2. Semiconductors and Display devices

Syllabus:

Semiconductors: Hall Effect - Schottky junction - Ohmic contacts – Schottky diode - optical absorption and solar cell – LED construction and working (White LED's – organic LEDs) – Laser diode - LCD construction and working.

2.1 Hall effect

"*When the conductor carrying a current (I) is placed in a perpendicular magnetic field (B), a potential difference is developed inside the conductor in a direction normal to the directions of both the current and magnetic field*". This phenomenon is known as Hall Effect and the corresponding voltage thus generated is called Hall voltage

Explanation

Consider an external field applied along the X-axis of the specimen. Assuming that the material is *n*-type semiconductor, the current flow consists mainly of electrons moving from right to left, corresponding to the conventional current direction. When this specimen is placed in a magnetic field 'B' and if '*v*' is the velocity of the electrons perpendicular to the magnetic field then each one of them will a experience a downward force of magnitude Be*v*

This downward force (Lorentz Force F_L) due to magnetic field causes the electrons to be deflected in the downward direction and hence there is an accumulation of negative charges on the bottom face of the slab. This causes the bottom face of the slab to be more negative with respect to the top face and a potential difference is established from top to bottom of the specimen. This potential difference causes a field E_H called Hall field in negative y direction. There is a force eE_H acting on the electron in the upward direction due to this field.

Theory of Hall Effect

At equilibrium, the downward force Bev will balance the upward force eE_H

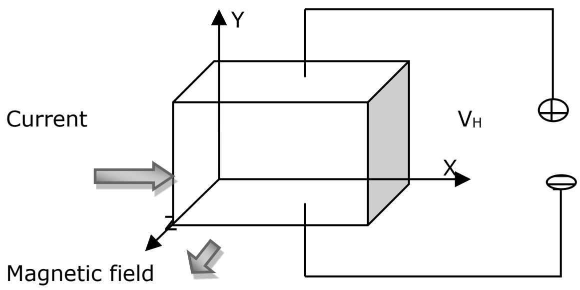
$$Bev = eE_H \qquad (1)$$

In a uniform sample, the electric current density (J) is related to the drift velocity as

$$J = -neV$$

Where n is the concentration of electrons.

$$V = \frac{-J}{ne} \qquad (2)$$



Substituting equation (2) in (1),

$$E_H = \frac{-BJ}{ne}$$

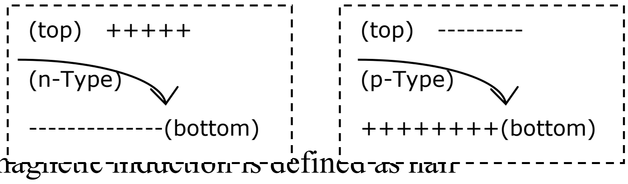
This can be written as $E_H = BJR_H$ (4)

Where R_H = - 1 / ne is called Hall coefficient

The negative sign indicates that the developed field is in the negative y direction.

III^{rly}, the Hall coefficient for p – type semiconductor is R_H = 1 / p e.

Where p is the concentration of holes



Determination of Hall coefficient

The hall field per unit current density per unit magnetic induction is defined as hall coefficient.

If t is the thickness of the sample and V_H is the hall voltage, then $V_H = E_H\, t$ (5)

Where E_H is hall field.

From equation (4), we get $E_H = R_H J_x B$

Substituting the value of (5) in above equation, we get $V_H = R_H\, J_x\, B\, t$ (6)

Now the current density J_x can be written as $J_x = \frac{I_x}{bt}$ (7)

Where 'b ' is the width and bt is the area of cross section of the sample

Substituting equation (7) in equation (6), we get $V_H = \frac{R_H I_X Bt}{bt}$

$$V_H = \frac{R_H I_X B}{b} \quad (8)$$

(or) $$\boxed{R_H = \frac{V_H b}{I_X B}} \quad (9)$$

For an n – type semiconductor $\boxed{R_H = \frac{-V_H b}{I_X B}}$ (10)

Mobility of charge carriers

We know that hall coefficient $R_H = \frac{-1}{ne}$

This expression is correct only when the charge carriers is free from any attractive force in energy band and moves with constant drift velocity. But this is not true in the case of semiconductors.

