Note:- The quantity ϕ (volts) is a characteristic of the particular metal used. when ϕ is multiplied by the electronic charge, an energy (Joules) is obtained which represents the minimum energy required for an electron to escape from the metal into a vacuum. The energy $q\phi$ is called the work function of the metal.

SCHOTTKY BARRIERS AND OHMIC CONTACTS:-

Not all diode junctions involve contacts between different doping types of the same semiconductor (homojunctions). The junctions between dissimilar materials or heterojunctions are generally divided into metal/ semiconductor and semiconductor/ semi-conductor junctions. A sufficiently degenerate semiconductor behaves essentially as a metal and produces results nearly identical to the metal/ semiconductor behaviour.

Metal/ semiconductor junctions turn out to have either linear (ohmic) or diode-like current voltage characteristics and are called ohmic contacts or Schottky diodes.

IDEAL METAL/ SEMICONDUCTOR JUNCTIONS:-

To figure out the consequences of a junction between a metal and a S.C., we need to know how electrons flow upon making the contact. Consequently, we need to know the chemical potentials (fermi energies) of electrons in the two materials. The materials property describing the electron chemical potential in metals is the work function, ϕ. It measures the position of the fermi energy with respect to the vacuum level. (the lowest energy to which an electron must be raised to escape from the surface). This is well-defined constant for a given pure metal.

The work function of a s.c. also measures the position of the fermi level. However, this value changes with doping. The energies of the band edges with respect to the vacuum level do not depend significantly upon doping so they are much better choices. The conduction band energy relative to the vacuum level. (the electron affinity χ_s) is there-fore used to quantify the general properties of semiconductor.

<u>Schottky Barriers</u>:- when negative charges are brought near the metal surface, positive (image) charges are induced in the metal. when this image force is combined with an applied electric field, the effective work function is somewhat reduced. Such barrier lowering is called the Schottky effect. Although the Schottky effect is only a part of the explana-tion of metal-semiconductor effects, rectifying contacts are generally referred as Schottky barrier diode.

The Schottky barrier diode :- (formed by contacting an n-type s.c. with metal and $\phi_m > \phi_s$)

In this section, we will consider the metal-s.c. rectifying contact or Schottky barrier diode.
The ideal energy band diagram for a particular metal and n-type semiconductor before making contact is shown in fig(1).(a). The vacuum level is used as a reference level. The parameter ϕ_m is the metal work function. ϕ_s is the s.c. wave function and χ is known as electron affinity. The ideal thermal-equilibrium metal-s.c. energy band diagram for $\phi_m > \phi_s$ is shown in figure1(b).
Before contact, the fermi level in the s.c. was above that in the metal. In order for the fermi level to become a constant through the system in thermal equilibrium, electrons from the s.c. flow into the lower energy states in the metal. Positively charged donor atoms remain in the s.c. creating a space charge region.

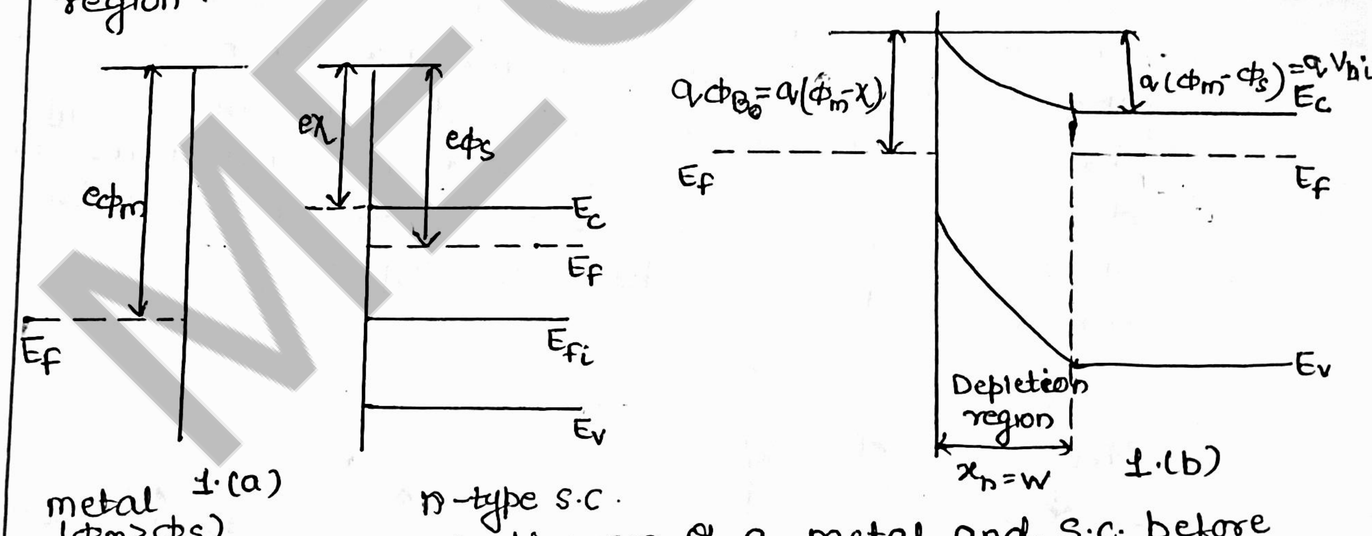


Fig.1 (a) Energy-band diagram of a metal and s.c. before contact (b) ideal energy-band diagram of a metal-n-s.c. junction for $\phi_m > \phi_s$.

The parameter ϕ_{B0} is the ideal barrier height of s.c. contact, the pot. barrier seen by electrons in the metal trying to move into the s.c.

This barrier is known as the Schottky barrier, and is given by,

$$\boxed{\phi_{B0} = \phi_m - \chi} \quad \text{——— (1)}$$

On the s.c. side, V_{bi} is the built-in potential barrier. This barrier, similar to the case of the p-n junction, is the barrier seen by electrons in the CB. trying to move into the metal. The built in pot. barrier is given by

$$\boxed{V_{bi} = \phi_m - \phi_s} \quad \text{——— (2)}$$

If we apply a positive voltage to the s.c. with respect to the metal, the s.c. to metal barrier height increases, while ϕ_{B0} remains constant in this idealized case. This bias condition is the reverse bias. If a positive voltage is applied to the metal with respect to s.c., the semiconductor-to-metal barrier V_{bi} is reduced while ϕ_{B0} again remains essentially constant. In this situation, electrons can more easily flow from the s.c. into the metal since the barrier has been reduced. This bias condition is the forward bias. The energy-band diagram for the reverse and forward bias are shown in fig 2(a) and (b). where V_R is the reverse bias voltage and V_a is forward bias voltage.

