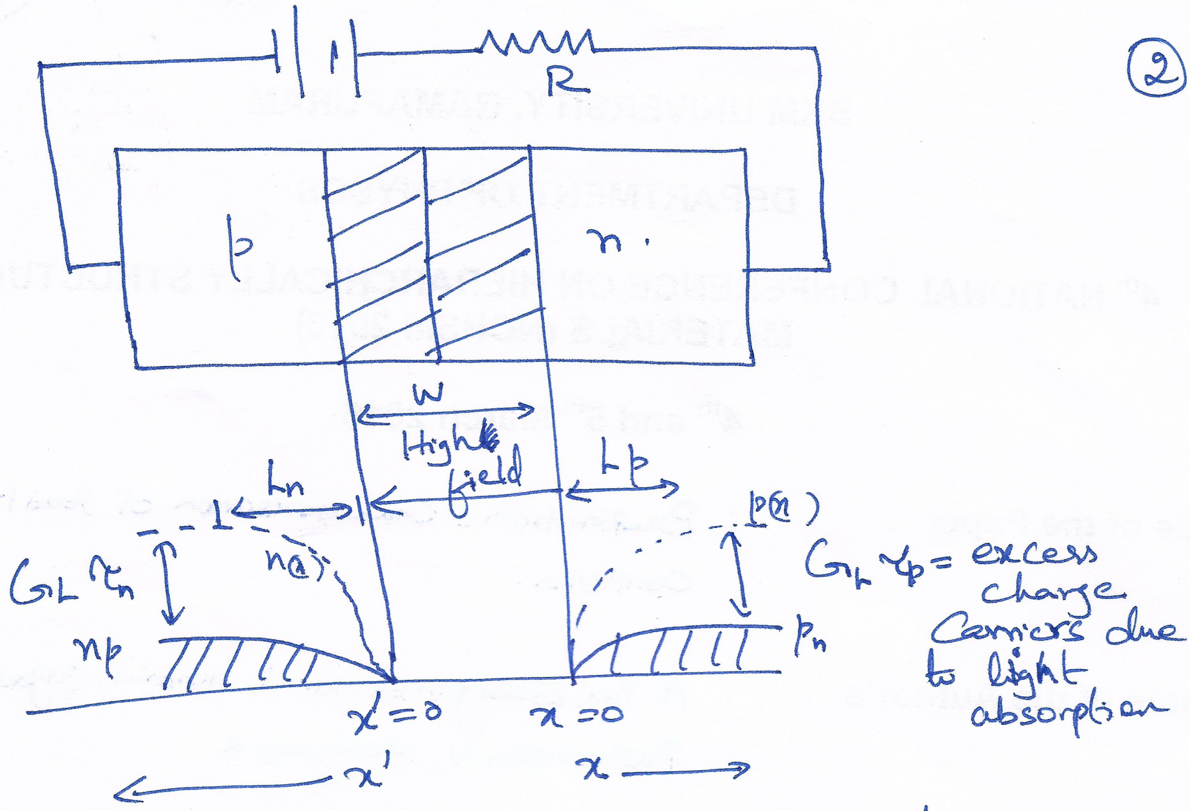
e → Charge of carriers.

G_L → charge (e-h pair) generation due to absorption

→ These holes and electrons are contributing to I_{L1}, are moving under high electric fields, leading to fast response

→ This component of the current is called as prompt photo current.

→



[A schematic of a n-p diode and minor charge carrier concentration in absence and presence of light. The minority charge goes to zero at the depletion region edge due to the high field which makes charge move. The equilibrium minority charge is p_n and n_p in the n- & p- sides, respectively.]

→ In addition to the carriers generated in the depletion region, e-h pairs are generated in the neutral n- & p-regions of the diode.

→ It is expected that holes are generated within a distance of L_p (the diffusion length) of the depletion region edge ($x=0$). They will be able to enter the depletion region from where the electric field will ~~st~~ make them move into p-side.

→ Similarly, for electrons.

→ Hence, the photocurrent should be from all carriers generated in a region, i.e, $W + L_n + L_p$.

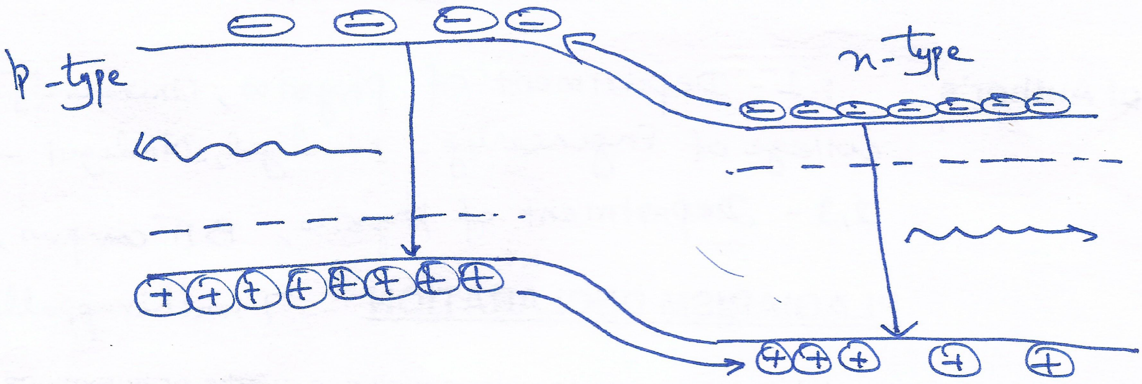
Light Emitting Diodes (LED) ①

LED is a semiconductor p-n junction diode which converts electrical energy to light energy under forward biasing.

Principle:

→ The diode is forward biased, hence the majority charge carriers from 'n' region cross the junction and goto 'p' region and become minority carriers in p-region. and vice-versa.

→ This phenomenon is called minority carrier injection.



Radiation/Radiative Recombination

→ On further increasing the voltage, these excess minority carriers diffuse away from the junction and radiatively recombine with the majority charge carriers.

→ The electrons which are excess minority carriers in 'p'-region recombine with holes which are majority charge carriers in 'p'-region and emit light.

→ The radiative recombination event leads to photon emission

→ The number of radiative recombination is proportional to the carrier injection rate and total current flowing through the device is given by:

$$I = I_0 \left[\exp\left(\frac{eV}{\beta KT}\right) - 1 \right]$$

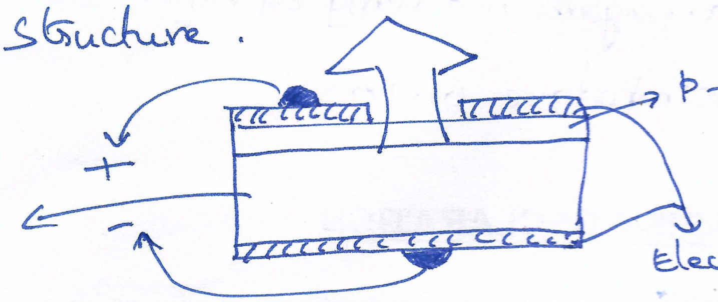
where, $I_0 \rightarrow$ Saturation Current, $V \rightarrow$ forward bias voltage. (2)
$k \rightarrow$ Boltzmann Constant
$\beta \rightarrow$ Varies from 1 to 2 depending on Semiconductor and temperature.

The optical photon emitted due to radiative recombination has the energy very close to bandgap energy E_g and the frequency of emitted photon is given by:

$$E_g = \frac{hc}{\lambda}$$

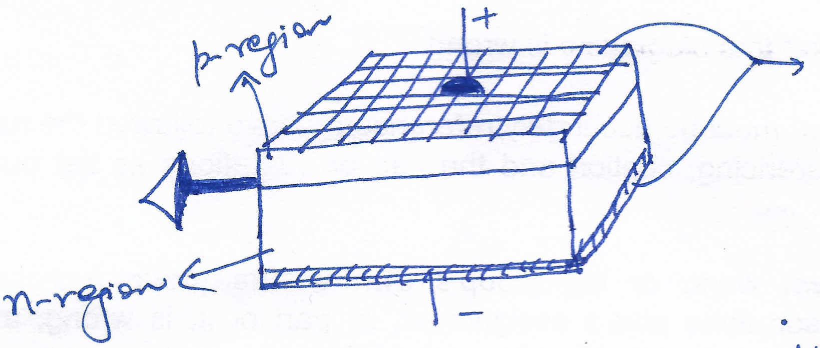
LED Construction

→ An LED must be constructed such that the light emitted by the radiative recombination events can ~~escape~~ escape the structure.