Considering the average speed, it is shown that $R_H = \frac{-1.18}{ne}$ for electrons and $R_H = \frac{1.18}{pe}$ for holes.

We know that the electrical conductivity and mobility is related by $\sigma = n\, e\, \mu_e$

(or) $\mu_e = \frac{\sigma}{ne}$ & hence $\mu_e = \frac{\sigma_e}{ne}$ and hence $\mu_e = \frac{-R_H \sigma_e}{1.18}$ (11)

Similarly $\mu_h = \frac{-R_H \sigma_h}{1.18}$ (12)

Experimental Determination of Hall Coefficient:

The experimental setup for the measurement of Hall voltage is shown in figure.

A semiconducting material is taken in the form of a rectangular slab of thickness *'t'* and breadth *'b'*. A suitable current I_x ampere is allowed to pass through this sample along the X axis by connecting it to battery

The sample is placed between the poles pieces of an electromagnet such that the applied magnetic field coincides with the z – axis.

Hall voltage (V_H) which is developed in the sample is measured by fixing two probes at the centers of the bottom and top faces of the sample.

By measuring Hall voltage, Hall coefficient is calculated from the formula $R_H = \frac{-V_H b}{I_x B}$

Applications

(i) The sign of the hall coefficient is used to determine whether a give semiconductor is *n* – type or *p* – type

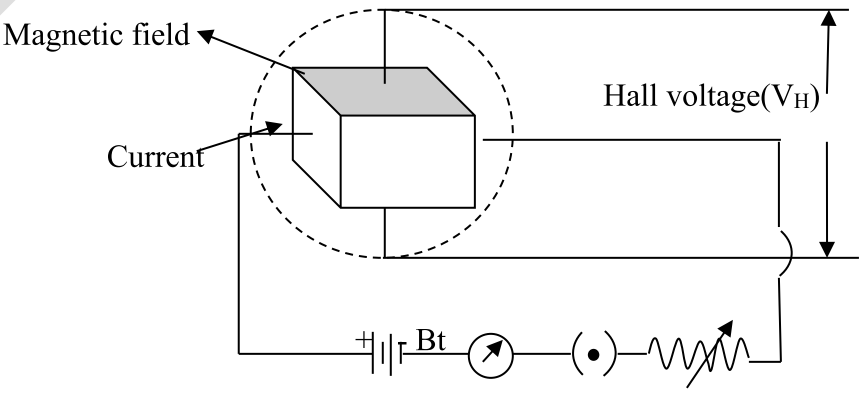
(ii) Once Hall coefficient R_H is measured, the carrier concentration can be determined from

$n = 1/e R_H$

(iii) The mobility of charge carriers can be obtained if conductivity is known. $\mu_e = \sigma_e R_H$

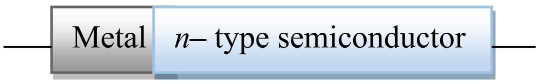
(iv) Hall voltage V_H for a given current is proportional to *B*. Hence measurement of V_H measures the magnetic field *B*.

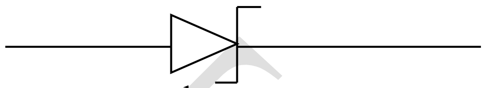
(v) This instrument gives an output proportional to the product of two signals. Thus if current *I* is made proportional to one input and if *B* is made proportional to the other input, then the Hall voltage V_H is proportional to the product of the two inputs.



2.2 Schottky diode

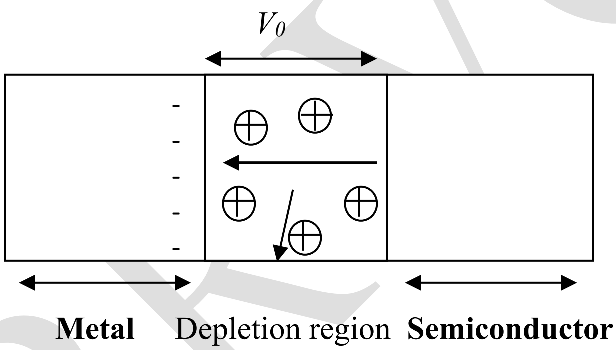
It is the junction formed between a metal and n – type semiconductor. When the metal has a higher work function than that of n – type semiconductor then the junction formed is called Schottky diode. The Fermi level of the semiconductor is higher (since its work function is lower) than the metal. Figure shows Schottky diode and its circuit symbol.