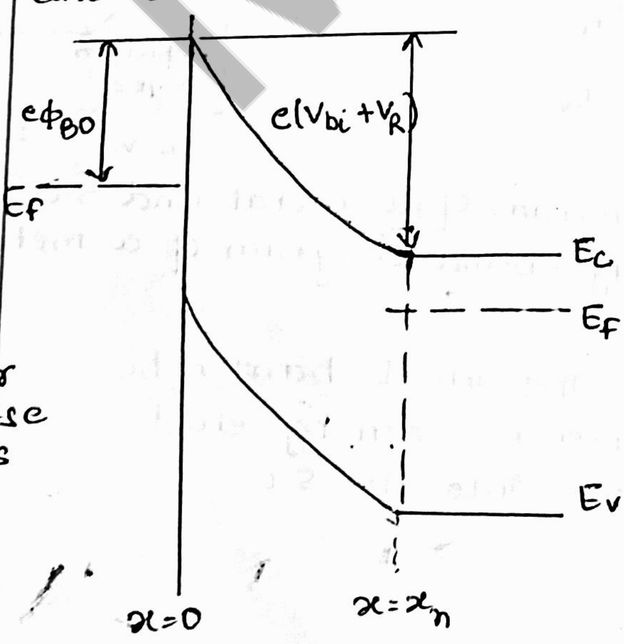
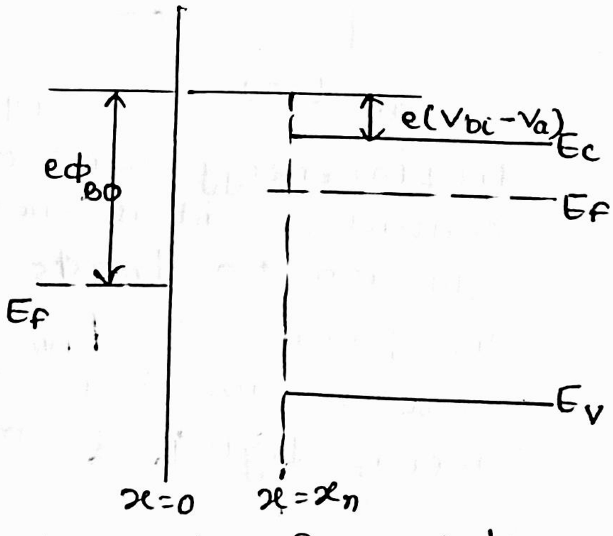


fig 2.(a): under reverse bias



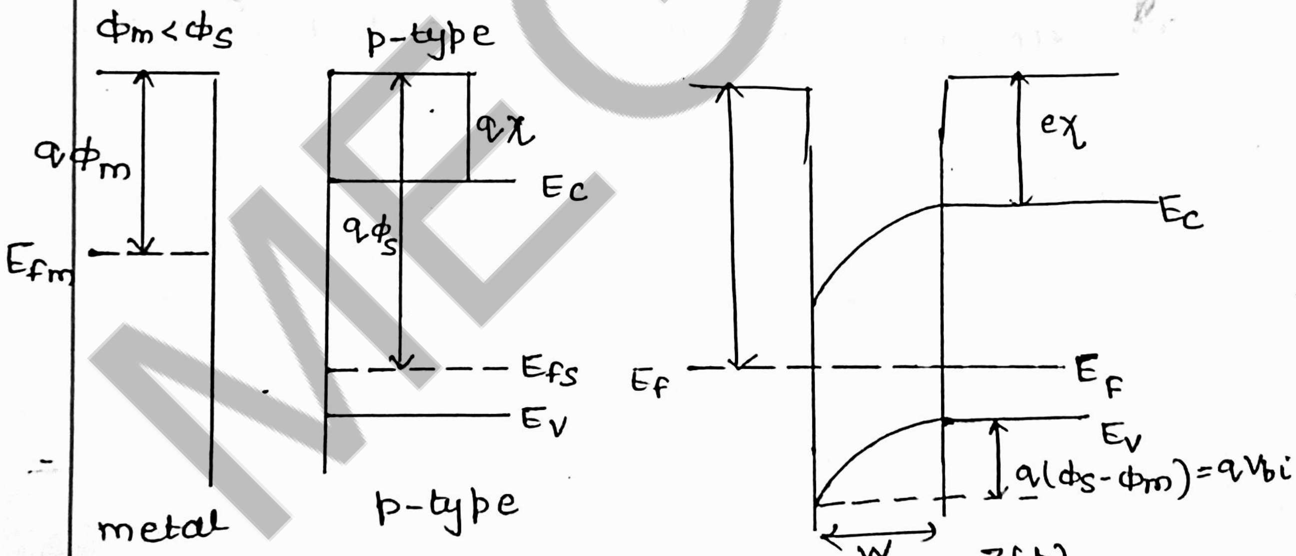
2(b) under forward bias

The Schottky barrier diode :-

Case II :- formed by contacting an p-type s.c. with metal and $\phi_m < \phi_s$:-

Fig. 3a illustrates a Schottky barrier on p-type s.c. with $\phi_m < \phi_s$. In this case aligning the fermi levels at equilibrium requires a positive charge on the metal side and a negative charge on the semiconductor side of the junction. The negative charge is accommodated by a depletion region W in which ionized acceptors are left uncompensated by holes. The potential barrier V_{bi} retarding hole diffusion from the s.c. to the metal is $\phi_s - \phi_m$.

$$V_{bi} = \phi_s - \phi_m$$

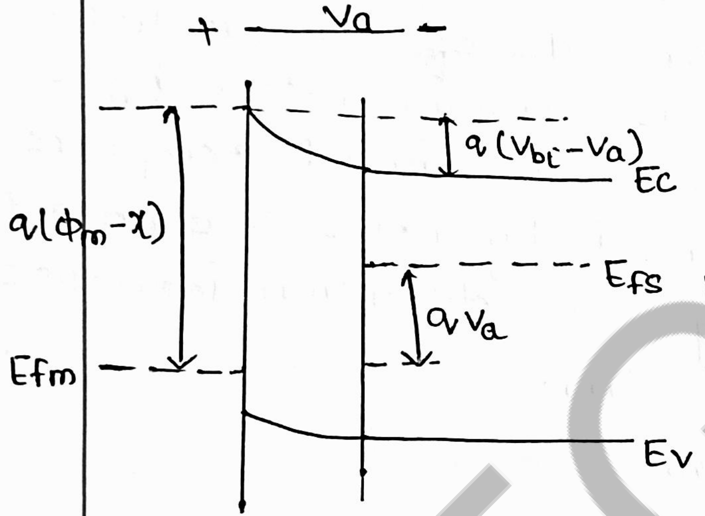


3(a) 3(b)