→ 

Surface emitting LED

Surface emitting LED can be made such that bottom edge reflects light back towards the top surface to enhance the output intensity.

→ 

Edge Emitting LED

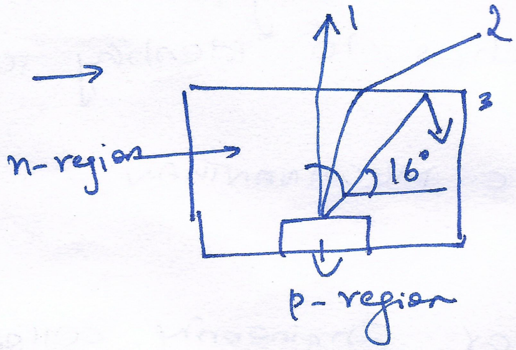
The main advantage of edge emitter LED is the emitted radiation is relatively direct and have a higher efficiency in coupling to an optical fibre.

LED Efficiency:

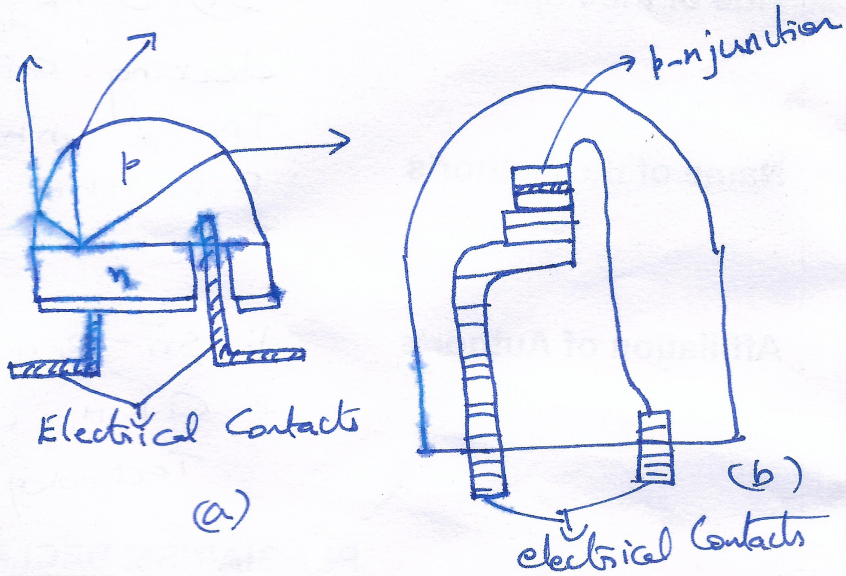
→ The internal quantum efficiency of LED is 100%, but external efficiencies are lower.

→ Most of the emitted light radiation strikes the material interface at greater than Critical angle and trapped within the device

→



Critical Angle



To Reduce Reflection loss in LED

→ Internal Critical angle at Semi Conductor air boundary,

$\sin\theta_c = \frac{n_2}{n_1}$ where, $n_1 = 1$ (refractive index of air)
$n_2 \rightarrow$ refractive index of Semiconductor.

→ for group III Semiconductor, $n_2 = 3.5$, $\theta_c = 16°$

→ All rays of light striking the Surface at an angle exceeding 16° suffer total internal reflection and hence most of the emitted light is reflected back inside the Semiconductor.

→ To improve the external efficiency losses, bulk absorption has to be increased.

→ One method is give Semiconductor a dome structure as shown in fig(a)

→ Other method, Hemi Spherical domes made of plastics are effective in increasing external efficiency.

Optoelectronic Integrated Circuits

→ Optoelectronic devices have made tremendous progress.

→ Optics provides the inherent advantages of large bandwidth parallelism and reconfigurable configurations.

→ However optics does not provide input-output isolation, as electronic devices do, and it is difficult to focus multiple beams in a parallel system.

→ Hence, it is logical to couple electronic and photonic devices, resulting in optoelectronic integration.

→ Interconnect medium is an important aspect of both optical communication systems and computing systems

→ The performance of conventional electrical interconnects is adversely affected by increase in reactance and reflections due to impedance mismatch at high frequencies.

→ As an alternative, an optical interconnect medium can be used, which can take the form of free space, integrated optical waveguides or optical fibres.

→ Optical interconnects and transmission media provides large bandwidth, high speed data transmission, immunity to mutual interference and crosstalk, and freedom from capacitive loading effects.

→ The large bandwidth translates eventually into system size reduction, reduced ~~power~~ system power. ~~and~~ is

→ Optoelectronic integrated ~~ac~~ circuits (OEIC) involve the integration of electronic and optical components, and optical interconnects.

→ Expectation is that monolithic integration of electronic and optical devices on the same chip will lead to high-speed, high-sensitivity, compactness and reliability, at at a low cost.

Organic LED

→ Recently, Certain organic Semiconductors have been studied for electroluminescent applications.

OLED & PLED

→ OLEDs are made from Small molecules or polymers.

→ Commonly, macro-molecules with a molecular weight greater than 10000 atomic mass units (amu) are Called polymers.

→ whereas lighter molecules are referred to as Small molecules.

→ A small molecule light emitting diode is referred to as an OLED, because the first high efficiency OLED was made from Small molecules.

Preparation of OLED.

→ The Structures of OLED prepared by Vacuum deposition techniques or the PLED prepared by Spin-Coating, Screen printing, etc with ~~an~~ amorphous nature.

Conductivities of Polymers and Small molecules

→ Carbon existing in one of the primary ~~hydro~~ hybrid structures

→ It has ~~hexago~~ hexagonally directed Covalent bonds (sp^2 hybridized) with planar geometry, as in graphite and Conjugated Polymers (eg: ethylene, C_2H_4)

→ The electron orbital will form a weak delocalized $\pi-\pi$ bond with neighbouring Carbon atoms to result in alternating Single and double bonds. The Structure is Said to be Conjugated.

→ The π electrons do not belong to a Single bond or atom, but rather to a group of atoms.

→ The electrons in the π-bonds are less Strongly bound than the electrons in σ-bonds and have the potential to display either Semi conducting or metallic behaviour.

→ In OLED, the benzene ring is an important base and is in-charge of electron transport within small molecules; however charge transport across molecules is ascribed to hopping process.

→ In most organic semiconductors, the mobility increases with temperature due to higher thermal energy.

→ for OLED, the mobility is low and related to disordered nature of solid-state nanostructure

Band gap:

→ An organic molecule is covered with electrons with a specific spatial distribution and energy, which is the molecular orbital.

→ Electrons occupy the molecular orbitals from the lower first to higher higher level.

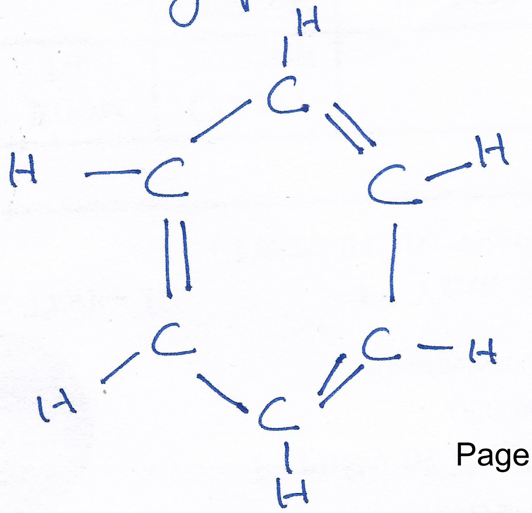
→ HOMO ⇒ Highest occupied molecular orbital.
LUMO ⇒ Lowest Unoccupied molecular orbital.

→ when two molecules interact, a splitting of the HOMO & LUMO energy levels will be induced.

→ HOMO (Organic) = Valence band (Inorganic)
LUMO (organic) = Conduction band (Inorganic).