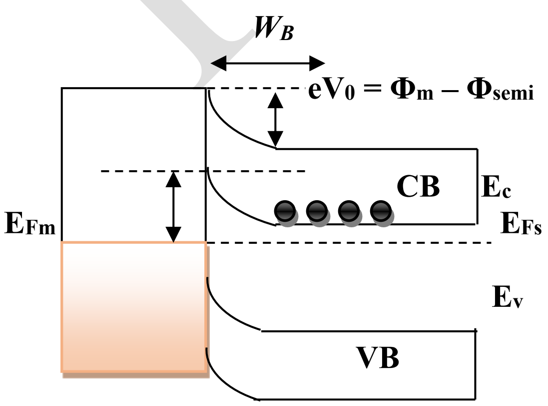


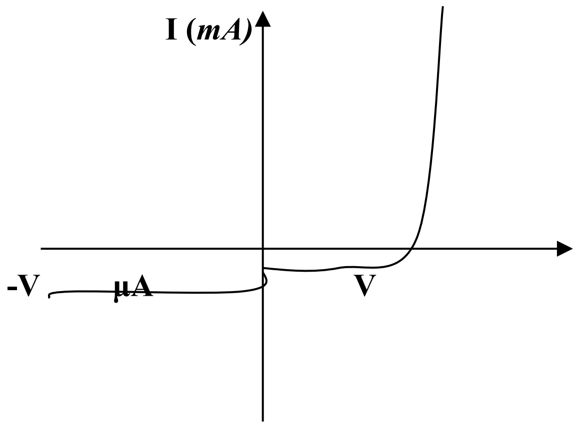
The electrons in the conduction level of the semiconductor move to the empty energy states above the fermi level of the metal. This leaves a positive charge on the semiconductor side and a negative charge (due to the excess electrons) on the metal sie as shown in figure. This leads to a contact potential.

When a Schottky junction is formed between metal and semiconductor, fermi level lines up. Also a positive potential is formed on the semiconductor side. The formation of a depletion region of width W_D within the semiconductor is shown in figure. Because the depletion region extends within a certain depth in the semiconductor, there is bending of the energy bands on the semiconductor side. *Band* bend up in the direction of the electric field produced in depletion region. There is a built in potential V_o in the Schottky junction. From the figure this is given by the difference in work functions $eV_0 = \varphi_m - \varphi_{semi}$



Energy band diagram





Working

The behaviour of Schottky diode is further studied by forward and reverse bias.

(a)Forward Bias

In this bias, metal is connected to positive terminal and $n-type$ semiconductor is connected to negative terminal of the battery. In the forward biased Schottky junction, the external potential opposes the in- built potential. The electrons injected from the external circuit into the $n-type$ semiconductor have a lower barrier to overcome before reaching the metal. This leads to a current in the circuit which increases with increasing external potential.

(b) Reverse Bias

In reverse bias, metal is connected to negative terminal and $n-type$ semiconductor to positive terminal of the battery. In the case of reverse bias, the external potential is applied in the same direction as the junction potential. This increases the width of depletion region further and hence there is no flow of electron from semiconductor to metal. So Schottky junction acts as rectifier. i.e., it conducts in forward bias but not in reverse bias.

$V-I$ Characteristics

The $V-I$ characteristics of the junction is shown in figure. There is an exponential increase in current in the forward bias while there is a very small current in reverse bias.

Advantages

It has very low capacitance
It will immediately switch from ON to OFF state (fast recovery time)
Applying a small voltage is enough to produce large current
It has high efficiency
It operates at high frequencies
It produces less noise.

