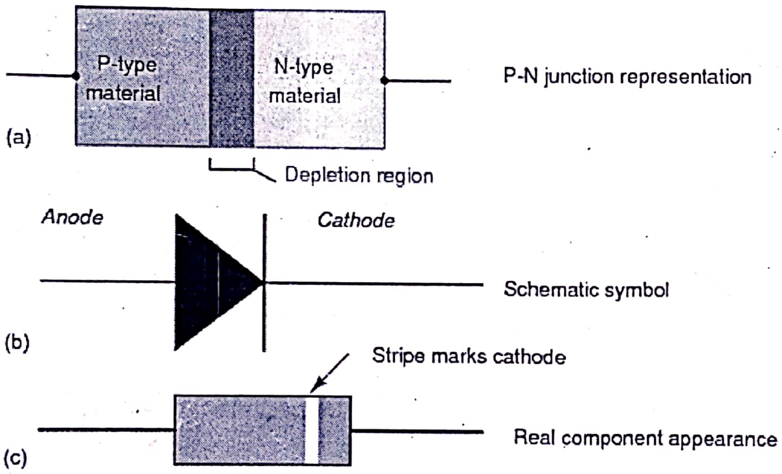
UNIT-II

I-V characteristics of a Diode: P-N Junction Diode - Biasing Concept

A **current–voltage characteristic** or **I–V curve** (current–voltage curve) is a relationship, typically represented as a chart or graph, between the electric current through a circuit, device, or material, and the corresponding voltage, or potential difference across it.

There are three possible biasing conditions and two operating regions for the typical PN-Junction Diode, they are: zero bias, forward bias and reverse bias.

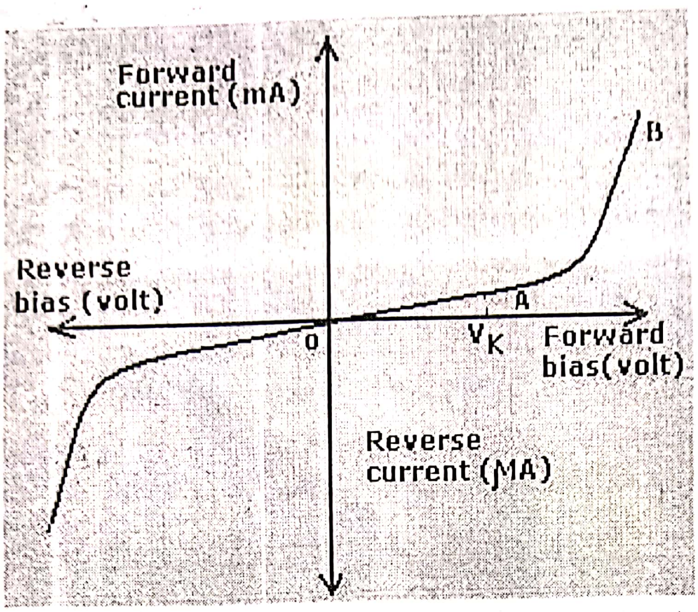
When no voltage is applied across the PN junction diode then the electrons will diffuse to P-side and holes will diffuse to N-side through the junction and they combine with each other. Therefore, the acceptor atom close to the P-type and donor atom near to the N-side are left unutilized. An electronic field is generated by these charge carriers. This opposes further diffusion of charge carriers. Thus, no movement of the region is known as depletion region or space charge.



PN Junction Diode

If we apply forward bias to the PN-junction diode, that means negative terminal is connected to the N-type material and the positive terminal is connected to the P-type material across the diode which has the effect of decreasing the width of the PN junction diode.

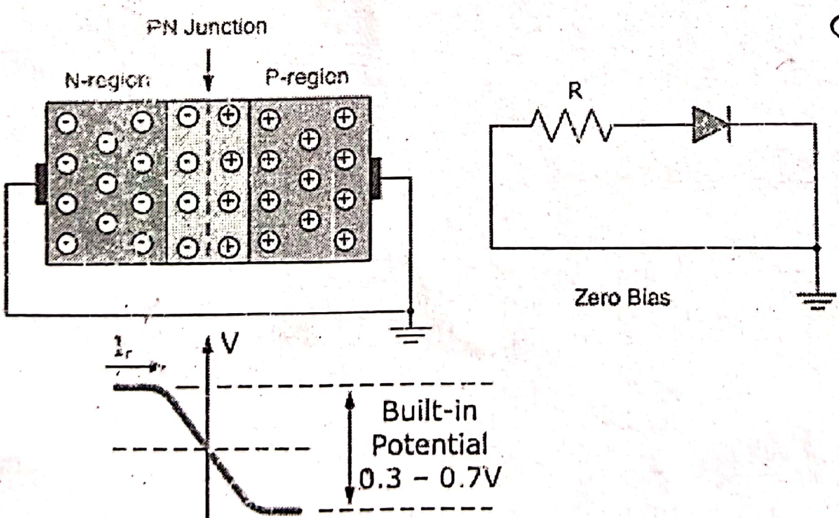
If we apply reverse bias to the PN-junction diode, that means positive terminal is connected to the N-type material and the negative terminal is connected to the P-type material across the diode which has the effect of increasing the width of the PN junction diode and no charge can flow across the junction.



VI Characteristics of PN Junction Diode

Zero Biased PN Junction Diode

In the zero bias junction, potential provides higher potential energy to the holes on the P and N side terminals. When the terminals of the junction diode are shorted, few majority charge carriers in the P-side with plenty energy to overcome the potential barrier to travel across the depletion region. Therefore, with the help of majority charge carriers, the current starts to flow in the diode and it is denoted to as forward current. In the same way, minority charge carriers in the N-side move across the depletion region in reverse direction and it is referred to as reverse current.



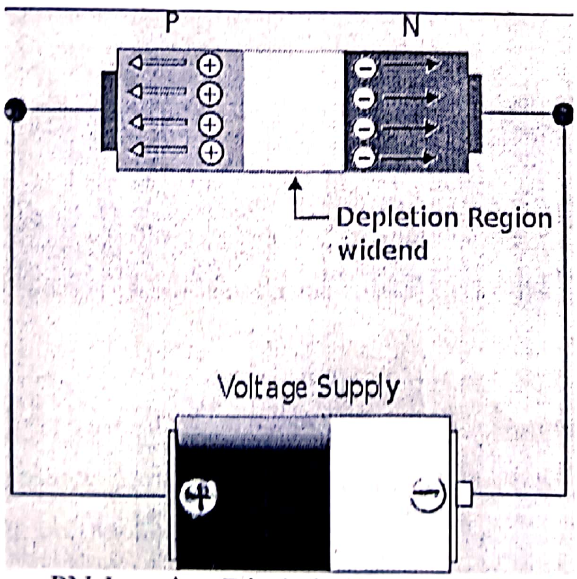
Zero Biased PN Junction Diode

Potential barrier opposes the movement of electrons & holes across the junction and permits the minority charge carriers to drift across the PN junction. However, the potential barrier helps minority charge carriers in P-type and N-type to drift across the PN-junction, then an equilibrium will be established when the majority charge carriers are equal and both moving in reverse directions, so that the net result is zero current flowing in the circuit. This junction is said to be in a state of dynamic equilibrium.

When the temperature of the semiconductor is increased, minority charge carriers have been endlessly generated and thus leakage current starts to rise. But, electric current cannot flow since no external source has been connected to the PN-junction.

PN Junction Diode in Forward Bias

When a PN-junction diode is connected in a forward bias by giving a negative voltage to the N-type and a positive voltage to the P-type material. If the external voltage becomes more than the value of the potential barrier (estimate 0.7 V for Si and 0.3V for Ge) the opposition of the potential barriers will be overcome and the flow of current will start.Because, the negative voltage repels electrons near to the junction by giving them the energy to combine and cross over with the holes being pushed in the opposite direction to the junction by the positive voltage.