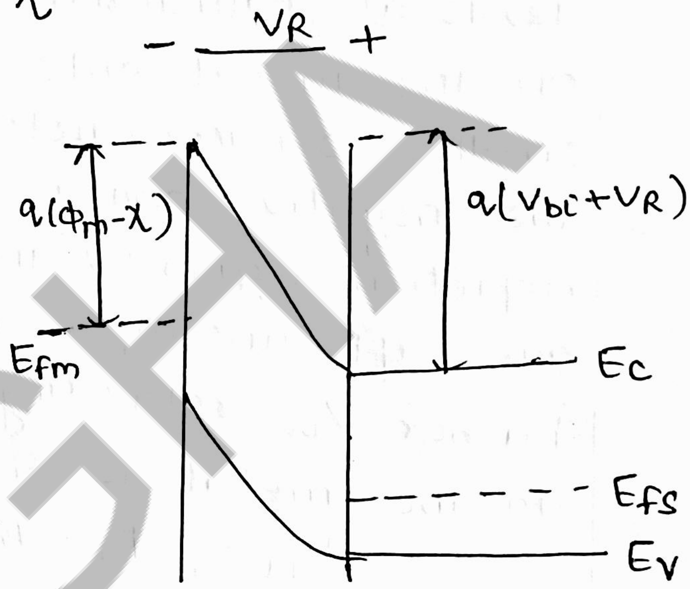
When a forward bias voltage Va is applied to the schottky barrier (fig 3b), the contact pot. is reduced from V_{bi} to $V_{bi} - V_a$ (fig 3c). As a result, electrons in the semiconductor conduction band can diffuse across the depletion region to the metal.

This gives rise to a forward current (metal S.C.) through the junction.

Conversely a reverse bias increases the barrier to $V_{bi} + V_R$ and electron flow from S.C. to metal becomes negligible. In either case, flow of electrons from the metal to S.C. is retarded by the barrier $\phi_m - \chi$.



3(c), forward bias



3(d) Reverse bias.

METAL - SEMICONDUCTOR OHMIC CONTACTS:-

Contacts must be made between any s.c device or integrated circuit and the outside world. These contacts are made via ohmic contacts. Ohmic contacts are metal-to-semiconductor contacts, but in this case they are not rectifying contacts. An ohmic contact is a low-resistance junction providing conduction in both directions between the metal and semiconductor. Ideally, the current through the ohmic contacts is a linear function of applied voltage and the applied voltage should be very small. Two general types of ohmic contacts are possible.

(i) ideal non rectifying barrier
ii) tunneling barrier.

Ideal Nonrectifying Barriers :- Let us consider an ideal metal-to-n-type s.c. contact for the case when $\phi_m < \phi_s$. figure 1(a) shows the energy levels before contact and fig. 1(b) shows the barrier after contact for thermal equilibrium. To achieve thermal equilibrium in this junction, electrons will flow from the metal into the lower energy states in the s.c., which makes the surface of the s.c. more n-type. The excess electron charge in the n-type s.c. exists essentially as a surface charge density.

If a positive voltage is applied to the s.c., the effective barrier height for electrons flowing from the metal into the s.c. will be approximately $\phi_{Bn} = \phi_n$, which is fairly small for a moderately to heavily doped s.c. For this bias condition, electrons can easily flow from the metal into the s.c..

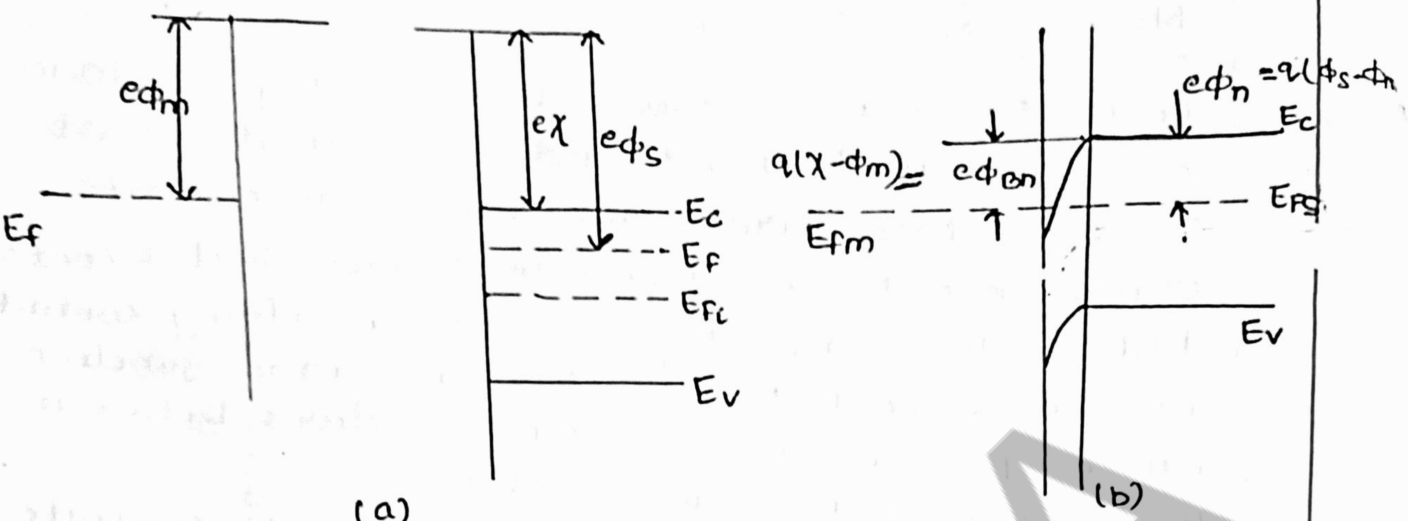
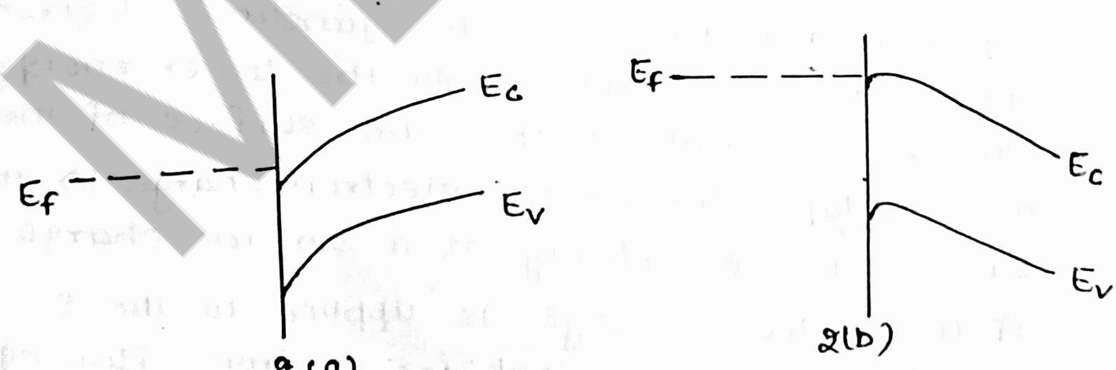