2.3 Ohmic contact

An ohmic contact is a type of metal semiconductor junction. It is formed by a contact of a metal with a heavily doped semiconductor. When the semiconductor has a higher work function than that of metal, then the junction formed is called the ohmic junction.

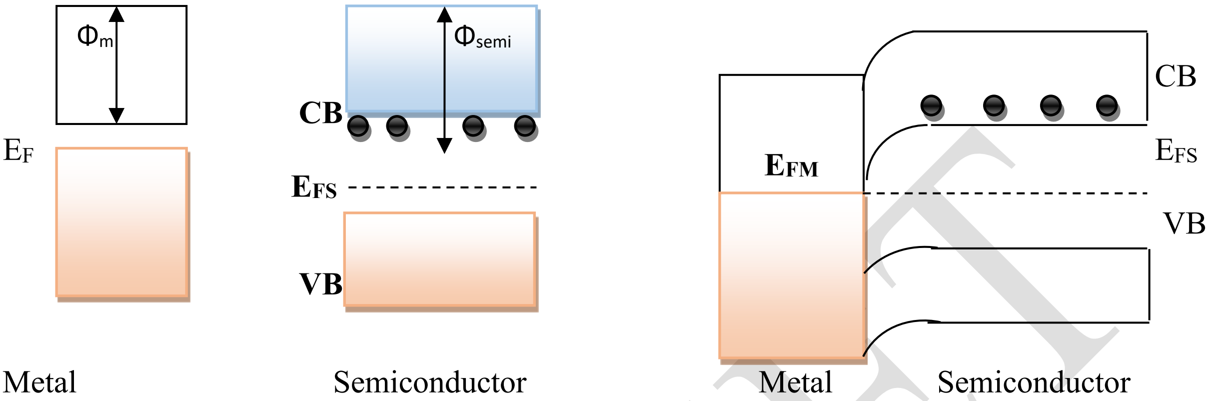
Here, the current is conducted equally in both directions and there is a very little voltage drop across the junction. Before contact, fermi levels of the metal and semiconductor are at different positions as shown in figure.

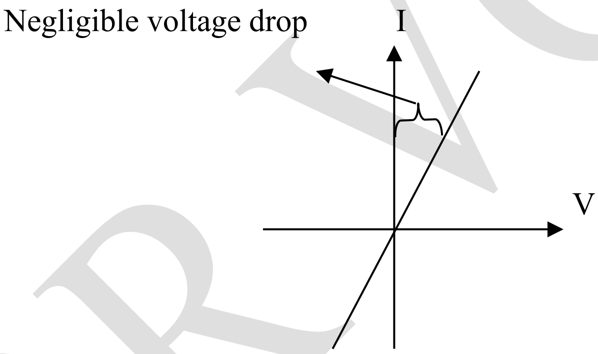
Working

After contact, the ohmic junction is shown in figure. At equilibrium, the electrons move from the metal to the empty states in the conduction band of semiconductor. Thus, there is an accumulation region near the interface (on the semiconductor side). The accumulation region has higher conductivity than the bulk semiconductor due to this higher concentration of electrons. Thus, a ohmic contact behaves as a resistor conducting in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor.

V – I Characteristics

The *V-I* characteristics of the ohmic contact is shown in figure. The current is directly proportional to the potential across the junction and it is symmetric about the origin, as shown in figure. Thus, ohmic contacts are non-rectifying and show negligible voltage drop and resistance irrespective of the direction and magnitude of current.





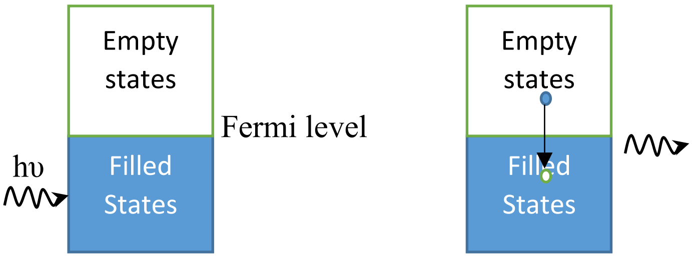
Applications

The use of ohmic contacts is to connect one semiconductor device to another, an IC, or to connect an IC to its external terminals.