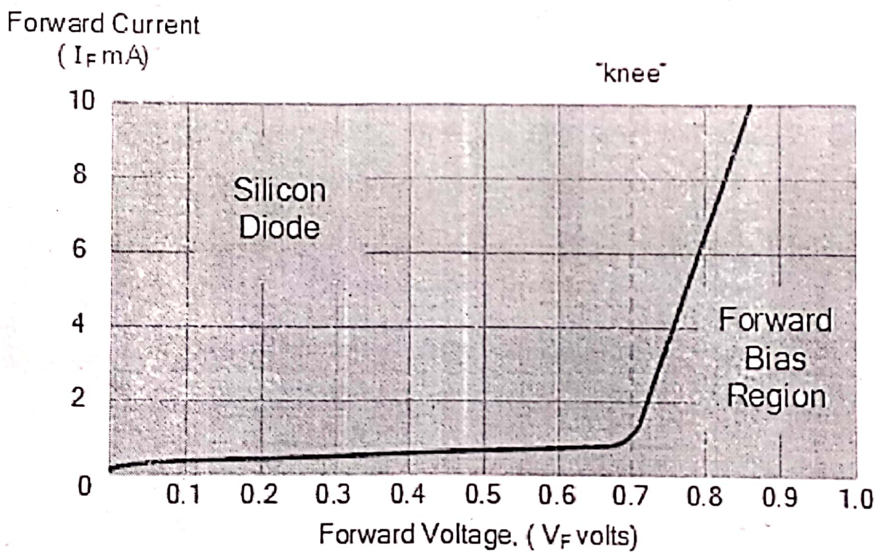


PN Junction Diode in Forward Bias

The result of this in a characteristic curve of zero current flowing up to built in potential is called as "knee current" on the static curves & then a high current flow through the diode with a slight increase in the external voltage as shown below.

VI Characteristics of PN Junction Diode in Forward Bias

The VI characteristics of PN junction diode in forward bias are non linear, that is, not a straight line. This nonlinear characteristic illustrates that during the operation of the N junction, the resistance is not constant. The slope of the PN junction diode in forward bias shows the resistance is very low. When forward bias is applied to the diode then it causes a low impedance path and permits to conduct a large amount of current which is known as infinite current. This current starts to flow above the knee point with a small amount of external potential.



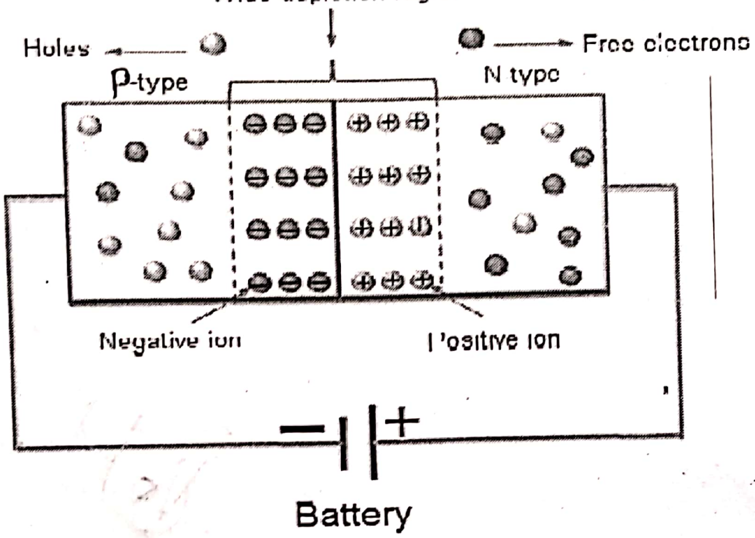
PN Junction Diode VI Characteristics in Forward Bias

The potential difference across the PN junction is maintained constant by the depletion layer action. The max amount of current to be conducted is kept incomplete by the load resistor, because when the PN junction diode conducts more current than the normal specifications of the diode, the extra current results in the heat dissipation and also leads to serve damage to the device.

PN Junction Diode in Reverse Bias

When a PN junction diode is connected in a Reverse Bias condition, a positive (+ Ve) voltage is connected to the N type material & a negative (-Ve) voltage is connected to the P-type material.

When the +Ve voltage is applied to the N-type material, then it attracts the electrons near the positive electrode and goes away from the junction, whereas the holes in the P-type end are also attracted away from the junction near the negative electrode.

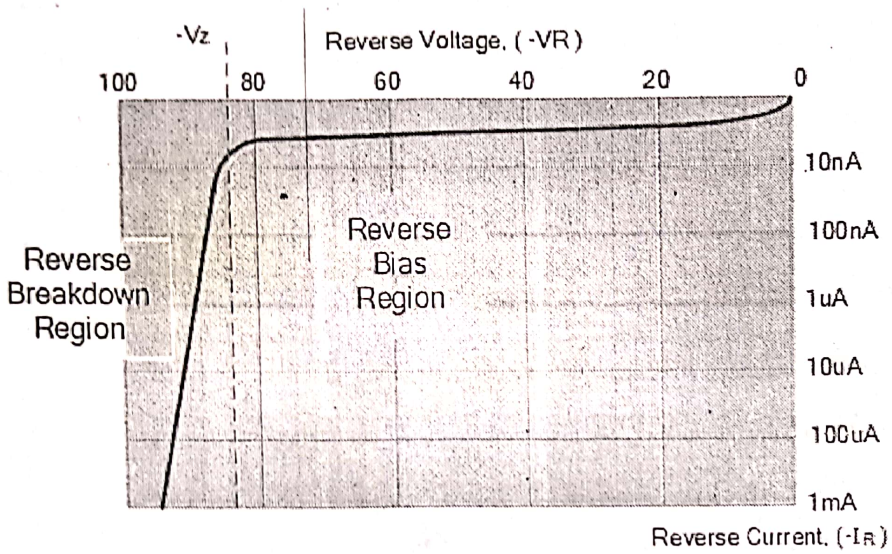


PN Junction Diode in Reverse Bias

In this type of biasing, current flow through the PN junction diode is zero. Though, the current leakage due to minority charge carriers flows in the diode that can be measured in a uA (micro amperes). As the potential of the reverse bias to the PN junction diode ultimately increases and leads to PN junction reverse voltage breakdown and the current of the PN junction diode is controlled by an external circuit. Reverse breakdown depends on the doping levels of the P & N regions. Further, with the increase in reverse bias the diode will become short circuited due to overheat in the circuit and max circuit current flows in the PN junction diode.

VI Characteristics of PN Junction Diode in Reverse Bias

In this type of biasing, the characteristic curve of diode is shown in the fourth quadrant of the below figure. The current in this biasing is low till breakdown is reached and hence the diode looks like as open circuit. When the input voltage of the reverse bias has reached the breakdown voltage, reverse current increases enormously.



PN Junction Diode VI Characteristics in Reverse Bias

Carrier Transport – Drift and Diffusion Current.

The net flow of the 'electron and holes' in a semiconductor generates the current. The process through which these charged particles move is called transport.

Basic modes: Drift and Diffusion.

Carrier transport phenomena are the foundation for finally determining the current-voltage characteristics of semiconductor devices.

Drift – Electric field (E) is involved in the movement of the charge carrier. (fig 1a).

Diffusion – Movement or flow of charge carrier due to density gradient (dn/dx) fig (1b).

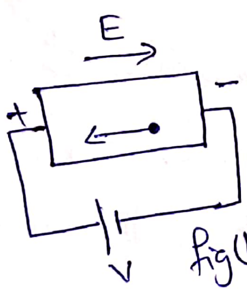


fig (1a)

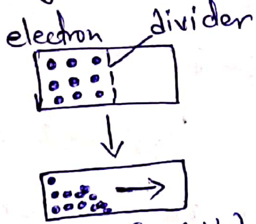


fig (1b)

Drift Current – In semiconductors, the drift current is due to the carrier drift. Carrier drift is there when an electric field is applied across the semiconductors. Carriers move with a constant drift velocity.