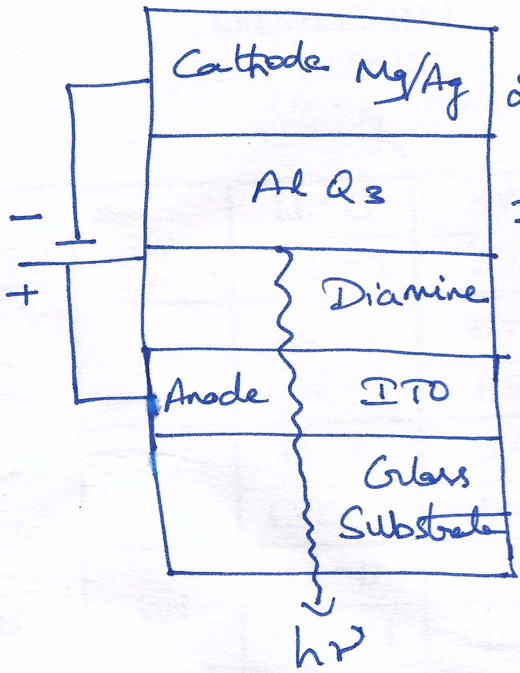
→ Bandgap = energy difference of highest energy of HOMO band and the lowest energy of LUMO band.

→ The optical emission and absorption of OLED depends on its bandgap.

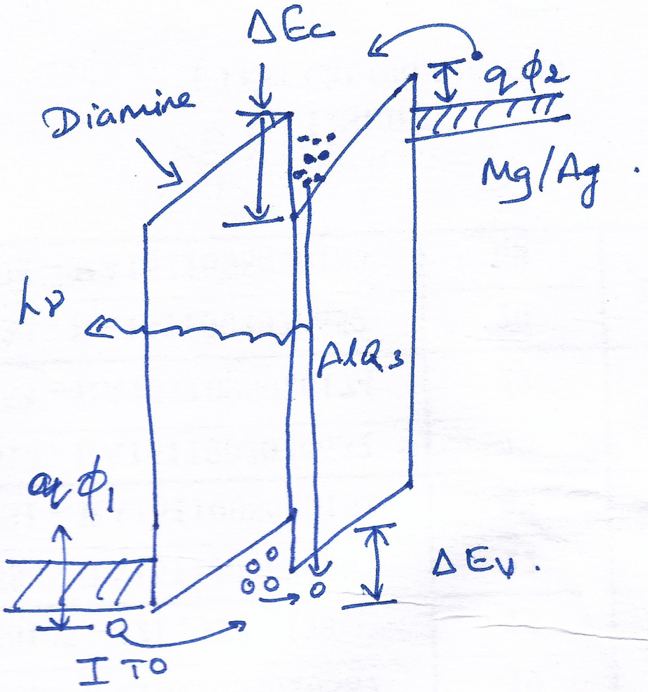


Structure and delocalised π-bond and σ-bond of benzene.

Structure of OLED:



(a) OLED Cross Sectional View.



(b) Band diagram of an OLED.

→ High-performance OLED was developed using concept of multilayer structures.

→ Double layer structure with two organic semiconductors.

→ ETL [Electron Transport Layer]

- The tris (quinolin-8-olato) aluminium, AlQ_3 contains six benzene rings connected to a central aluminium atom, which can strongly attract electrons and creates an electron-deficient state ~~that~~ is an ETL.

→ HTL [Hole Transport Layer]

- The aromatic diamine also has six benzene rings but with a different molecular arrangement.
- Nitrogen in the diamine structure has a lone electron pair which is easily ionized to accept holes.
- Therefore diamine is a hole transport layer.

→ Transparent Conductive anode ⇒ Indium doped tin oxide (ITO)

→ Cathode layer ⇒ Mg alloy with 10% Ag

4

→ A heterojunction is formed between AlQ_3 and diamine

→ Under proper biasing, electrons are injected from the cathode and move toward the heterojunction interface.

→ Whereas holes are injected from the anode and also move towards the interface.

→ Because of energy barriers ΔE_c and ΔE_v, these carriers will accumulate at the interface to enhance the chance of radiative recombination.

Definition of Extrinsic Semiconductor

A semiconducting material in which the charge carriers originate from impurity atoms added to the material is called impurity semiconductor or extrinsic semiconductor. The process of deliberate addition of controlled quantities of impurities to a pure semiconductors is called doping. The addition of impurity increases the carrier concentration leading to increase in conductivity of the conductor.

Differentiate p-type and n-type semiconductors

	n-type semiconductor	**p-type semiconductor**
1	Pentavalent impurity added to intrinsic semiconductor. Eg. P, As, Sb	Trivalent impurity added to intrinsic semiconductor. Eg. B, Ga, In
2	Electrons are majority charge carriers	Holes are majority charge carriers
3	Energy level of donor atoms are very close to the bottom of conduction band	Energy levels of acceptor atoms are very close to the top of valence band
4	Fermi level of n-type is above intrinsic semiconductor	Fermi level of p-type is below intrinsic semiconductor

Variation of Fermi level of n-type semiconductor with temperature

Extrinsic, n-type semiconductor, is formed by adding pentavalent impurity to intrinsic semiconductor. These dopant atoms are called donor atoms, as they contribute one electron for conduction towards conduction band. Eg. P, As, Sb.

At 0 K, the electronic system is the lowest energy, ground state, such that valence electrons are still in the valence band and donor atoms are unionized. The energy levels of donor atoms are close to the bottom of conduction band. Most of the donor level electrons are excited into the conduction band at room temperature and become majority charge carriers.

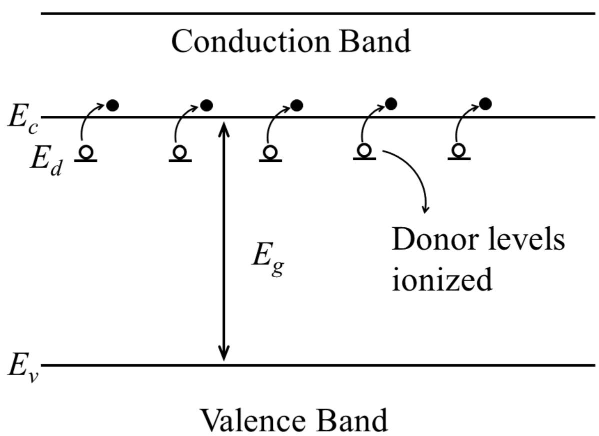


Figure 1: T > 0 K

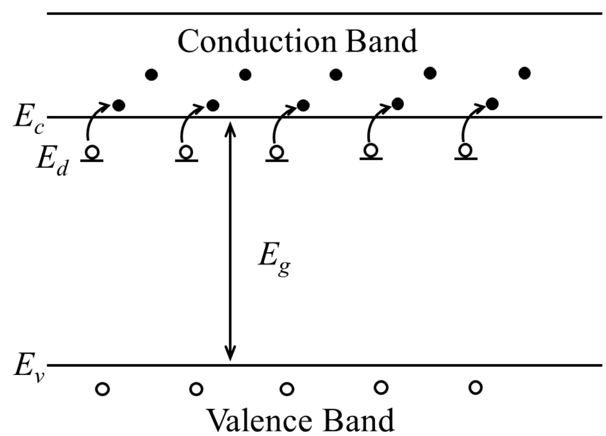


Figure 2: T = 300 K

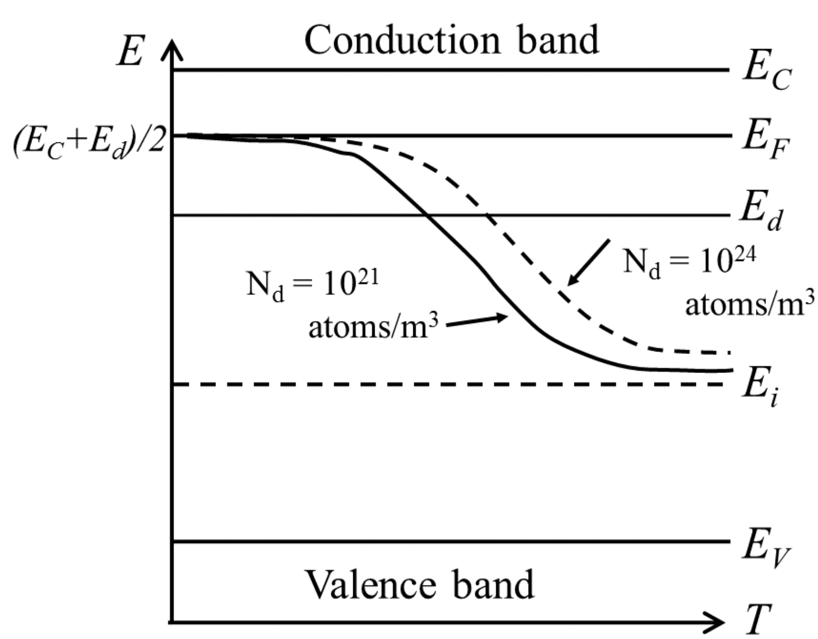


Figure 3: Variation of Fermi level with temperature - n-type semiconductor

The Fermi energy for p-type semiconductor is given by

$$E_F = \frac{E_C + E_d}{2}, \text{ for T = 0 K}$$

$$E_F = \frac{E_C + E_d}{2} + \frac{kT}{2} ln \left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} \right], \text{ for T > 0 K}$$

Fermi level is exactly at the middle of conduction band on top of the donor level.

$$E_F = \frac{E_C + E_d}{2} + \frac{kT}{2} ln \left(\frac{N_d}{N_x}\right), \text{ where } N_x = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}$$

$$E_F = \frac{E_C + E_d}{2} - \frac{kT}{2} ln \left(\frac{N_x}{N_d}\right)$$

As the temperature increases, the Fermi level drops towards intrinsic Fermi level, which is also dependent on concentration of N_d atoms. More and more donor atoms are ionized with temperature and at a point all donor atoms are ionized. After this point, the generation of electron-hole pair due to the breaking of covalent bonds takes place and the material tends to behave in the intrinsic manner.