2.4. Absorption and Emission of Light in Metals

Metals

Metals are **opaque** because of the incident light radiation excites electrons into unoccupied energy states above the Fermi energy. As a result the incident radiation is absorbed. Total light absorption is within a very thin outer layer usually less than 0.1 μm. Hence metallic films thinner than 0.1 μm are capable of transmitting visible light. Moreover metals are **opaque** at lower frequencies (radio frequency to mid of ultraviolet radiation) and **transparent** to high frequency X – rays and γ rays. Most of the absorbed radiation is reemitted from the surface in the form of visible light of same wavelength which appears as **reflected light**. The reflectivity in the most of the materials will be between 0.9 and 0.95. The colour of a metal is determined by the wavelength distribution of the reflected radiation.



Absorption and emission of light in Insulators

Absorption of a light photon may occur in an insulator. It results in excitation of an electron from valence band to conduction band after crossing the energy gap E_g. A free electron in the conduction band and a hole in the valence band are created. The excitation of an electron due to absorption of light can take place only if the light photon energy ($\Delta E = h\upsilon$) is greater than that of band gap E_g.

i.e., $\Delta E = h\upsilon$.

Here, light photon absorption takes place only when $h\upsilon > E_g$

(or) $hc/\lambda = E_g$.

Thus, for a visible light the wavelength is typically of about 0.4µm, then the band gap energy for the light is about 3.1 eV. Thus no visible light is absorbed by materials having band gap energies greater than about 3.1 eV. These materials appears transparent and colourless if they are high purity state.

2.5. Absorption and emission of light in Semiconductors

In semiconductors, light photons is absorbed in several ways. In intrinsic semiconductors light photons is absorbed to create electron - hole pairs. This absorption causes electrons to jump across the energy band gap from the valence band to the conduction band. Hence the excitation of electrons due to absorption can takes place if the photon energy is greater than that of the band gap E_g, The maximum wavelength for visible light λ_{max} is about $0.7\mu m$. Therefore the minimum bandgap energy $E_{g\,(min)}$ for which there is absorption of visible light is given by $E_{g\,(min)} = hc / \lambda_{max}$

Here, $E_{g\,(min)}$ is found to be 1.8 eV. Hence all visible light is absorbed by those semiconductors having band gap energies less than about 1.8eV, thus these semiconductors are **opaque**.

In extrinsic semiconductors, the presence of acceptor and donor impurities creates new energy levels namely acceptor level (p - type) and donor level (n - type). These impurity level lie within the bandgap of the material. Light radiation of specific wavelength may be absorbed as a result of electron transitions from or to these impurity levels within the band gap.

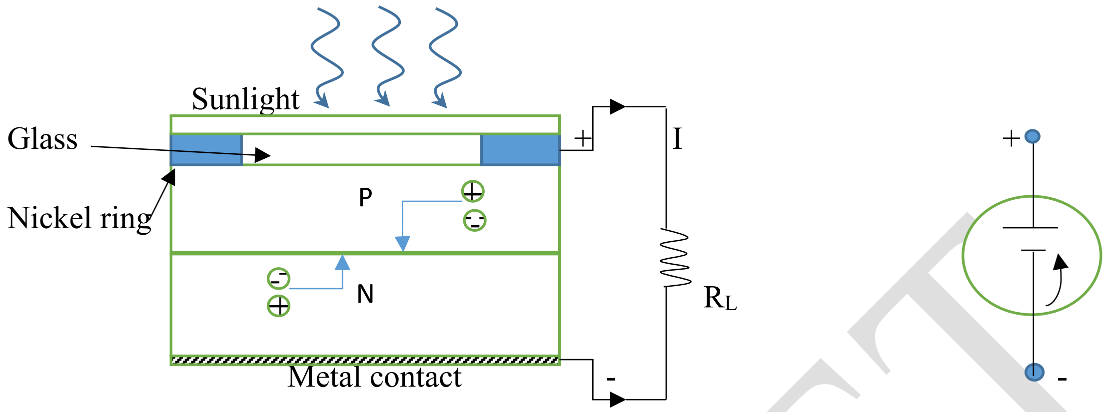
2.6 Solar cell

It is a p - n junction diode which converts solar energy (light energy) in to electrical energy.