Fig (1) (a) Ideal energy band diagram before contact (b) after contact for a metal/semiconductor for $\phi_m < \phi_s$

Fig 2(a) shows the energy-band diagram when a positive voltage is applied to the metal with respect to s.c. Electrons can easily flow 'downhill' from the s.c into the metal. Fig 2(b) shows the case when a positive voltage is applied to the s.c. with respect to the metal. Electrons can easily flow over the barrier from the metal into the semiconductor. This junction is then an ohmic contact.



Fig(2): Ideal energy band diagram of metal-n-s.c. ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the s.c.

Fig (3) shows an ideal nonrectifying contact between a metal and a p-type semiconductor. Fig (3)a shows the energy levels before contact for the case when $\phi_m > \phi_s$. When contact is made, electrons from the semiconductors will flow into the metal to achieve thermal equilibrium, leaving behind more empty states, or holes. The excess concentration of holes at the surface makes the surface of the semi-conductor more p-type. Electrons from the metal can readily move into the empty states in the s.c. The charge movement corresponds to holes flowing

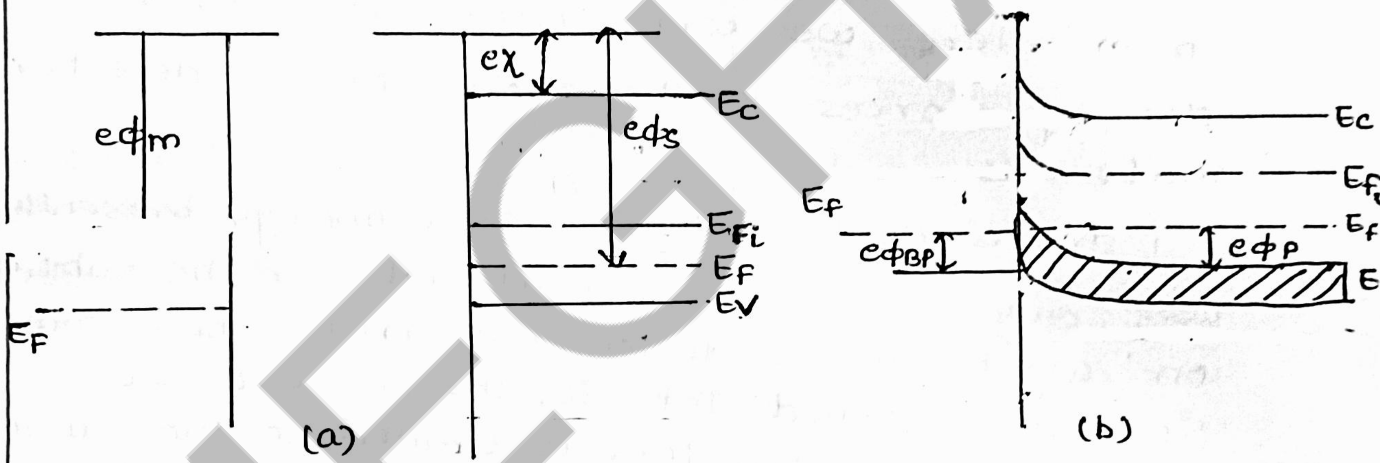


Fig (3) Ideal energy band gap (a) before contact and (b) after contact for a metal-n-semiconductor for $\phi_m > \phi_s$

from the s.c. into the metal. We can also visualize holes in the metal flowing into the semiconductor. This junction is also an <u>ohmic contact</u>.

Semiconductor materials of interest for optoelectronic devices :-

Essentially all optical detectors based upon semiconductors depend upon converting an optical signal to an electrical signal. This involves the creation of electron-hole pairs. Since essentially all semiconductors have some electronic response to an optical signal provided that the wave-length of the photons is properly chosen, there is a wide selection of materials to choose from. Here we will discuss some broader driving forces in the choice of S.C. detector materials.

Substrate Availability :- S.C. technology presently uses only a very few materials for the substrate on which active devices are grown. These are Si, GaAs, Ge and InP. So, the choice of S.C. materials for detectors is limited to those which have good lattice matching with the substrate. S.C.s alloys are widely used for detectors and one can find compositions which lattice match to some substrate.

Long distance communication Applications :-
For long distance communications, the photons with wavelength of 1.55 µm or 1.3 µm are used since the transmission losses in an optical fiber are very low at these wavelengths. A detector is thus needed to respond to these energies.

Among compound S.Cs, the alloy systems of InGaAs, InGaAsP, GaAlSb, HgCdTe can all be tailored to respond at these energies. The most widely used detector material is $In_{0.53}Ga_{0.47}As$ lattice matched to InP for long haul communication.
In addition to compound S.C, Ge is also used for long haul communication.

Local area Networks:-
In the local area Networks (LANs), where the optical signal has to propagate about a Kilometer, GaAs based emitters can be used. The compound semicon-ductor detectors used for long distance communication can be used for LANs as well, but Si forms a good detector material. Silicon avalanche photodiodes are used widely for LAN applications.

Long wavelength detection:- An important application of detectors is in the area of thermal imaging for night vision on medical diagnostics. Detectors for such applications must be either based on very narrow band gap materials, extrinsic defect levels or hetero-structure concept. Among narrow band gap materials important choices are HgCdTe alloys, PbTe, PbSe, InSb. Extrinsic detectors based on Si and Ge implanted with impurities can also be used.

High Speed detectors:- An important advance in high speed detector response has been the recent discovery of low temp. GaAs. This material is grown at very low substrate temp. where a large no. of defects are incorporated into the material. These defects decrease the e-h recombination time to $\sim 1\,ps$ in contrast to about $1\,ns$ for high quality GaAs. The very short response time leads to high speed optical detection system.

1.8 Photonic Materials – Light Emitting Diodes

LED (Light Emitting Diode) is a semiconductor p-n junction diode which converts electrical energy to light energy under forward biasing.