Variation of Fermi level of p-type semiconductor with temperature

Extrinsic, p-type semiconductor, is formed by adding trivalent impurity to intrinsic semiconductor. These atoms are called acceptor atoms, as they contribute one hole for conduction towards valence band. Eg. B, Ga, In.

At relatively low temperatures, acceptor atoms get ionized taking electrons from valence band, resulting in the creation of holes in valence band for conduction. Due to the ionization of acceptor atoms, only holes and no electrons are created. The energy level of the acceptor atoms are close to the top of the valence band.

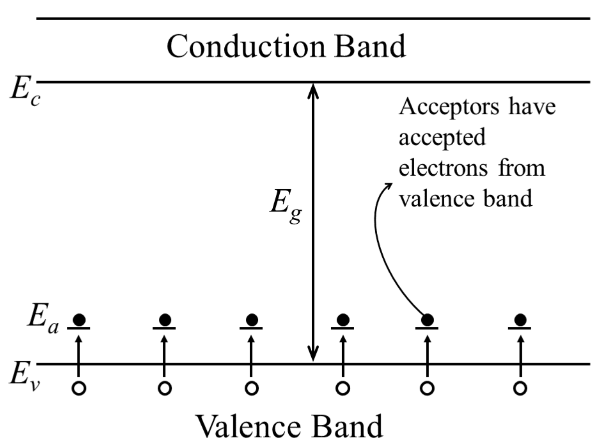


Figure 1: T > 0 K

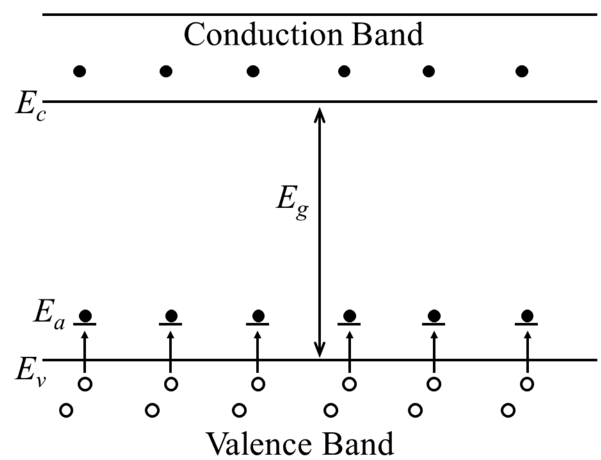


Figure 2: T = 300 K

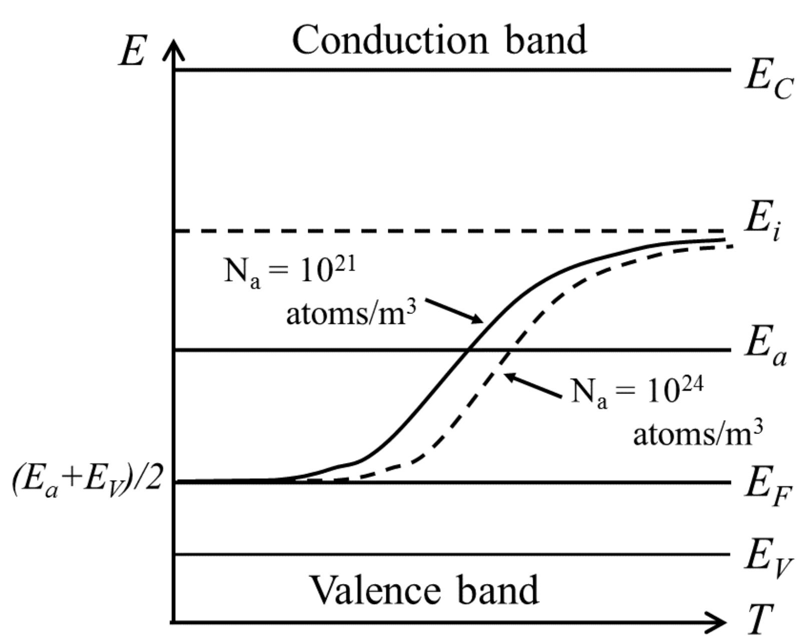


Figure 3: Variation of Fermi level with temperature - p-type semiconductor

The Fermi energy for p-type semiconductor is given by

$$E_F = \frac{E_V + E_a}{2}, \text{ at T} = 0 \text{ K}$$

$$E_F = \frac{E_V + E_a}{2} - \frac{kT}{2} ln \left[\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \right], \text{ at T} > 0 \text{ K}$$

Fermi level is exactly at the middle of acceptor level on top of the valence band.

$$E_F = \frac{E_V + E_a}{2} - \frac{kT}{2} ln \left(\frac{N_a}{N_y} \right), \text{ where } N_y = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}$$

$$E_F = \frac{E_V + E_a}{2} + \frac{kT}{2} ln \left(\frac{N_y}{N_a} \right)$$

As the temperature increases, the Fermi level rises towards intrinsic Fermi level, which is also dependent on concentration of N_a atoms. More and more acceptor atoms are ionized with temperature and at a point all acceptor atoms are ionized. After this point, the generation of electron-hole pair due to the breaking of covalent bonds takes place and the material tends to behave in the intrinsic manner.

Generation & Recombination Process.

→ At thermal equilibrium, the thermal ~~...~~ energy enables a valence electron to make an upward transition to conduction band, leaving a hole in valence band. This process is called carrier generation, ~~and~~ represented by G_{th} (no. of electron-hole pairs generated/cm^3-s) ($pn = n_i^2$)

→ This creates a non-equilibrium condition by creation of excess charge carriers. If excess charge carriers are introduced to a semiconductor, making value of $pn > n_i^2$, then non-equilibrium situation is attained.

→ In semiconductor; the creation of charge carriers in excess of thermal equilibrium values.

$$G = G_L + G_{th}$$

→ Whenever thermal equilibrium condition is disturbed, processes exist to restore the system to equilibrium.

→ Depending on nature of recombination process, the energy released from the recombination process can be emitted as photon (radiative recombination) or emitted/dissipated as heat (non-radiative recombination). R_{th}

→ When an electron make a transition downward from the conduction band to valence band, an electron-hole pair is annihilated. The reverse process of generation is called as recombination (R_{th}).

→ Recombination can be classified as:

(a) Direct: This type of recombination is observed in direct-bandgap semiconductors (GaAs).

(b) Indirect: This type of recombination is observed in indirect-bandgap semiconductors (Si).

Direct Recombination:

→ When ~~the~~ excess charge carriers are introduced, the probability that electrons and holes will recombine directly, because ~~of~~ ~~...~~ the bottom of conduction band and top of valence band have same momentum and no additional momentum is required for transition across the bandgap.

→ The rate of direct recombination R is expected to be proportional to the number of electrons available in Conduction band (n) and no: of holes in valence band (p).

$$R = \beta n p$$

β → proportionality constant

→ At thermal equilibrium,

$$G_{th} = R_{th} = \beta n_o p_o$$ → at thermal equilibrium

→ ~~G~~ Generation Rate: $G = G_L + G_{th}$

→ ~~Regeneration~~ Recombination Rate : $R = \beta n_n p_n$

$$R = \beta (n_o + \Delta n)(p_o + \Delta p).$$

Δp, Δn → excess Carrier Concentrations.