Note: – obeys ohm's law

Relevantly, in semiconductors, current flow is due to (2)
e^- & hole movement. Current densities due to drift of
e^- & holes are:

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

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

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

On comparing with $J = \sigma E$ we get

$$\sigma = n\mu_n e + p\mu_p \cdot e$$

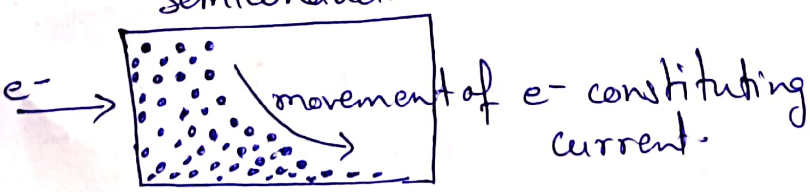
for intrinsic semiconductor $n = p = n_p$

or $\sigma_i = n_i e(\mu_n + \mu_p)$

<u>Carrier Diffusion & Diffusion Current:</u>

This is due to thermally induced random motion, mobile particles tend to move from a region of high concentration to a region of low concentration.
Current flow due to mobile charge diffusion is proportional to the carrier concentration gradient. Proportionality constant is the diffusion current.

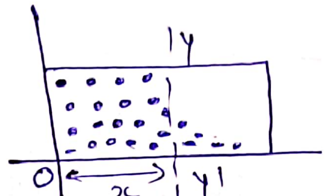
Semiconductor material



<u>Note:</u> Obey's Fick's law.

When there is electric field applied & due to thermal agitation or e⁻ injection, e⁻ starts moving from higher concentration to lower concentration constituting diffusion current.

Example -



let the Δn (concentration) of e⁻ changes with x

then $\frac{d(\Delta n)}{dx}$; concentration gradient.

As stated by fick's law, carrier diffusion is proportional to density gradient & moves in the negative direction of gradient. Now the rate of flow of e⁻ is proportional to $-d(\Delta n)/dx$.

Rate of flow across unit area is

$$-D_n \frac{d(\Delta n)}{dx}$$; D_n = Diffusion coefficient of e⁻

J_n (diffusion) = $-(e)$ (rate of flow across unit area)

$$= e D_n \frac{d(\Delta n)}{dx}$$

Similarly for holes, hole diffusion is in the same direction at a rate of per unit area $= -D_p \frac{d(\Delta p)}{dx}$

or J_p (diffusion) = $+(e)$ (rate of flow across unit area)

$$= -e D_p \frac{d(\Delta p)}{dx}$$; D_p = hole diffusion coefficient.

Total ~~of~~ hole current is

$$J_p = J_p(\text{drift}) + J_p(\text{diffusion})$$

$$J_p = pe\mu_p - eD_p\, d(\Delta p)/dx$$

Similarly for e^-

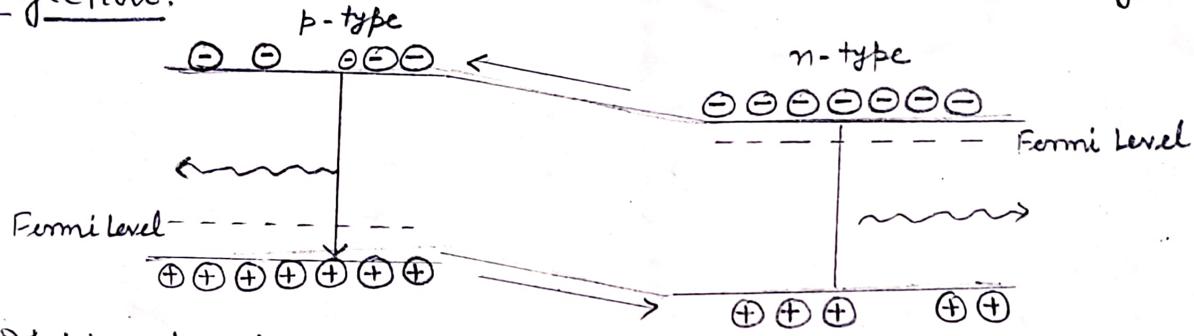
$$J_n = ne\mu_n + eD_n\, d(\Delta n)/dx$$

x —— x —— x

Light Emitting Diodes (LED) :⇒ LED (Light emitting diodes) is a semiconductor p-n junction diode ~~with~~ which convert ~~light~~ electrical energy to light energy under forward biasing.

Principle :⇒ When the diode is in forward bias electrons which are majority carriers in 'n'-regions cross the junction and go to 'p'-region and become minority carriers in 'p'-regions.

Likewise holes which are majority carriers in 'p'-region cross the junction and go to 'n'-region and become minority carrier in 'n'-region. This phenomenon is called minority carriers injection.



If biased voltage is further increased these exess minority carriers diffuse from junction and they recombine with majority carriers. So the electrons which are minority carriers in 'p'-region recombine with holes which are majority carriers in 'p'-region and emit light. Similarly holes are ~~majority~~ minor carriers in 'n'-regions recombine with electrons which are majority carriers in 'n'-region and emit light. Thus radiative recombination leads to photon emission.

The no. of radiative recombination is proportional to carrier injection rate and hence current flow through device

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

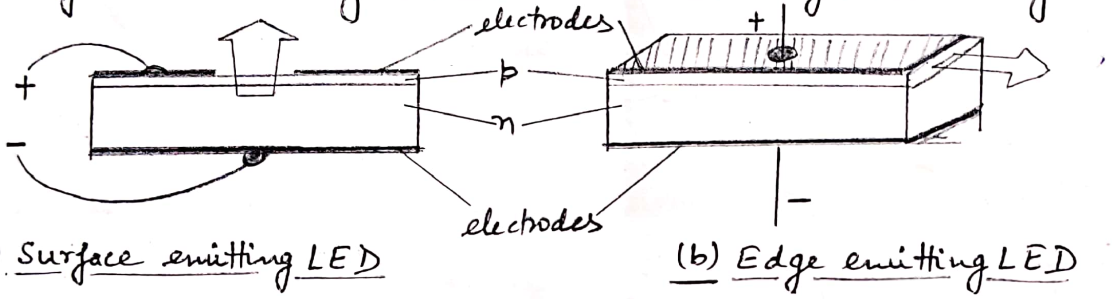
where I_0 = saturation current, V = forward bias Voltage, k = Boltzman Con
β varies from 1 to 2 depending upon superconductor & temp.
1 – Ge & 2 – Si, β – Emission Coefficient

The optical photon emitted due to radiative recombination has the energy very close to bandgap Eg and frequency of emitted photon is

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

<u>LED Construction</u> :⇒ An LED must be constructed such the the light emitted by radiative recombination event can escape the structure. The LED can be of two different type.

① Surface Emitting LED ② Edge emitting LED.



<u>(a) Surface emitting LED</u> <u>(b) Edge emitting LED</u>

① <u>Surface Emitting LED</u> :⇒ Surface emitting LED can be made such that the bottom edge reflect light back towards the top surface to enhance the output intensity.

② <u>Edge Emitting LED</u> :⇒ In edge emitting LED the emitted radiation is relatively direct by side edge. Hence it has higher efficiency

Although the internal quantum efficiency is 100%, the external efficiencies are much lower. The main reason is that most emitted light radiation strikes the material interface at greater angle than critical angle.