Construction

It consists of p - n *junction* diode made of silicon. The p - n diode is packed with glass window on top such that light may fall up on p and n type materials. The symbol of the solar cell is shown in figure.

The thickness of *p* and *n* regions are kept very small. As a result electrons or holes generate near the surface of *p* or *n* region can diffuse to the junction before they recombine. A nickel ring is provided at the top of the *p* layer which acts as the positive output terminal. A metal contact at the bottom serves as the negative output terminal.



Working

When light radiation from sun falls on the *p - n* junction diode, the photon energy is sufficient to break the covalent bond and produce electron hole pair. These electrons and holes reach the depletion region by diffusion and they are separated by the strong barrier electrical field existing there.

The minority carrier electrons in the *p* - side cross the barrier potential to reach *n* side and the holes in *n* - side move to the *p* - side. Their flow constitutes the minority current which is directly proportional to the illumination of light and the surface area being exposed to light.

The electrons and holes accumulated on either sides of junction leads to open circuit voltage V_{oc} as a function of illumination. In case of silicon solar cell, V_{oc} is typically 0.6*V* and the short circuit current is about 40 mA/cm^2 in bright noon day sun light. The *I - V* characteristics of solar cell shows maximum power output when the solar cell is opened at the knee of the curve

Advantage:

(1) It operates with fair efficiency
(2) It can be mass produced
(3) It has high power capacity per weight
(4) Its size is small and compact.

Disadvantage

(1) Solar energy is not available during winter season and night time
(2) We need an additional equipment like inverter to store the electrical energy
(3) The output which is in DC is converted to AC

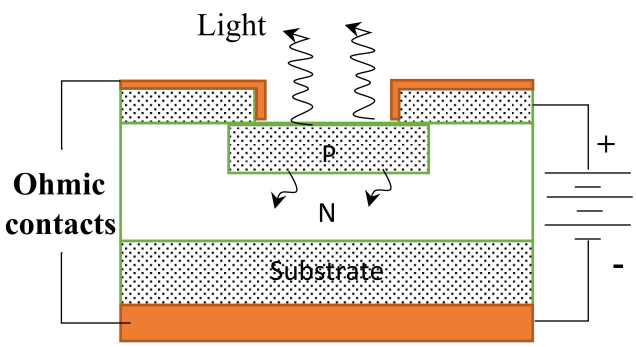
Uses

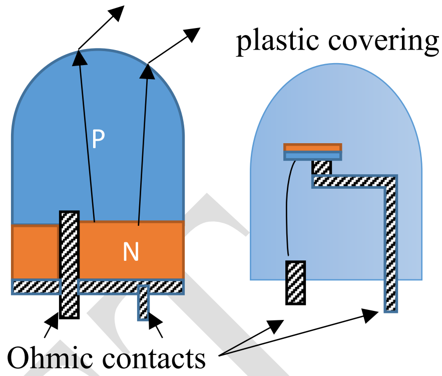
(1) It is used in satellites and space vehicles to supply power to electronic and other equipment's
(2) It is used to give power to the calculators and watches
(3) They are used to provide commercial electricity.

2.7. Light Emitting Diode (LED)

Principle

Injection luminescence is the principle used in LED. When *p* - *n* junction (LED) is forward biased, the majority carriers moves from *p* to *n* region and vice versa. These excess minority carriers diffuse through the junction and recombine with majority charge carriers respectively to produce (light) photons.





Fabrication

Here *n* - type layer is grown on a substrate and *p* - type layer is deposited above it by diffusion. *p* type is grown as a top layer because of the recombination process takes in this region. For maximum light emission, a metal film anode is deposited at the outer edges of the *p* - type layer and the bottom of the substrate is coated with gold film (metal).This metal surface reflects the light and also act as cathode.