Here $\Delta p = \Delta n$, to maintain charge neutrality

→ Net recombination rate, $G_L = R - G_{th} \equiv U$

$$U = \beta (n_{no} + p_{no} + \Delta p)\, \Delta p$$

$$U \cong \beta n_{no} \Delta p = \frac{p_n - p_{no}}{\frac{1}{\beta n_{no}}}$$ (For low level injection, Δp, $p_{no} << n_{no}$.

→ Net recombination rate is proportional to excess minority Carrier Concentration

→ $U = 0$, at thermal equilibrium

→ $1/\beta n_{no}$ is called lifetime τ_p of excess minority Carrier.

$$U = \frac{p_n - p_{no}}{\tau_p}$$

$$\tau_p = \frac{1}{\beta n_{no}}$$

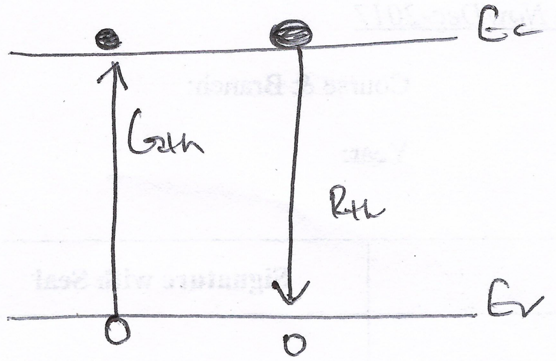
Indirect Recombination:

→ For indirect bandgap Semiconductors, electrons at bottom of Conduction band have non-zero momentum with respect to holes at top of valence band.

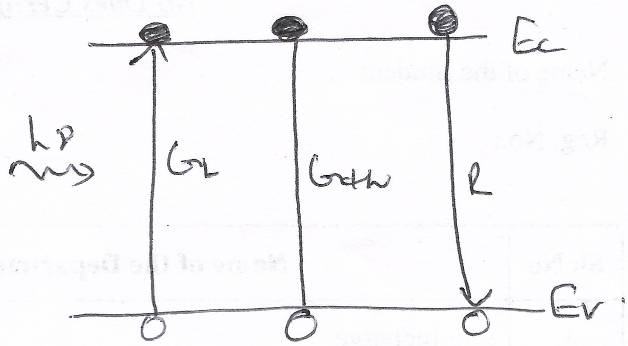
→ A direct recombination that Conserves both energy and momentum is not possible ~~to~~ without a Simultaneous lattice interaction.

→ Therefore dominant recombination process in such Semiconductors is indirect via localised energy States in forbidden energy gap.

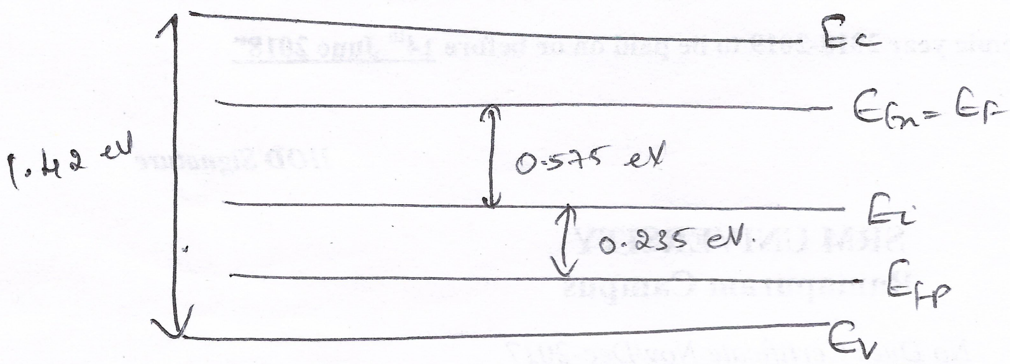
→ These states act as stepping stones between conduction band and Valence band.



At thermal equilibrium



Under illumination:



Indirect Recombination with intermediate Energy levels.

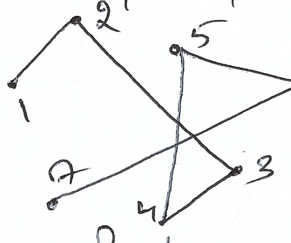
Carrier Drift

①

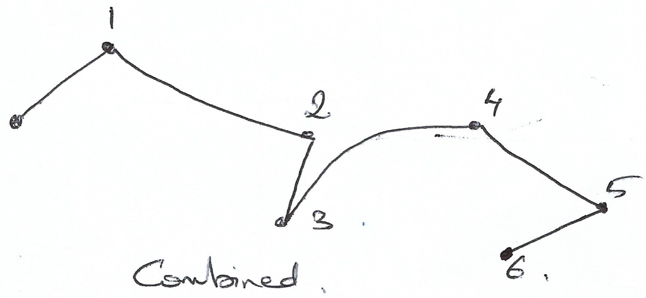
- → Consider n-type Semiconductor
- → electrons are free particles, not associated with any lattice or donor sites
- → influence of lattice exhibited as effective mass.
- → Theorem for equipartition of energy, $\frac{1}{2}kT$ / degree of freedom.
- → Kinetic energy of electrons; for 3-d.

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

- → e^- move rapidly in all directions.
- → Succession of random scattering from collisions with lattice atoms, impurity atoms, other scattering centres.
- → Zero net displacement.
- → Mean free Path : average distance between collisions. $(10^{-5}m)$
- → Mean free Time τ_c : average time between collisions $(10^{-12}s)$.
- → when a Electric field E is applied, electrons experience a force $-qE$ from the field & get accelerated along the field.
- → Along with ~~with~~ thermal velocity, another velocity is superimposed
- → Drift velocity : displacement due to electric field. (v_n)



Random



Combined.

- → Momentum, $qE\tau_c = m_n v_n$.

$$v_n = \left(\frac{q\tau_c}{m_n}\right)E = -\mu_n E \qquad \mu_n = \frac{q\tau_c}{m_n}.$$

- → μ_n : Mobility of electrons. ⇒ determines how strongly the motion of electron is influenced by an applied electric field.
- → for holes, $v_p = \mu_p E$
- → The Drift Current density,

$$J_n = e\mu_n nE$$

$$J_p = e\mu_p pE$$

Diffusion Current

(1)

→ It is possible to obtain a non-uniform concentration of particles in a semiconductor, by disturbing the thermal equilibrium.

→ Then, in that condition, particles tend to move from a region of higher concentration to a region of lower concentration

→ This movement of particles due to concentration gradient is called diffusion.

→ The current through the material due to diffusion is called diffusion current

→ Consider that concentration "p" of holes varies with distance "x" in the semiconductor in such a way that the hole concentration is greater for lower values of "x".

→ Diffusion Current: Then there is a concentration gradient $\frac{-dp}{dx}$ in the density of holes resulting in a hole flow along ~~with~~ the positive x-direction.

→ The diffusion hole current density J_p is proportional to the concentration gradient and is given by.

$$J_p = -eD_p \frac{dp}{dx}.$$

where, $e \rightarrow$ charge of electron.

$D_p \rightarrow$ diffusion constant or diffusivity of holes.

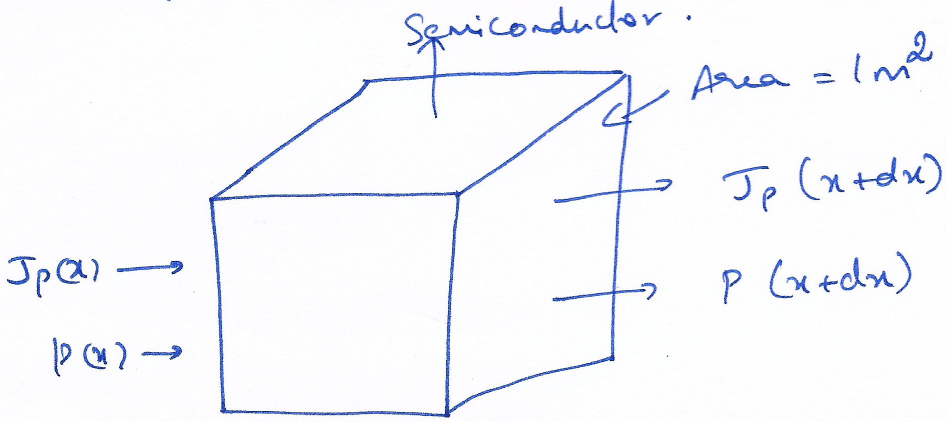
→ for holes, $J_n = -eD_n \frac{dn}{dx}.$

The Continuity Equation.