The internal critical angle at semiconductor.

$$\boxed{\sin \theta_c = \frac{n_2}{n_1}}$$

n_1 & n_2 are refractive index of <u>air = 1</u> & Semiconducter of group <u>III = 3.5</u>, <u>$\theta_c = 16$</u>

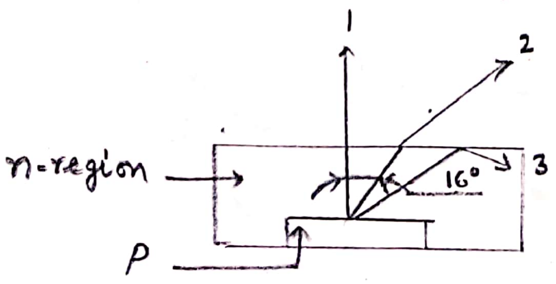
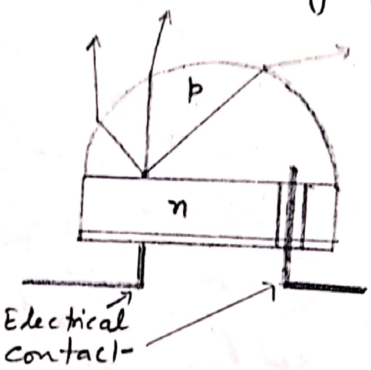
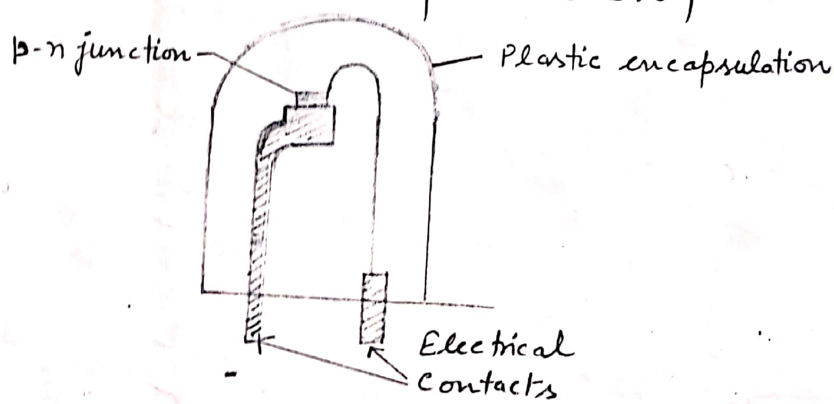


Fig:- <u>Critical Angle</u>

So All striking light rays having angle exceeding 16° suffe total internal reflection and as a result most of ~~reflected~~ emitted light is reflected back inside semiconductor crysta

Hence to improve the external efficiency loss the semiconductor is given a dome shape. Hemi-spherical domes made from plastics are effective in increasing the external efficiency by a factor 2 or 3. There will be some losses at plastic/air interface but these are easily minimize by molding plastics in hemispherical shape.



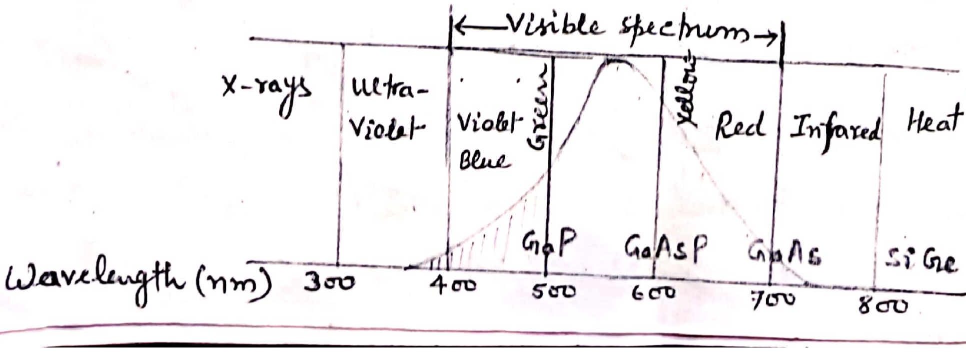


LED Materials :⇒

(1)- The choice of material for an LED is decided by spectral requirement. The most commonly used materials for LED are GaP, GaAs and their related ternary compound $GaAs_xP_{1-x}$.

(2)- The band gap radiation of GaP, GaAs & GaAsP is shown in Fig GaP gives a peak of 560nm is very close to wavelength of eye.

(3)- The GaP one of the most useful of all visible semiconductor light sources since in addition to green light both red and other colour can be produced by dopant.



Semiconductor materials of interest for optoelectronic device

Optoelectronic devices find various applications in telecommunication, military services, medical field and automatic control system. Devices and the material used are as follo

1- Photovoltaic Cell :- Photo electric transducers generate electric current when exposed to light. A photovoltaic cel consist of many p-n junctions connected in series. One of the junction is very thin, so light can easily pass throu it. When light passes, charge carriers such as holes & electrons are produced proportional to incident light. Solar cells & solar batteries are used in satellites.

Eg. of Materials :- Some common solar cell material sc conductors are, Si - single crystal, Si - polycrystal, Amorpho Si - Ge : H films, GaAs, GaAlAs, Ga.InP, CdTe thin fil

(2) Photoconducting cells :- LDRs are typical photoconduc cell Eg. cadmium sulphide (Cds)

(3) Light Emitting Diodes :- A semiconductor diodes that emits narrow - spectrum light when electrically biased in forward direction. Eg. GaAs, AlGaAs, InGaN

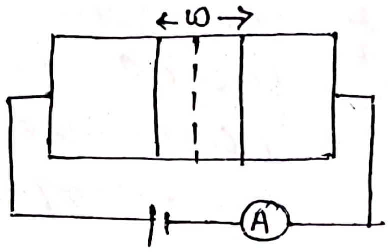
(4) Diode Lasers :- Based on Semiconductors (III-V) grou Inadian Phosphide, Gallium antimonide & gallium nitride are some examples of compound semiconductor that can be used to create junction diodes that em light.

(5) Photo diode & Photo current :- A photodiode is semiconduc device that converts light into an electrical current. Photo diodes are similar to regularly semiconductor diodes except

that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber conn-ction to allow light to reach the sensitive part of the device.

Materials :- Silicon → $\lambda = 190 - 1100$ (nm), Inadium Gallium Arsen $\lambda = 800 - 2600$ nm,

Ge → $\lambda = 400 - 1700$ nm, Mercury Cadmium telluride = 400-14…



Light creats the carriers that move in the same direction as minority carriers in reverse biased junction (in the darkness).

Therefore under illumination there is a photo current whose direction corresponds to reverse current of the junction. Incident photon flux (n/A/sec) $\phi_0 = \frac{P_{inc}}{Ah\nu}$ (1

where θ_R = reflection coefficient of top surface

A = Area of device, P_{inc} = incident optical power

Drift current density $J_{dr} = q\phi_0(1 - e^{-\alpha W})$

In case depletion region is thick enough i.e. $\alpha W >> 1$

$$J_{dr\,max} = q\phi_0,$$

Total Photo current $\boxed{I_{dr} = Aq\phi_0(1 - e^{-\alpha W})}$

CLASSIFICATION of LED :-

LED's are p-n junction that can emit spontaneous radiation in UV, visible or IR regions. The visible LED has a multiple of applications as an information link b/w electronic instruments and their uses.

(1) Visible LED :- Multiple application as an information link b/w electronic instruments and their uses.

① Visible LEDs → That generates visible illumination when charged with electrical currents. They are used in many electronic devices as indicator lamps, as rear-window & brake lights, full-color posters, in auto-focus cameras, in TV remote controls and also as light sources in fibre-optic communication systems.

$\lambda = (0.4 - 0.7\,\mu m)$

② IR LEDs → The infra-red LED is a special purpose LED emitting infrared rays ranging from 700nm to 1mm wavelength. They are made of GaAs, AlGaAs. They are commonly used as sensors. It works on the photo-coupler or opto-coupler

③ White LEDs → This displays the white light in colour when all the primary colors mixes well. Secondly, by the use of a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, as similar to ~~flo~~ fluorescent light bulb works.