Principle

The diode is forward biased. Due to forward bias, the majority carriers from 'n' and 'p' regions cross the junction and become minority carriers in the other junction (i.e.) Electrons, which are majority carriers in 'n' region cross the junction and go to 'p' region and become minority carriers in p-region

Similarly, holes which are majority carries in 'p' region cross the junction and go to 'n' region and become minority carriers in 'n' region and this phenomenon is called *minority carrier injection.*

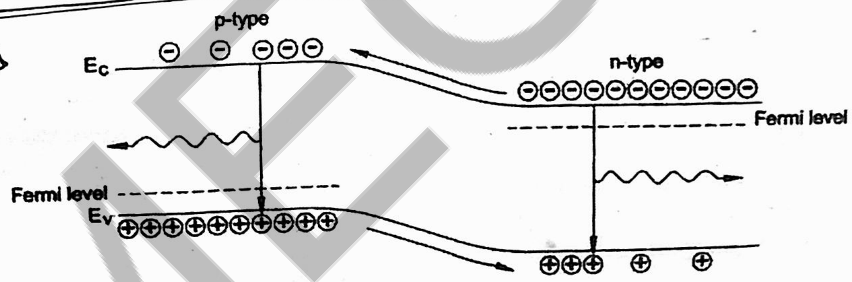


Fig. 1.20. Radiative recombination

Now if the biasing voltage is further increased, these excess minority carriers diffuse away from the junction and they directly recombine with the majority carriers. (i.e.) the electrons, which are excess minority carriers in p-region recombine with the holes which are the majority carriers in 'p' region and emit light. Similarly, the holes which are excess minority carriers in 'n' region recombine with the electrons which are majority carriers in 'n' region and emit light. This phenomenon is illustrated in Fig.1.20.

Thus radiative recombination events lead to photon emission. The number of radiative recombination is proportional to the carrier injection rate and hence to the total current flowing through the device as given by

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

where I_0 - the saturation current ; V- the forward bias voltage; k - the Boltzmann constant ; β -varies from 1 and 2 depending on the semiconductor and temperature.

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

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

where λ - the photon wavelength; h - Plancks constant; c - the velocity of light in vacuum.

LED Construction

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

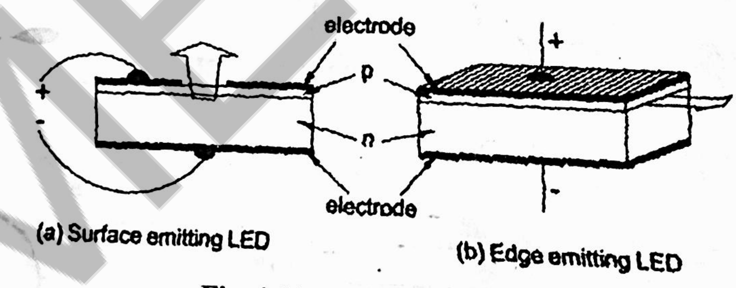


Fig. 1.21. Sketches of LEDs

LEDs can be designed as either surface or edge emitters as shown in Fig. 1.21. Surface emitting LEDs can be made such that the bottom edge reflects light back towards the top surface to enhance the output intensity. The main advantage of edge emitter LEDs is the emitted radiation is relatively direct. Hence edge emitter LEDs have a higher efficiency in coupling to an optical fibre.

Although the internal quantum efficiency of LEDs is 100%, the external efficiencies are much lower. The main reason is that most of the emitted light radiation strikes the material interface at greater than critical angle and hence trapped with in the device.

The internal critical angle at the semiconductor – air boundary is given by

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

where n_2 is the refractive index of air = 1.0

n_1 is the refractive index of the semiconductor

For group III semiconductor $n_1 = 3.5$

Therefore $\theta_c = 16°$

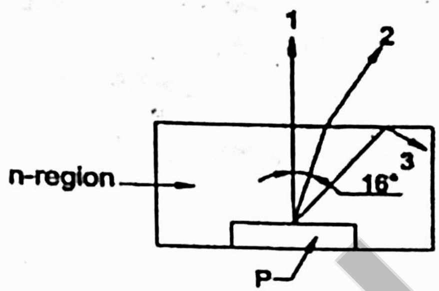


Fig.1.22. Critical angle

Therefore all rays of light striking the surface at an angle exceeding 16° suffer total internal reflection and as a result most of the emitted light is reflected back inside the semiconductor crystal as shown in Fig. 1.22.

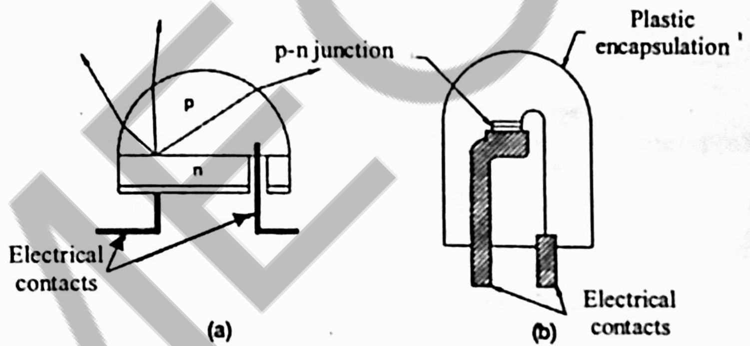


Fig.1.23. Two methods used to reduce reflection losses in LEDs

Hence to improve the external efficiency losses caused bulk absorption has to be minimized and the surface transmission has to be increased. One method to achieve this is to give the semiconductor a dome structure as shown in Fig. 1.23 (a). 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 the plastic/ air interface but these are easily minimized by molding the plastic into an approximately hemispherical shape as shown in Fig.1.23 (b).

Materials

- The choice of the materials for an LED is decided by the spectral requirements for a particular application. The most commonly used materials for LEDs are GaP, GaAs and their related ternary compound Ga As_x P_{1-x}
- The bandgap radiation of GaP, GaAs and GaAs P is shown in Fig.1.24. GaP which gives a peak at 560 nm is very close to the wavelength of maximum eye response.

- This makes GaP one of the most useful of all visible semiconductor light sources since in addition to green light both red and other colours can be produced by appropriate dopants as shown in Table 1.2.