→ When the equilibrium concentration of carriers in a semiconductor, the concentrations of holes and electrons vary with time approaching the equilibrium value exponentially.

→ The carrier concentration in the body of a semiconductor is a function of both time and distance.

→ The differential equation governing this functional relationship is called continuity equation.



→ Consider an infinitesimal element of volume of unit area and length dx.

→ By shining light on the material, it is possible to create excess charge carriers when compared to equilibrium value.

→ The rate of generation G and rate of recombination R, is created due to disturbance in equilibrium.

→ The particles may also flow away from a point at a rate which depends upon the differential current dJ/dx

→ The time rate of change of particle density ρ,

$$\frac{d\rho}{dt} = g - r - \frac{dJ}{dx}$$

→ but $J = D\frac{d\rho}{dx}$. where D → diffusion constant or diffusivity.

→ The diffusion equation.

$$\frac{dp}{dt} = g - r + D\frac{d^2p}{dx^2}$$

→ In addition to diffusion, ~~drift~~ drift takes place Simultaneously, then J is given by.

$$J = -D\frac{dp}{dx} + \mu Ep$$

where, $\mu \rightarrow$ mobility of charge carriers.

→ Then, $$\frac{dp}{dt} = g - r + D\frac{d^2p}{dx^2} - \mu\frac{d(pE)}{dx}$$

→ If no field is applied to semiconductor, it is in thermal equilibrium with its surroundings

then, $J = 0$, $\frac{dp}{dt} = 0$ due to steady state and p becomes p_0.

→ $$g - r = 0 \quad , \quad g = r$$

→ Rate of recombination "r" is proportional to charge density $r = k p_0$

→ In thermal ~~equilib~~ equilibrium

$$g = r = k p_0 = \frac{p_0}{\tau_p}$$

$\tau_p \rightarrow$ mean life time of charge carriers

→ for $p_0 \rightarrow p$

$$g - r = \frac{p_0}{\tau_p} - \frac{p_0 + \delta p}{\tau_p} = \frac{-\delta p}{\tau_p} = \frac{p - p_0}{\tau_p}$$

→ Finally,

$$\frac{dP}{dt} = \frac{P - P_0}{\tau_p} + D\frac{d^2P}{dx^2} - \mu\frac{d(PE)}{dx}$$

This equation is known as Continuity Equation for Charge.

→ The Continuity equation for electrons in N-type Semiconductor is obtained by replacing P by $-en$ and is given by.

$$\frac{dn}{dt} = \frac{n - n_0}{\tau_n} + D\frac{d^2n}{dx^2} - \mu\frac{d(nE)}{dx}.$$

where, $n \rightarrow$ average electron Concentration within the volume.

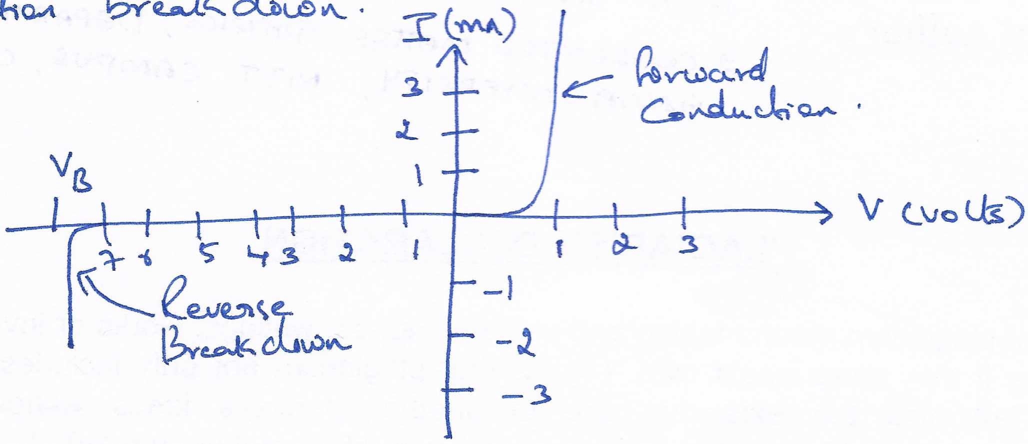
Basic Structure of p-n Junction. ①

→ The most important characteristic of p-n junctions is that they rectify: they allow current to flow only in one direction

→ When we apply "forward-bias" (positive voltage to p-side) to the junction, current increases rapidly as voltage increases

→ when we apply "reverse-bais" (positive voltage to n-side), virtually no current flows initially.

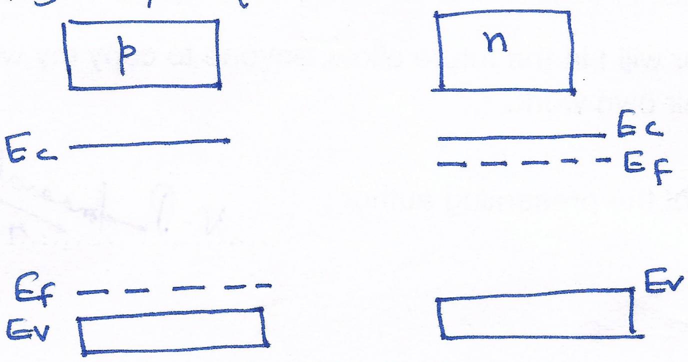
→ As the reverse bias is increased, the current remains very small untill a critical voltage is veltage, at which point the current suddenly increases, which phenomenon is referred to as junction breakdown.



V-I characteristics of a typical p-n junction.

Band Diagram of p-n Semiconductor before the Junction is formed at thermal equilibrium.

→ Before the formation of a junction, two separate regions of p- and n-type semiconductor materials that are uniformly doped and phyically separated.

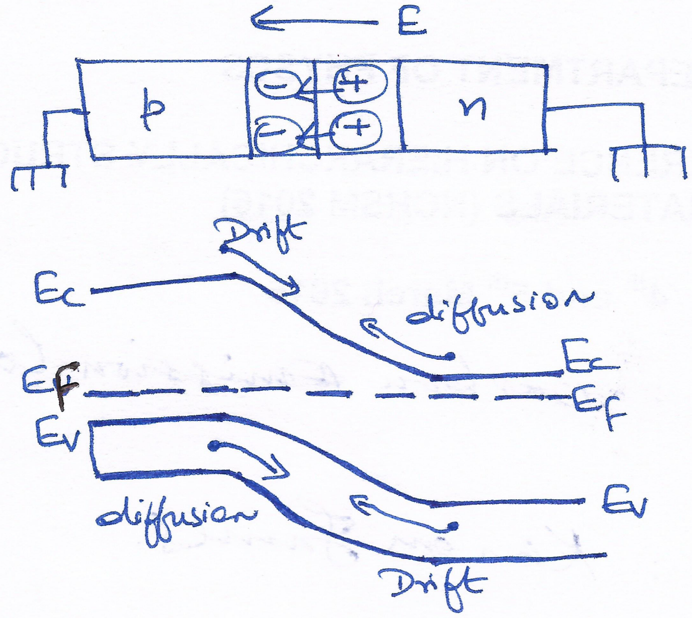


Uniformly doped p- & n-type Semiconductors before the junction is formed.

Band diagram of a p-n Junction at the Thermal Equilibrium

②

→



Electric field in the depletion region and energy band diagram of a p-n junction in thermal equilibrium.

Before Junction is formed:

→ The Fermilevel Ef is near the valence band edge in p-type material and near the Conduction band edge in n-type material.

→ while p-type material Contains a large Concentration of holes with only few electrons. The opposite true for n-type material.

After Junction is formed:

→ when p- & -n-junctions are joined together, the large Carrier Concentration gradients at junction Cause Carrier diffusion

→ Holes from p-side diffuse into n-side and electrons from the n-side diffuse into p-side.

→ As holes Continue to leave p-side, Some of acceptor (-ve) ions (N_A^-) near the junction are left uncompensated because the acceptors are fixed in Semiconductor Lattice, whereas holes are mobile.

→ Similarly, Some of the posite donor ions (N_D^+) near the junction are left uncompensated as the electrons leave n-side.

→ Consequently a space-charge is Created.

→ Like, a negative Space charge is Created near p-side of the junction.

3

→ A positive Space Charge is Create ~~near~~ the n-side of junction

→ This Space charge region Creates an electric field that is directed from the positive charge towards the negative charge.

→ The electric field is in the direction opposite to the diffusion Current for each type of Charge carrier

→ The hole diffusion Current flows from left to right, whereas the hole drift Current due to ~~of~~ electric field flow from right to left.