Methods of mixing colors to get White LED

① Blue LED + Green LED + Red LED
② Near-UV / UVLED + RGB phosphor.
③ Blue LED + Yellow phosphor

(2) White LED'S :- Key component in backlight source for liquid crystal flat-panel display & street lamp.

(3) IR LED'S :- Useful in opto-electronic applications. Like opto-isolators, Optical Fiber communications and health care applications.

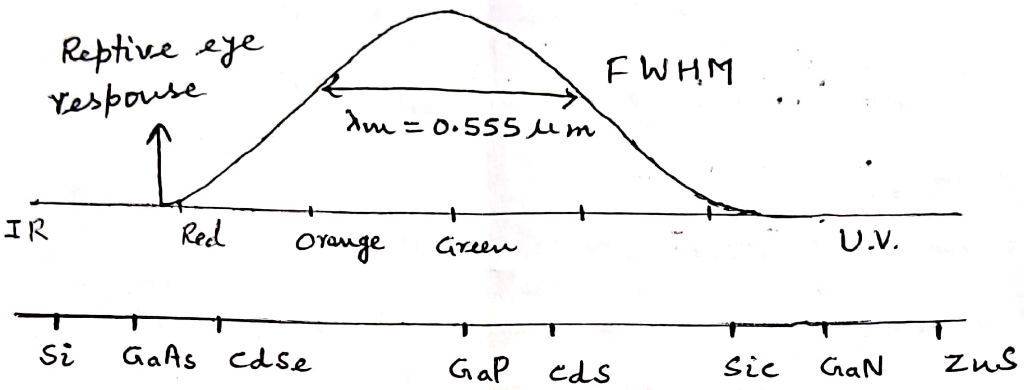
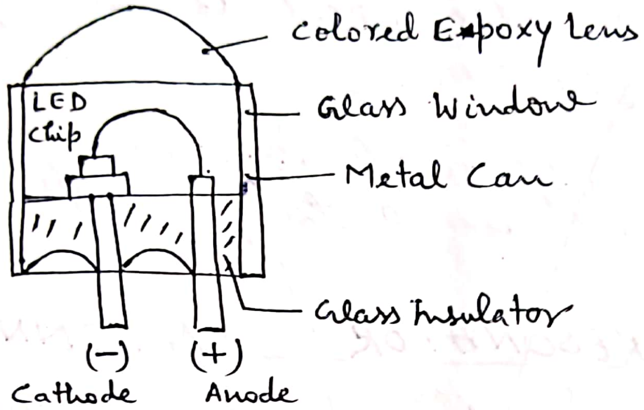


Fig. Eye Response Curve

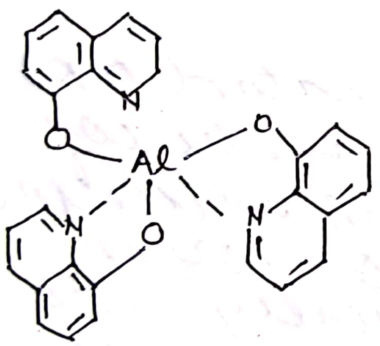
Materials	Wavelength
InAsSbP / InAs	4200 (nm)
InAs	3800 (nm)
GaSb	1800 (nm)
SiC	1300 (nm)
GaAs : Si	940 nm
GaP	690 nm
SiC	400 - 460 nm
BN	260, 310, 490 nm

Organic LED :- In recent years certain organic semiconductor have be studied for electroluminescent applications. Organic LED (OLED) is particularly useful for a multicolour large area flat panel display because of its attributes of low power consumption & excellent emissive quality with a wide viewing angle.

OLED's are made from small molecules are polymers. Commonly macro particles/molecules with a molecular weight greater than 10000 atomic mass unit (amu) are called polymers, whereas ligher molecules are referred to small molecules. Usually a polymer light emitting diode is referred to as PLED. Structure of OLED prepared by vacuum depositi technique.



- High pressure/performance OLED was developed using the concept of multilayer structures. Fig. below shows the moleculer structure of two representative organic semicon-ductors used for a double layer structure. They are the tris (quinolin-8-olato) aluminium (AlQ3), Aromatic diamine.



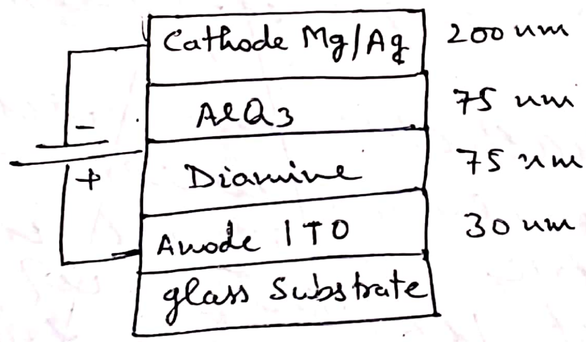


Fig:- Organic Semiconductor & OLED Cross-section View.

The organic material is electrically conductive due to de-localization of pi-e⁻ caused by conjugation over all or part of molecule & the material therefore acts as organic Semiconductor.

Advantages → Thin- low cost displays with low driving voltage; Wide-viewing angle, high contrast and color. Polymer LEDs are beneficial for printable & flexible displays. OLEDs — digital Cameras, MP3 players etc.

Explanation of carrier generation & recombination process :-

Carrier Generation (free e- and holes)

Process by which free e- and holes are generated in pair is called carrier generation
In other words, when the e- in the valence band get enough energy, they absorb the energy and jumps to conduction band. The jumped e- is called free e- & the place from where e- is left is called hole. Similarly, two type of charge carriers (e- & holes) are generated.

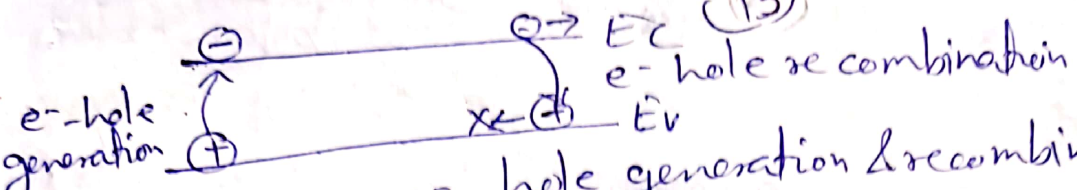
Recombination (free e- and holes)

The process by which free e- and holes gets eliminated is called recombination of carriers. When free e- in the conduction band falls into hole in the valence band, the free e- and hole gets eliminated.

e- hole pair is the fundamental unit of generation and recombination corresponding to an e- transitioning between valence band and conduction band where generation of e- is a transition from the valence band to the conduction band and recombination is a reverse process.

Recombination and generation are regularly happening in semiconductors. With the change (sudden) in temperature, will increase the rate at which e- and holes are thermally generated so that their concentrations will change with time until new equilibrium values are reached. An external excitation such as light can also generate e- & holes, creating non-equilibrium condition. let us first consider the band-to-band generation and recombination and then later on effect of allowed electronic energy states within the band-gap referred as trap / recombination ~~ce~~ centres.

In equilibrium state e- and holes are independent of time. However e- ~~and~~ are continually thermally excited from valence to conduction band. At the same time, e- randomly moving through the crystal in the conduction band may come near to hole & fall into the empty states in the valence band. This rate of generation & recombination should be equal.



e-- hole generation & recombination
fig-1

let G_{no} & G_{po} be the thermal generation rates of e- & holes resp. given in the units of #/cm³-s.
For direct band-to-band generation, e- & holes are created in pairs, so

$$G_{no} = G_{po} \quad \text{—— (1)}$$

let Let R_{no} & R_{po} be the recombination rates of e- & holes, in units of #/cm³-s. In direct-band-to-band recombination, e- & holes recombine in pairs, so that

$$R_{no} = R_{po} \quad \text{—— (2)}$$

In thermal equilibrium -

$$G_{no} = G_{po} = R_{no} = R_{po} \quad \text{—— (3)}$$

⇒ Excess Carrier Generation and Recombination

When high energy photons are incident on a semiconductor, not only e- is being created in the conduction band but the hole is also being created in the valence band. This additional e- and holes created are called excess e- & hole

These excess e^- & holes are generated by an external force at a particular rate. Let g_n' be the generation rate of excess e^- and g_p' be the excess holes in units of $\#/cm^3$-s.