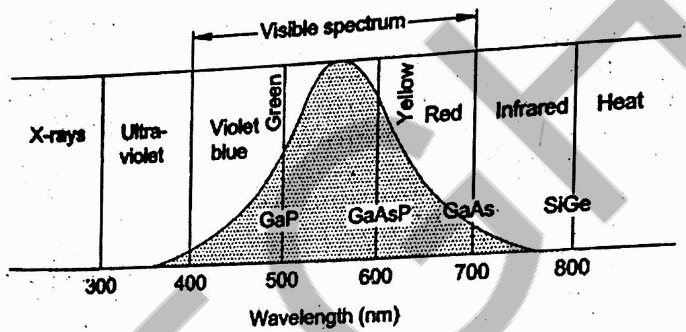
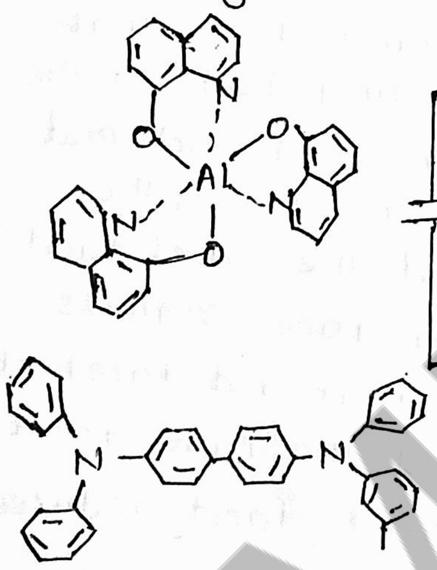


Fig.1.24. Wavelength response of LED materials

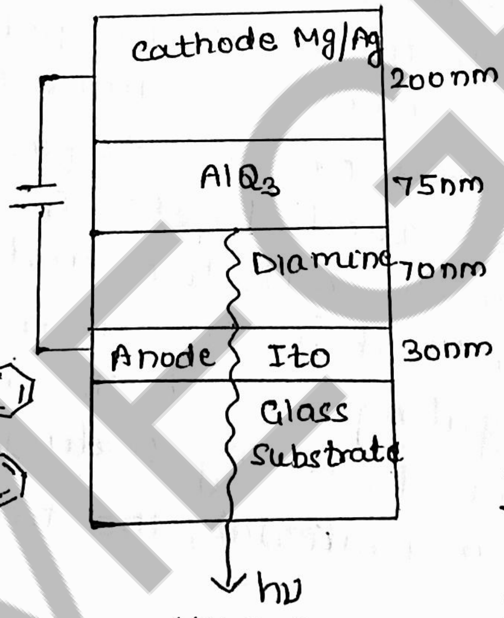
Table 1.2 LED materials properties

Material	Dopant	Bandgap (eV)	Wavelength (Nm)	Quantum efficiency (%)
GaP	N	2.88	430	0.6
GaP	Zn0	1.80	690	0.2
GaP	N	2.25	550	0.1
GaAs	P	1.88	660	0.2
AlGa	As	1.84	675	0.2

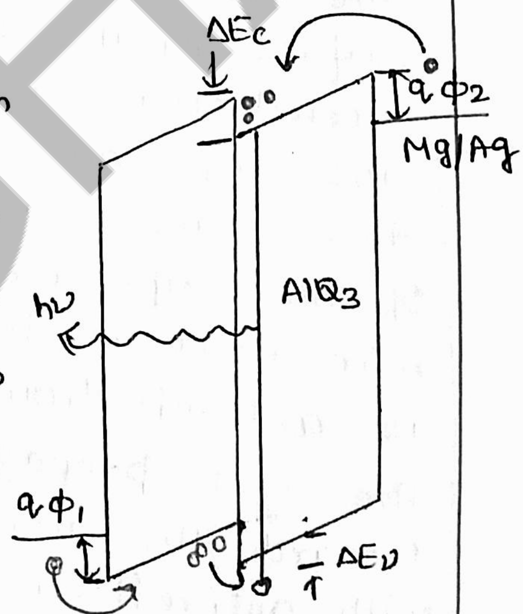
<u>Organic LEDs</u> :- The organic light-emitting diode (OLED) is particularly useful for multicolour, large area flat panel display because of its attributes of low-power consumption and excellent emissive quality with a wide view angle.



(a)



(OLED)
(b)



(c) Band diagram OLED

Fig (a) shows the molecular structures of two representative organic semiconductors. They are the tris (8-hydroxy-quinolinato) aluminium (AlQ_3), which contains six benzene rings connected to a central aluminium atom, and the aromatic diamine, which also contains six benzene rings but with a different molecular arrangement.

A basic OLED has a no. of layers on a transparent substrate (glass). Onto the substrate we deposit, in sequence, a transparent conductive anode [e.g. ITO (Indium tin oxide)], the diamine as a hole transport layer, the AlQ_3 as the electron transport layer, and the cathode contact (e.g. Mg alloy with 10% Ag). (fig. b)

Fig. c. shows the band diagram of the OLED. It is a basically a heterojunction formed between AlQ_3 and diamine. Under proper biasing conditions, electrons are injected from the cathode and move toward the heterojunction interface whereas holes are injected from the anode and also move toward the interface. Becoz of the energy barriers ΔE_c and ΔE_v, these carriers will accumulate at the interface to enhance the chance of radiative recombination.

For AlQ_3, the emitted light is green. By choosing different organic semiconductors with different band gaps, various colours including red, yellow, and blue can be obtained.

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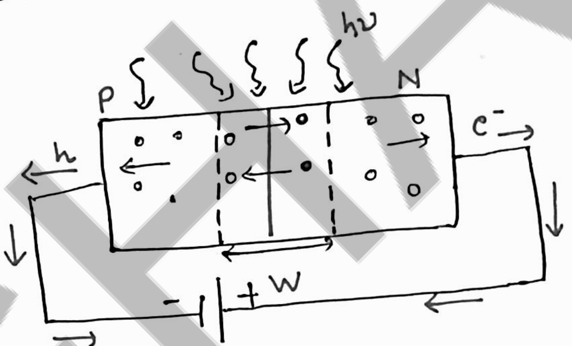
Photo Current in Photo Diode :-

The photocurrent generated in photodiode has three component -

1. Photo generated current in space-charge region.
2. Photo generated current in n-region
3. Photo generated current in p-region



If G is the generation rate of excess carrier and A is diode area then photo current, the excess carrier in depletion region quickly moved by electric field (e⁻ to n-region and holes to p-region)

The photo generated current in the depletion region is

$$I_1 = Ae\int G\,dx = eGWA$$

where, W → depletion width and this current is very fast (prompt photocurrent)

In addition to the carriers generated in the depletion region, e-hole pairs are generated in the neutral n-region and p-region of the diode.

we may expect that hole generated within a distance L_p (the diffusion length) of the depletion region edge will be able to enter the depletion region from where the electric field will sweep them into p-side.

$$I_p = eG_L L_p A$$

Ill^ly, excess electrons produced in p-region will give photo current.