→ Due to the negative Charge of electrons, they diffuse from right to left (opposite to the direction of electron Current) and the electron drift Current flows from left to right.

Metal - SemiConductor Junctions. ①

→ When a p-n junction is considered, the assumption is that the semiconductor material was same throughout the material. structure. This type of junction is referred to as homojunction.

→ Now, SemiConductor devices or integrated circuits, must make contact with outside world. This contact is made through non-rectifying metal-semiconductor junctions or ohmic ~~contacts~~. Contacts.

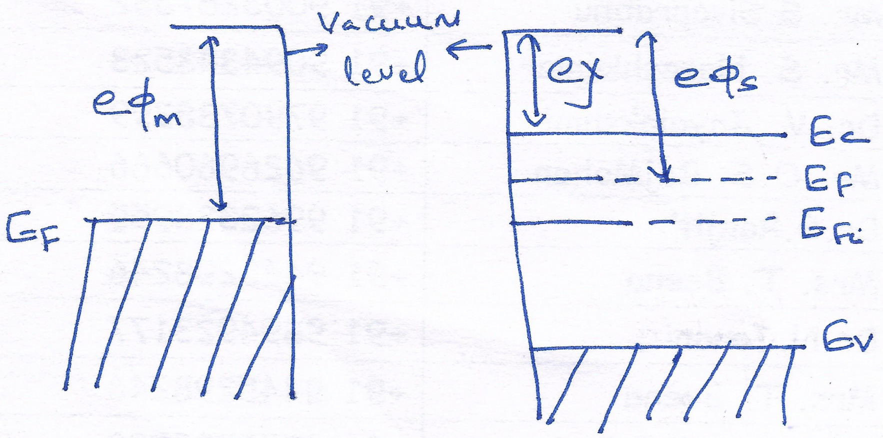
→ An ohmic Contact is a low-resistance junction providing current conduction in both directions.

→ The metal-semiconductor junction and the semiconductor heterojunction, in which the material on each side of junction is not same. These junctions also produce diodes.

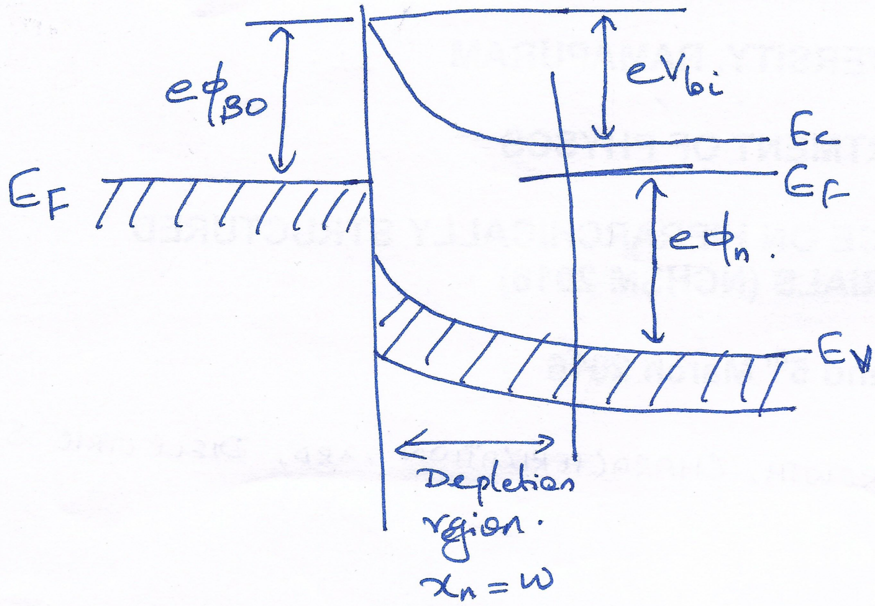
Schottky Barrier Diode / Contact.

→ One of the most first practical SemiConductor devices used in early 1900s was metal semiconductor diode. This diode also called a point contact diode, was made by touching a metallic whisker to an exposed semiconductor surface.

→ In most cases, in the metal-semiconductor rectifier contact or Schottky barrier diode, the rectifying contacts are made on n-type semiconductors.



(a) Energy band diagram of a metal semiconductor before contact.



(b) Ideal energy-band diagram of a metal & n-semiconductor junction for $\phi_m > \phi_s$

Consider a ideal energy-band diagram for a particular metal and n-type semiconductor before making contact.

→ Vacuum level is the reference level.

→ ϕ_m (metal workfunction, measured in Volts).

→ ϕ_s (semiconductor work function)

→ χ (electron affinity).

Element	ϕ_m.	Element,	χ
Silver, Ag	4.26.	Germanium, Ge	4.13
Al, Aluminium	4.28	Silicon, Si	4.01
Au, Gold	5.1	GaAs	4.07
Pt, Platinum	5.65	AlAs	3.5

→ It is assumed that $\phi_m > \phi_s$

Now, consider the energy-band diagram after contact.

→ Before contact, the fermi level in semiconductor was above that in a metal.

→ To make fermi level constant throughout the system in thermal equilibrium, electrons from the semiconductor flow into the lower energy states in the metal.

→ Positively charged donor atoms remain in semiconductor creating a space charge region.

→ ϕ_{B0} (ideal barrier height of semiconductor contact). This is the potential barrier seen by electrons in metal trying to move into semiconductor.

→ This barrier is known as Schottky barrier, given ideally by

$$\phi_{B0} = (\phi_m - \chi)$$

→ On the semiconductor side, V_{bi} (is the built-in potential barrier).

→ Like in a p-n junction, this barrier is seen by electrons in the conduction band trying to move into the metal. This built-in potential barrier is given by,

$$V_{bi} = \phi_{B0} - \phi_n$$

→ Reverse bias:

- If we apply a positive charge to the semiconductor with respect to the metal, ~~metal~~ semiconductor-to-metal barrier height increases.
- while ϕ_{B0} remains constant in this idealized case
- This condition is the Reverse bias.

→ Forward Bias:

- If a positive voltage is applied to the metal with respect to the semiconductor, the semiconductor-to-metal barrier V_{bi} is reduced, while ϕ_{B0} ~~again~~ remains essentially constant.
- The electrons can more easily flow from the semiconductor into the metal, since the barrier has been reduced.
- This bias condition is forward bias.

Ohmic Contacts.

→ Contacts must be made between ~~any~~ any semiconductor device or integrated circuit, and the outside world.

→ These contacts are made via Ohmic contacts.

→ Ohmic contacts are metal-to-semiconductor contacts, which are non-rectifying contacts.

→ An ohmic contact is a low-resistance junction providing conduction in both directions between the metal and the semiconductor.

→ Ideally, the current through the ohmic contact is a linear function of applied voltage, and the applied voltage should be very small.

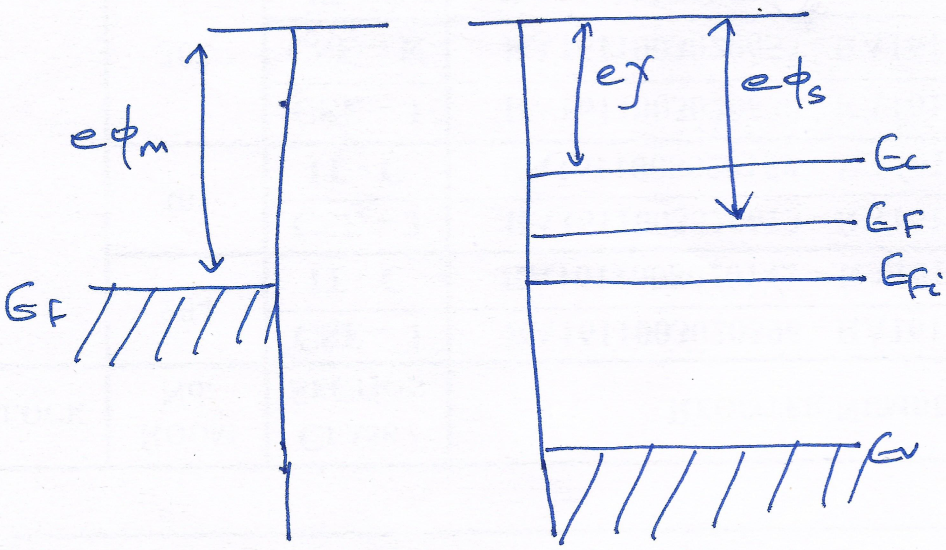
→ Two types of ohmic contacts are possible:

① Ideal non-rectifying barrier.