For direct band-to-band

$$g_n' = g_p' \quad \text{———} \quad (4)$$

~~they~~ When excess e^- and holes are created, conc^n of e^- and holes in the respective bands increases above their thermal equilibrium value.

$$\text{ie} \quad n = n_o + \delta n \quad \text{———} \quad 5(a)$$

$$\& \quad p = p_o + \delta p \quad \text{———} \quad 5(b)$$

where n_o & p_o are the thermal equilibrium conc^n & δn & δp are the excess e^- & hole conc^n.

from eq^n 5(a) & (b) we know that in non-equilibrium condition $np \neq n_o p_o = n_i^2$

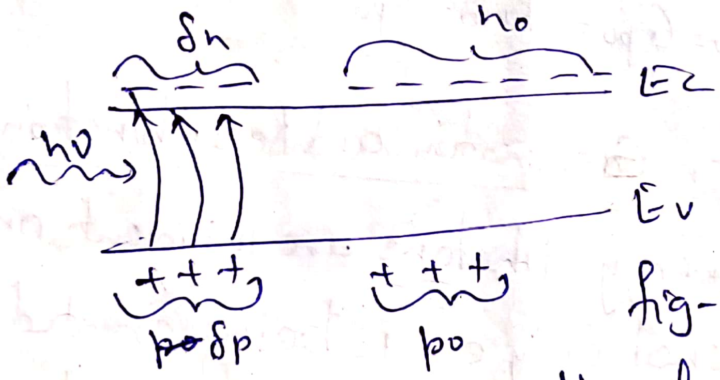
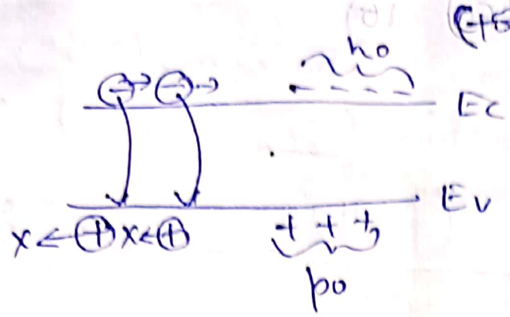


fig-2

Creation of excess e^- & hole densities by photon,

At steady state generation of excess e^- & holes will not cause a continual buildup of their carrier conc^n.

fig 3 -



Recombination of excess carriers reestablishing thermal equilibrium

Excess e^- & holes recombination rate is given as R_n' & R_p' in units of $\#/cm^3\text{-}s$. ie $R_n' = R_p'$ — (6)

Net rate of change in e^- concn can be written as

$$\frac{dn(t)}{dt} = \alpha_r \left[n_i^2 - n(t)\,p(t) \right] \quad \text{— (7)}$$

where $n(t) = n_o + \delta n(t)$ — 8(a)

$p(t) = p_o + \delta p(t)$ — 8(b)

In eqn (7) first term $\alpha_r n_i^2$ is the thermal equilibrium generation rate. Since excess e^- & holes are created & recombine in pairs, we have

$\delta n(t) = \delta p(t)$ (excess carriers as they are equal).

The thermal equilibrium ~~parat~~ parameters n_o & p_o are independent of time, ie eqn

(7) becomes —

$$\frac{d[\delta n(t)]}{dt} = \alpha_r \left[n_i^2 - (n_o + \delta n(t))(p_o + \delta p(t)) \right]$$

$$= -\alpha_r\, \delta n(t) \left[(n_o + p_o) + \delta n(t) \right] \quad \text{— 9}$$

(eqn can be solved by imposing the Conditions of low-level injection).

(18) ~~(16)~~

For ex. for p-type ($p_o >> n_o$) ie
for low-level injection ($\delta n(t) << p_o$),
then we have
$$\frac{d(\delta n(t))}{dt} = -\alpha_r p_o \, \delta n(t) \quad —(10)$$

Soln is with exponential decay from initial excess concentration
$$\delta n(t) = \delta n(0) e^{-\alpha_r p_o t} = \delta n(0) e^{-t/\tau_{no}} \quad —(11)$$

where τ_{no} = lifetime of minority charge carriers.

Eqn (11) describes the decay of excess minority carrier e⁻ so that τ_{no} is referred as excess minority carrier lifetime.

Now the recombination rate can be written as
$$R_n' = \frac{-d(\delta n(t))}{dt} = +\alpha_r p_o \, \delta n(t) = \frac{\delta n(t)}{\tau_{no}} \quad —(12)$$

for direct ~~band to~~ band-to-band recombination excess majority carrier holes recombine at the same rate, so that p-type material
$$R_n' = R_p' = \frac{\delta n(t)}{\tau_{no}} \quad —(13)$$

Similarly for n-type material-
$$R_n' = R_p' = \frac{\delta n(t)}{\tau_{po}} \quad —(14)$$

Generation rate of excess carriers are not functions of e⁻/hole concn. In general, generation & recombination rates may be functions of space & time.

x——x

I- Schottky Junction — When metal comes in contact with semiconductor, two types of junctions are formed depending upon their work functions of semiconductor and its relation with metal as

(i) Schottky junction – $\phi_m > \phi_{semi}$. – fig 1.

(ii) Ohmic junction – $\phi_m < \phi_{semi}$.

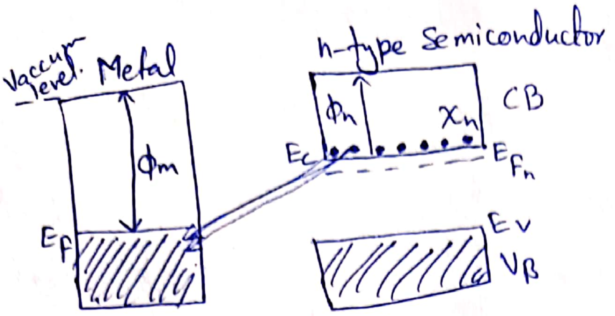
Ex- Metal and n-type semiconductor.

Work function of semiconductor is low, so its fermie level is higher as compared to metal. At equilibrium the fermi level must line up.

In another form, e- in the conduction level of semiconductor moves to the empty energy states above the fermi level of the metal. This creates +ve charges on the semiconductor side and due to excess e-, negative charge on the metal side, giving rise to 'contact potential'.

Due to this contact potential, low charge density on the semiconductor side ($\sim 10^{17} cm^{-3}$) e- are removed not only from the surface but also from a certain depth within semiconductor giving rise to depletion region within in semiconductor. (fig 2.)

fig 1-



Before Contact

Schottky junction acts as a rectifier i.e it conducts in forward bias & not in reverse bias.

fig 2.