$$I_n = eG_L L_n A$$

So, total current due to carriers in the neutral region and the depletion region is given by

$$\boxed{I_L = eG_L(L_p + L_n + A)A}$$

Light emitting diode (LED) :-

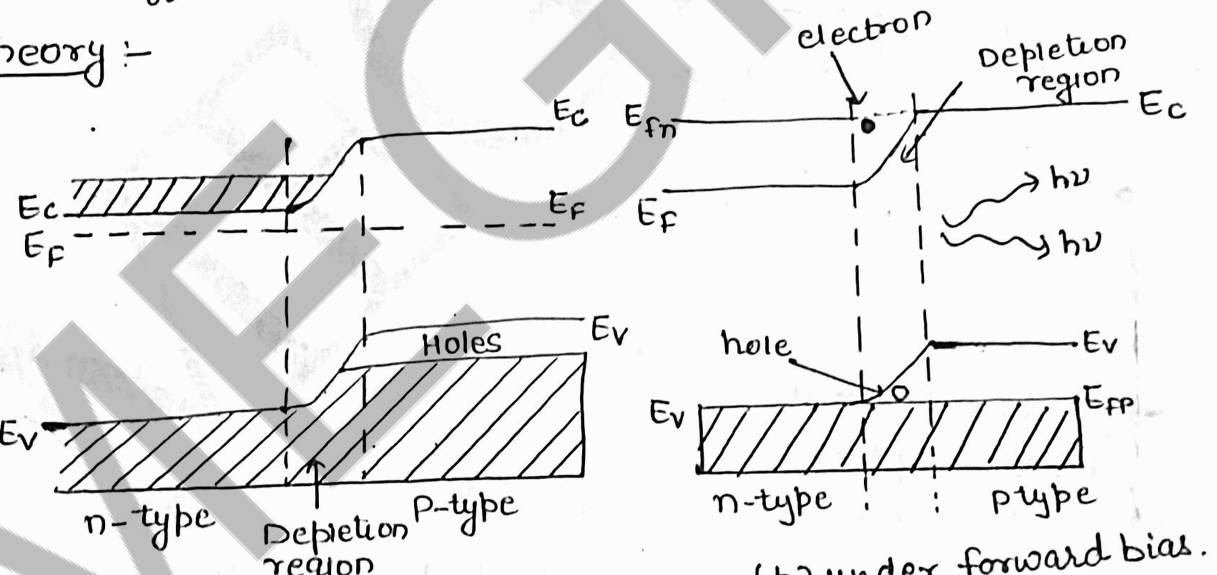
A light emitting diode (LED) is a heavily doped semiconductor diode that gives off light when it is forward biased. LEDs are generally fabricated using III - IV compound S.C., such as GaAs (for IR), GaAsP (for Red or yellow), GaP (Red or green) etc. which have a direct band gap.

principle :- when a p-n junction is forward biased, minority carriers flow in large numbers into regions where they can recombine with majority carriers producing light in the visible or IR region. The wavelength of light is given by

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \mu m$$

This effect is known as Injection electroluminescence.

Theory :-



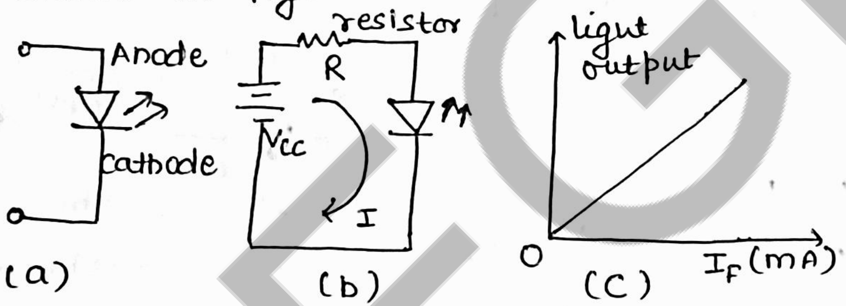
(a) without bias

(b) under forward bias.

The energy band diagram of a heavily doped p-n junction is shown in fig. There is a large concentration of electrons in the C.B. of n-region and a large concentration of holes in the V.B of p-region. When forward bias is applied, the electrons push into the depletion region and occupy energy levels in the

C.B.: Similarly, holes push forward into the depletion region and occupy energy levels in the valence band. The electrons in the C.B are directly above the holes at the edge of the valence band. The situation is highly conductive for direct recombination of electrons and holes. When an electron from the C.B. jumps into the hole in the V.B., recombination occurs and the excess energy is emitted in the form of a light photon.

Working :- LED is always forward biased. The forward voltage across an LED is considerably greater than an ordinary diode. (almost 1.2V - 3.2V). The LED emits light in response to a sufficient forward current. The amount of light emitted is directly proportional to the forward current, as shown in fig.



Applications :-

→ used as indicators and as a light source in fibre-optic communication.

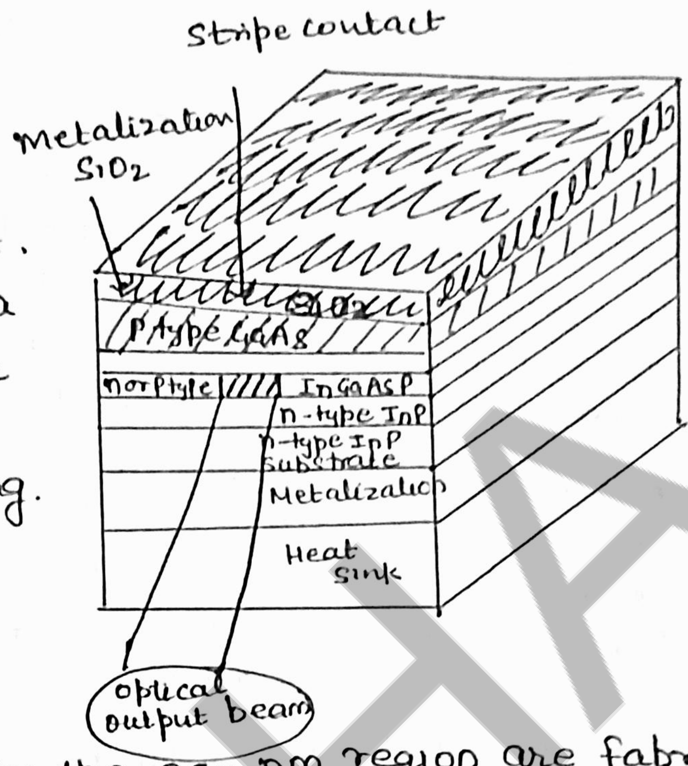
→ LEDs may be grouped to form a display.

→ used to generate a decimal number or alphabetical character.