② Tunnelling barrier.

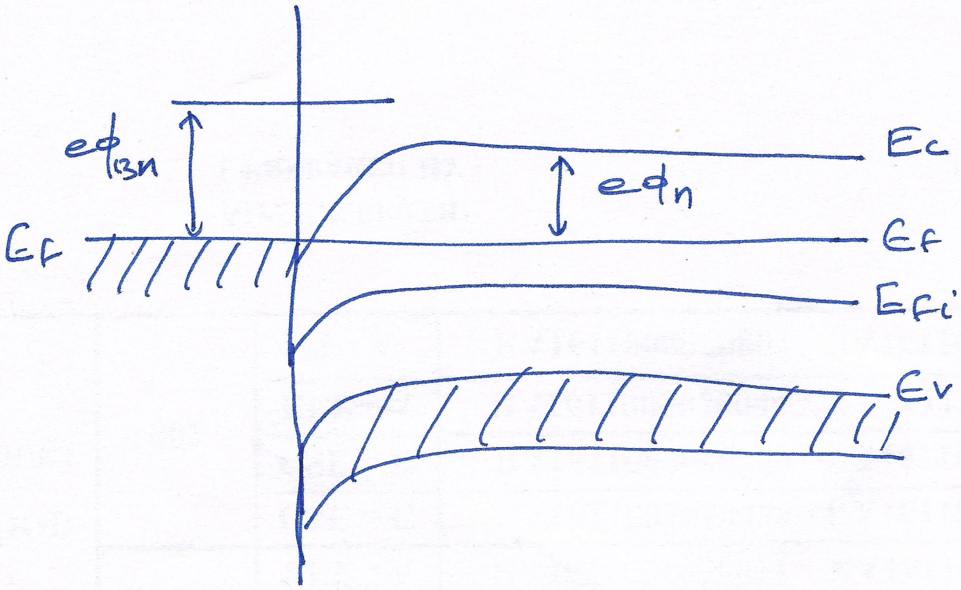
① Ideal Non-Rectifying Barrier

→ Consider an ideal metal-n-type semiconductor contact.



(a) Ideal energy band diagram before contact.

→ Here, it is assumed that $\phi_m < \phi_s$



(b) Ideal Energy band diagram after contact for a metal-n-type semiconductor junction for: $\phi_m < \phi_s$.

→ To achieve thermal equilibrium in this junction, electrons flow from the metal into the lower energy states in semiconductor, which makes the surface of semiconductor more n-type. The excess of electron charge in the n-type semiconductor exists essentially as a surface charge density

→ Positive Charge/voltage Applied to the Metal:

- If a positive charge is applied to the metal, there is no barrier to electrons flowing from the semiconductor into the metal.
- Electron can easily flow "downhill" (in terms of energy) from the semiconductor into the metal.

→ Positive Charge/voltage Applied to the Semiconductor:

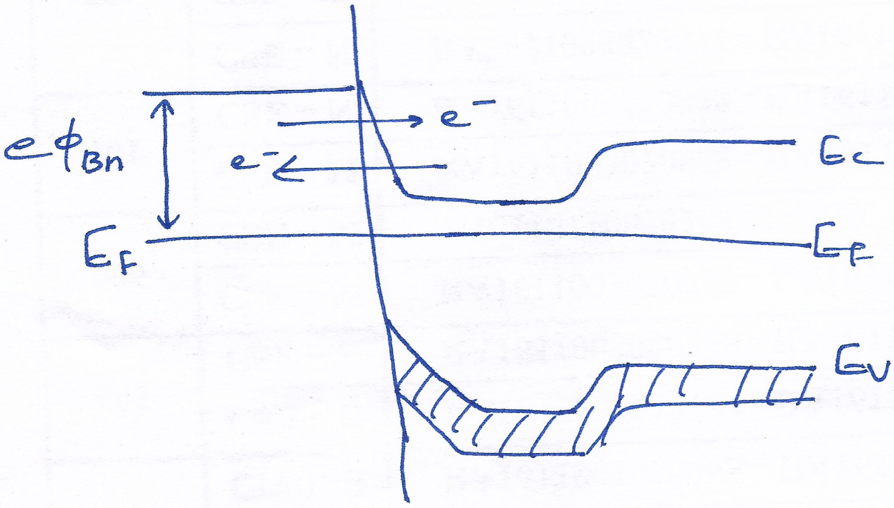
- If a positive voltage is applied to a semiconductor, the effective barrier height for electrons flowing from the metal into semiconductor will be approximately $\phi_{Bn} = \phi_n$
- This is fairly small for a moderately to heavily doped semiconductor and hence electrons can easily flow from the metal into the semiconductor.
- For this case, the electrons can easily flow over the barrier from the metal into the semiconductor.
- This junction is then an Ohmic Contact.

② Tunneling Barrier

→ The Space-charge width in a rectifying metal-semiconductor Contact is inversely proportional to the Square root of semiconductor doping. ~~The~~

→ The width of the depletion region decreases as the doping Concentration in the semiconductor increases.

→ Thus, as the doping Concentration increases, the probability of tunneling through the barrier increases.



(a) Energy-band diagram of a heavily doped n-semiconductor to metal junction.

→ In a heavily doped semiconductor, the depletion width is on the order of Å, so the tunneling is now a distinct possibility.

→ For these types of barrier widths, tunneling may become the dominant current mechanism.

Semiconductor Materials for Optoelectronic Applications ①

→ Optoelectronic devices based on Semiconductors depend on the Conversion of optical Signal into an electrical Signal.

→ Hence, optoelectronic devices have to perform the action of optical detection.

→ The detection involves the Creation of electron-hole pairs, by effective absorption of light energy and Conversion.

→ When the wavelength of the photons is ~~for~~ properly chosen, essentially all Semiconductors have electric response on application of an electronic Signal.

→ Hence, a wide range of Semiconductors are available for selection.

→ Even indirect bandgap materials, which cannot be utilized for the reverse process of efficient light emission can be made into a excellent detector.

The Selection of materials for the optoelectronic devices are based on the following Criterias:

① Substrate Availability:

→ There are only few materials available which can be used in the form of a Substrates to grow devices. They are Si, GaAs, Ge, and InP. Other Substrates available for devices are either very Costly or they have high defect density.

→ Hence, Choice of Semiconductor materials for detectors is limited to those which have a good lattice matching with Si, GaAs, Ge & InP.

② Long distance communication Applications.

→ For long distance communications, the photons with wavelength of 1.55μm or 1.3μm are used since the transmission losses in an optical fibre are very low at these wavelengths.

→ A detector is thus needed to respond to these energies.

→ GaAs, is not a Candidate, as its cutoff wavelength is ~0.8 μm.

→ The potential candidates are: InGaAs, InGaAsP, GaAlSb, HgCdTe, can be tailored.

~~→ to~~

③ Local Area Networks (LAN)

→ In LAN, where the optical signal have to propagate a long distance (~ about KMs), GaAs emitters can be used, as they are cheaper at 0.8 μm.

→ Si forms a good detector material for LAN.

④ Long wavelength Detection

→ Important application of detectors is in area of ~~light~~ thermal imaging for night vision and medical applications, around the wavelength of 20 μm.

→ The detector can be either based on very narrow bandgap materials, extrinsic defect levels or heterostructure concepts.

→ Material choices are: HgCdTe, PbTe, PbSe, InSb.

⑤ High Speed Detectors.

→ High speed detectors with very small response time.

→ GaAs grown at very low substrate temperature, which incorporates a large number of defects.

→ These defects decrease the e-h recombination time to ~1 ps in contrast to 1 ns for high quality GaAs.

→ The very short response time leads to high speed optical detection systems

Materials:

① InGaAs (Tunable Eg)

* Excellent material for long haul communications. at 1.55 μm.
* Can be lattice matched to InP.

② AlGaSb (Tunable Eg).

* Excellent optical properties.
* Can be used for long haul communications
* Suffers from poor substrate availability.

③ InGaAsP. (Tunable Eg).

* Suitable for both 1.55μm and 1.3μm applications, long haul
* Can be lattice matched to InP substrates

④ GaAs (Eg = 1.43 eV).

* Direct gap material.
* Not suitable for high quality avalanche detectors
* Not suited for long haul or LAN communications.

⑤ HgCdTe (Tunable Eg).

* Excellent material for long wavelength applications in night vision and thermal imaging.
* Can be used for 1.55μm and 1.3μm.