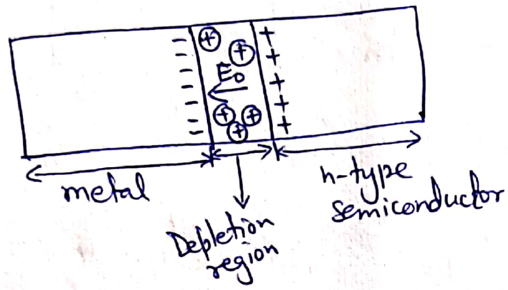
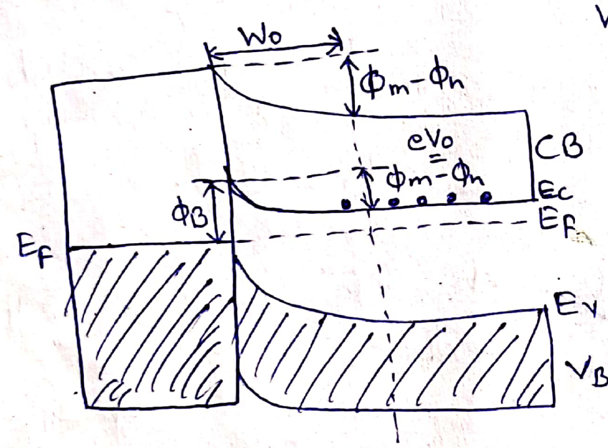


fig 3.



Wo = Depletion region / space charge region

Band bending on the semiconductor side. Semiconductor bands bend up takes place from semiconductor (+ve) to metal (-ve) in the direction as electric field.

So, in Schottky junction fermi-level lines up and also a positive potential is formed on the semiconductor side. The bending of energy bands towards the semiconductor side is there because of extension in depletion region within a certain depth in the semiconductor.

From this we have $eV_0 = \phi_m - \phi_{semi}$ —(1)

Metal work function is constant, while the semiconductor work function depends on the dopant concentration. Contact potential represents the barrier for the e^- movement from n-type semiconductor towards metal.

The contact potential formed prevents further motion (c) of the e⁻ from metal to semiconductor. This is known as Schottky barrier (ϕ_B) which is given as –

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

χ_n = e⁻ affinity of the n- type of semiconductor.

Now at equilibrium, e⁻ from semiconductor to metal is balanced by the contact potential and thus there is no net current. It can be biased by applying external potentials. The current flow depends on the type of bias and amount of applied external potential.

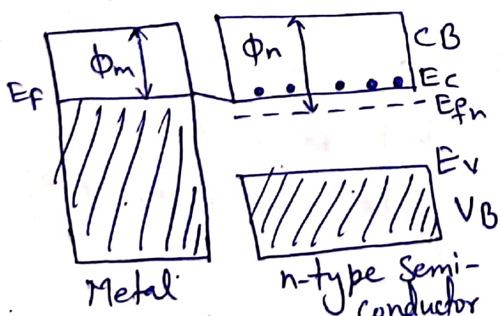
(i) Forward Bias – Metal – +ve terminal
Semiconductor – –ve terminal.

(ii) Reverse Bias – Metal – –ve potential
Semiconductor – +ve potential

II- Ohmic Junction

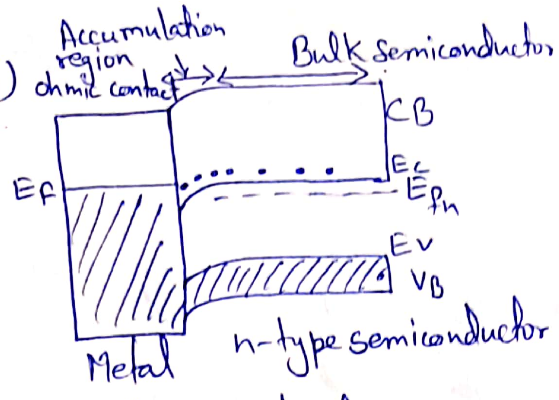
Ohmic Junction – When semiconductor has a higher work function than metal then the Ohmic junction is formed.

fig 4 –



(a) Before Contact.

fig 4 (b)



(b) After Contact.

At equilibrium, e- move from metal to the empty states in the conduction band so that there is "accumulation region near the interface i.e on the semiconductor side. This accumulation region has higher conductivity than the bulk semiconductor as the e- are high in concentration.

In this way, ohmic junction acts as a resistor in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor

Applications – (i) Thermoelectric devices where small volume can be cooled with the help of dc.

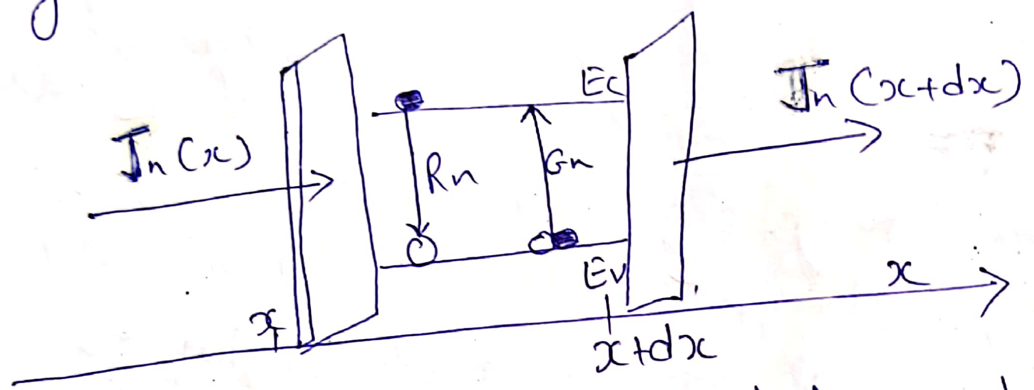
(ii) Digital electronics – charging & discharging ~~of the leads~~ is the major cause of power dissipation in high clock rate.

(iii) Due to contact resistance, power dissipation through joule heating it is applicable in low frequency and analog circuits ex- solar cells.

⇒ Applications (Schottky Junction) – In electronic industry, for voltage clamping applications, to prevent transistor saturation, in digital computers, power rectifier, ~~etc~~ radio frequency mixer and detector diode etc.

CONTINUITY EQUATION (DERIVATION)

It is the differential form of the conservation of charge equation, plus terms for carrier generation and recombination.



Charge is neither ~~con~~ created nor destroyed.
From the above figure –

$$\frac{\partial Q}{\partial t} = I(x) - I(x+dx) \quad \text{——— ①}$$

where Q – charge ; I – current.
Eqn ① shows, the change in charge / time = current in – current out.

For semiconductor, we consider unbound charge carriers, that can spontaneously appear from the lattice or spontaneously combine into the lattice.
On adding the terms of generation & recombination

$$\partial Q(\text{unbound}) / dt = I(x) - I(x+dx) + G - R.$$

where G = generation rate for whole volume.
R = recombination rate for whole volume.

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Consider that areas and volumes are uniform (26) ②

then ~~str~~ shrinking the volumes to 0.

$\cancel{q \times \frac{\partial n}{\partial t} \times dx \times A}$

$$q \times \frac{\partial n}{\partial t} \times dx \times A = A \times [J(x) - J(x+dx)] + qGAdx - qRAdx \quad ②$$

where n – no. of charge carriers.

q – charge on single carrier.

here G and R are numbers/volume.

~~inspite~~.

Dividing eqn ② by q, A & dx, b.h.s, we get

$\cancel{q \times \partial n}$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\left[J(x) - J(x+dx)\right]/dx + G - R$$

Taking the lim as $dx \to 0$ we get.

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J}{\partial x} + G - R \text{ (electrons)}, \text{ or } \frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J}{\partial x} + G - R \text{ (for holes)}$$

When J is figured out, J has two components, drift and diffusion.

Drift current = no. of charge carriers times their avg. velocity and avg. vel. is ~~∝ to~~ proportional to applied electric field through 'mobility term' all times the charge on single carrier.

(27)

J_n diff. $= eD_n \frac{\partial n}{\partial x}$; J_n drift $= neU_nE$.

an J_p diff. $= -eD_p \frac{\partial p}{\partial x}$; J_p drift $= peU_pE$.