Classification of LEDS :-

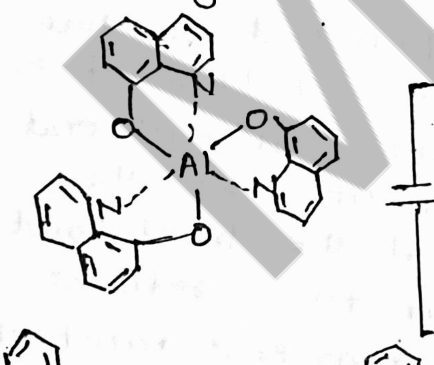
The basic LED type used for fiber optic communication systems are the surface-emitting LED (SLED) and the edge-emitting LED (ELED).

optical feedback and allows light emission. ELEDs emit light only through the front facet. ELEDs emit light in a narrow emission angle allowing for better source to fiber coupling.

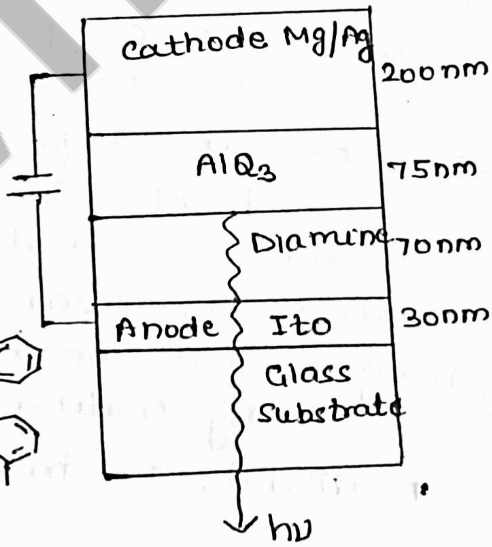


<u>Note</u> :- Typically LEDs for the 850 nm region are fabricated using GaAs and AlGaAs. LEDs for the 1300 nm and 1550 nm regions are fabricated using InGaAsP and InP.

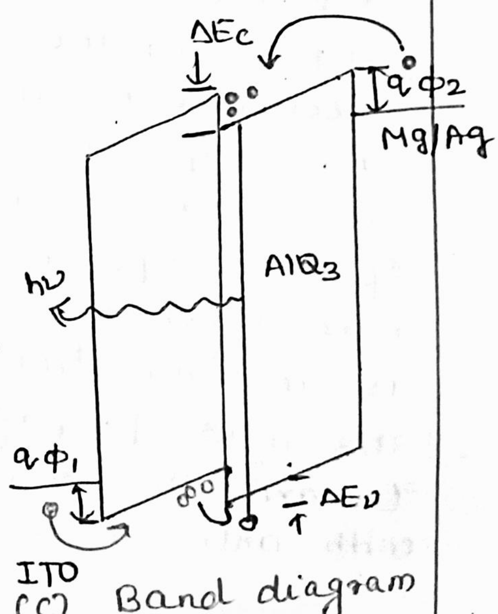
<u>Organic LEDs</u> :- The organic light-emitting diode (OLED) is particularly useful for multicolour, large area flat panel display because of its attributes of low-power consumption and excellent emissive quality with a wide view angle.



(a)



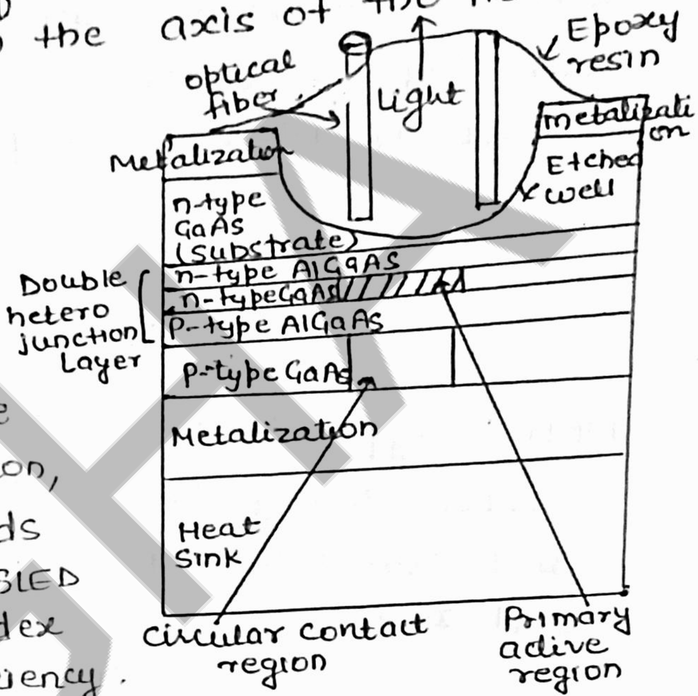
(OLED)
(b)



(c) Band diagram OLED

(a) Surface - Emitting LEDs :- In SLEDs, the size of
the primary active region is limited to a small
circular area of 20 um to 50 um in diameter. The
active region is the portion of the LED where
photons are emitted. The primary active region
is below the surface of the semiconductor subs-
-trate perpendicular to the axis of the fiber.

A well is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface. In addition, the epoxy resin that binds the optical fiber to the SLED reduces the refractive index mismatch, increasing efficiency.



(b) Edge - Emitting LEDs :- fig. shows a typical ELED
structure. It shows the different layers of s.c.
material used in ELED. The primary active region of
the ELED is a narrow stripe, which lies below the
surface of the semiconductor substrate. The semi-
-conductor substrate is cut or polished so that
the stripe runs between the front and back of the
device. The polished or cut surfaces at each end
of the stripe are called facets. In an ELED, the
rear facet is highly reflective and the front facet
is antireflection - coated. The rear facet reflects
the light propagating toward the rear end face back
toward the front facet. By coating the front facet
with antireflection material, the front facet reduces

Fig(a) shows the molecular structures of two representative organic semiconductors. They are the tris (8-hydroxy-quinolinato) aluminium (AlQ_3), which contains six benzene rings connected to a central aluminium atom, and the aromatic diamene, which also contains six benzene rings but with a different molecular arrangement.

A basic OLED has a no. of layers on a transparent substrate (glass). Onto the substrate we deposit, in sequence, a transparent conductive anode [e.g. ITO (indium tin oxide)], the diamine as a hole transport layer, the AlQ_3 as the electron transport layer, and the cathode contact (e.g. Mg alloy with 10% Ag). (fig.b)

Fig.c shows the band diagram of the OLED. It is a basically a heterojunction formed between AlQ_3 and diamene. Under proper biasing conditions, electrons are injected from the cathode and move toward the heterojunction interface whereas holes are injected from the anode and also move toward the interface. Becoz of the energy barriers ΔE_c and ΔE_v, these carriers will accumulate at the interface to enhance the chance of radiative recombination.

For AlQ_3, the emitted light is green. By choosing different organic semiconductors with different band gaps, various colours including red, yellow, and blue can be obtained.