~~We kno~~. We now have, equation as (using diffusion curr

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} - \frac{\Delta n}{\tau_n}$$

where $\Delta n = n_p(x) - n_{po}$

& $\Delta p = p_n(x) - p_{no}$

and $$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \frac{\Delta p}{\tau_p}$$

for steady state $\frac{\partial n}{\partial t} = \frac{\partial p}{\partial t} = 0$

ie $$\frac{\partial^2 n}{\partial x^2} = \frac{\Delta n}{D_n \tau_n} = \frac{\Delta n}{L_n^2}$$

& $$\frac{\partial^2 p}{\partial x^2} = \frac{\Delta p}{\tau_p D_p} = \frac{\Delta p}{L_p^2}$$

where L_p & L_n = Diffusion lengths

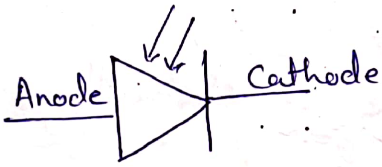
$$L_n = \sqrt{D_n \tau_n}$$

$$L_p = \sqrt{D_p \tau_p}$$

$D_p = D_n$ = Diffusion constt.

PHOTOCURRENT IN A P-N JUNCTION DIODE–

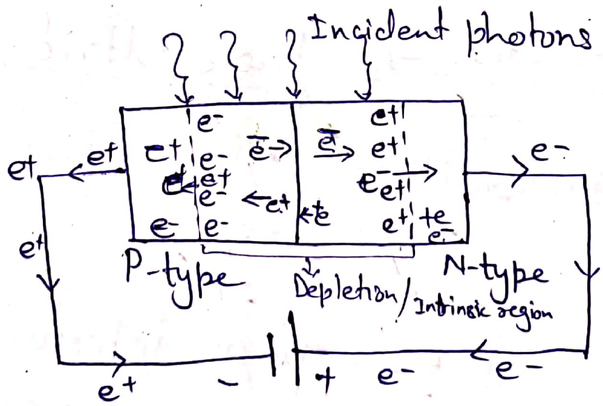
P-N junction diode is a photo diode that consumes light energy to produce electric current. They are also called as photo-detector, a light detector and photo sensor. These diodes are designed to work in reverse-bias condition.
Eg- Solar-cell, a photo-diode which converts solar energy to electric energy



p – -ve
n – +ve of battery

(A photo-diode symbol)

Working–



P-N JUNCTION DIODE

The photo diode continuously operates in reverse bias mode. Photo current is nearly independent of reverse bias voltage applied. For zero luminescence, photo current is almost zero excluding small dark current. It is of the order of

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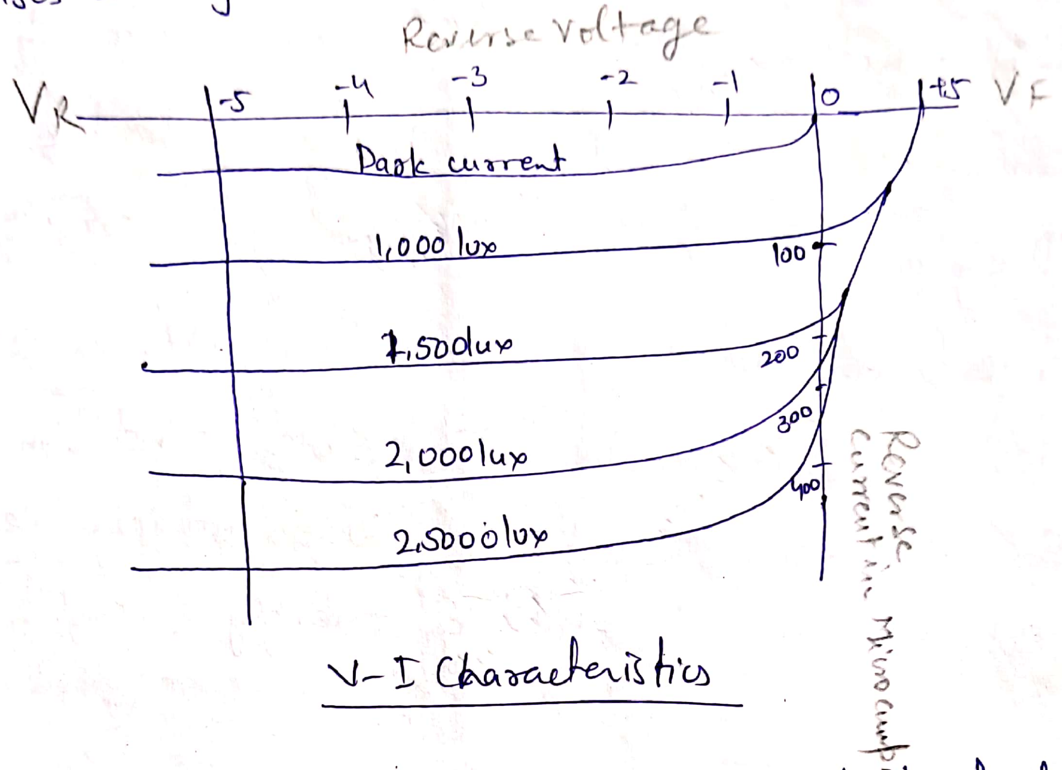
nano-amperes. As optical power rises, the photo current also rises linearly.



V-I Characteristics

Types – (1) PN photodiode (2) Schottky photo diode
(3) PIN photodiode (4) Avalanche photodiode.

Modes of Operation – (i) Photo voltaic mode –
(ii) Photoconductive Mode (iii) Avalanche Diode Mode –

Applications – (i) As a photodetectors viz CCD [charge-coupled devices], photo multiplier tubes. etc.
(ii) In smoke detectors, CD players, TV & remote controls in VCRs.
(iii) To analyze samples, detectors for computed tomography etc.
(iv) In clock radios, camera light meters, street lights. etc.

INTRODUCTION TO OPTOELECTRONIC INTEGRATED CIRCUITS –

Optoelectronics is the study of electronic devices and systems that source, detect and control light usually taken as sub-field of photonics.

It is based on quantum mechanical effects of light on electronic materials, especially semiconductors, sometimes in presence of electric fields.

Optoelectronic Integrated Circuits – (OEIC)
A monolithic device containing both photonic and electronic device sources, detectors, modulators etc. on a single semiconductor substrate.

Components:– It consists of active & passive components, monolithically integrated on the same substrate. Active components are those which have to be integrated with electronic circuits. Passive components are those which do not require electric signals for their operation.

Active Components:– Lasers, photodetectors, switches, modulators etc.

Passive Components:– spectral filters, couplers, lenses etc.

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Materials:-

Requirement - Material should be with nature of transparency and good optical properties in an appropriate part of spectrum (EMW). It should be feasible to fabricate with low loss thin film waveguides for optical interconnects, good electrical, electrooptical & accoustic-optical properties.

Semiconductor materials of III-V and their alloys (i.e. GaAs, InP, InGaAsP, InGaAs)

Fabrication Technique - Among the various methods, the mostly used ones are -

~~(i) Hy~~ (i) **Hybrid Integration** - Combination of best passive & active components from different materials. This improves the individual device performance and provides the flexibility of using different materials.

limitations:- On the alignment of different optical components & limits the frequency response of the device due to relatively higher capacitance as a result of parasitic effects.

P.T.O

(i) <u>Monolithic Integration</u> (33) – All components are fabricated on a single substrate essentially from the same material. This result low value of parasitic capacitance.

<u>limitations</u>:– Poor isolation between component.

- No possibility of fabrication of inductors.
- low power rating.
- lack of flexibility etc.

(ii) <u>lattice-mismatch</u> – InP and GaAs devices are integrated with Si VLSIs on a single chip since Si technologies are more advanced than InP and GaAs based materials.

<u>Applications</u> – ~~In optoelectronic processor~~

- In computing systems
  - in optical fibre local area networks
  - In optoelectronic processor
- In communication system.
- In diffuse optical tomography.