Working

(1) When a *p* - *n* junction is forward biased, the barrier width is reduced, raising the potential energy on the *n* side and lowering that of the *p* - side
(2) The free electron and hole have sufficient energy to move to the junction region.
(3) If a free electron recombine with a hole it will release a photon (light)
(4) This photons created in LED are due to electron and hole recombination that are injected into the junction by a forward biasing voltage.

Advantages

(1) Smaller in size
(2) Cost is very low
(3) Long life time
(4) Available in different colour at low cost
(5) Operates at very low voltage
(6) Fast response time (10^{-9} seconds)
(7) Operated at wide range of temperatures (0 ~ 70°C)
(8) Dome shaped LED has less scattering loss

Disadvantages

(1) Power output is low
(2) Intensity is less than laser
(3) Light cannot travel through long distance
(4) Light output in incoherent and not in phase

Dump shaped LED

In planar LED, the reflection loss is more because of the emitted light strikes at the materials surface at an angle greater than critical angle and suffers total internal reflection. Hence it will not come out of the interface and the light is lost. Hence by making *p* type in hemispherical shape or by covering the *p* - *n* junction diode by a hemispherical plastic medium of higher refractive index, the reflection loss is eliminated.

2.8. Organic Light Emitted Diode (OLED)

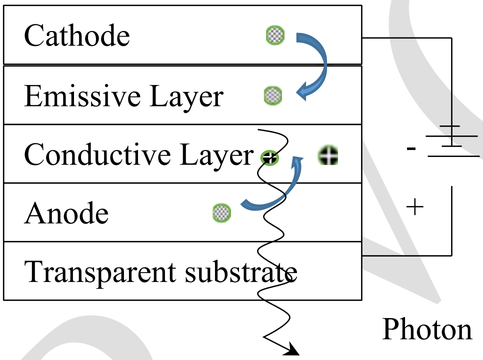
Principle

An electron moves from the cathode to the emissive layer and hole moves from the anode to the conductive layer and they recombine to produce photons.

Fabrication

The 2 - layer OLED consists of two organic layers in between a cathode and an anode.

The two organic layers are (i) emissive layer (ii) conductive layer, made up of different conductivities. All the layers are grown over a transparent substrate, through which the light has to be emitted. Necessary biasing is given or OLE in such a way that the anode is given positive and the cathode is given negative as shown in figure.



Working

(1) Voltage is applied across the OLED
(2) Due to the applied voltage, the cathode gives electrons to the emissive layer
(3) The anode withdraws the electron from the conductive layer and creates a hole in the conductive layer as sown in figure.
(4) That is the anode gives (electron – hole) **polarons** a quasi-particle - a positive (or) negative ion slightly attracted to a negatively (or) positively charge carriers respectively.
(5) Soon, the emissive layer has large number of negatively charged particles and the conductive layer has large number of positively charges particles.
(6) Due to electrostatic forces between these electrons and holes, they come closer and recombine with eachother.
(7)In OLED, the recombination occurs closer to the emissive layer, because in organic semiconductors, holes moves faster than electrons.
(8)This, the recombination of electrons and holes produces photons and is emitted through the transparent substrate as shown in figure.

Advantages

(i) It is very thin and more flexible
(ii) They are light in weight
(iii) Light emission is brighter than normal LED's
(iv) The conductive and emissive layers can be increased to increase the efficiency of OLED
(v) OLED does not require backlighting like LCD
(vi) They have large field of view (about 170°C)

Disadvantages

(1) Manufacturing cost is high
(2) It get damaged easily when water falls on it
(3) Blue OLED has less life time than Red OLED

Applications

(1) It is widely used in cell phones, digital cameras, etc.,
(2) It is used in TV screens, computer monitors
(3) Use in automotive dash boards, backlights in cars

Types

(1) Polymer Light Emitting diode (PLED)
(2) Patternable Organic Light Emitting Diode (POLED)
(3) Transparent Organic Light Emitting Diode (TOLED)
(4) Stacked Organic Light Emitting Diode (SOLED)
(5) Inverted Organic Light Emitting Diode (IOLED)

2.9. LASER DIODE

Principle

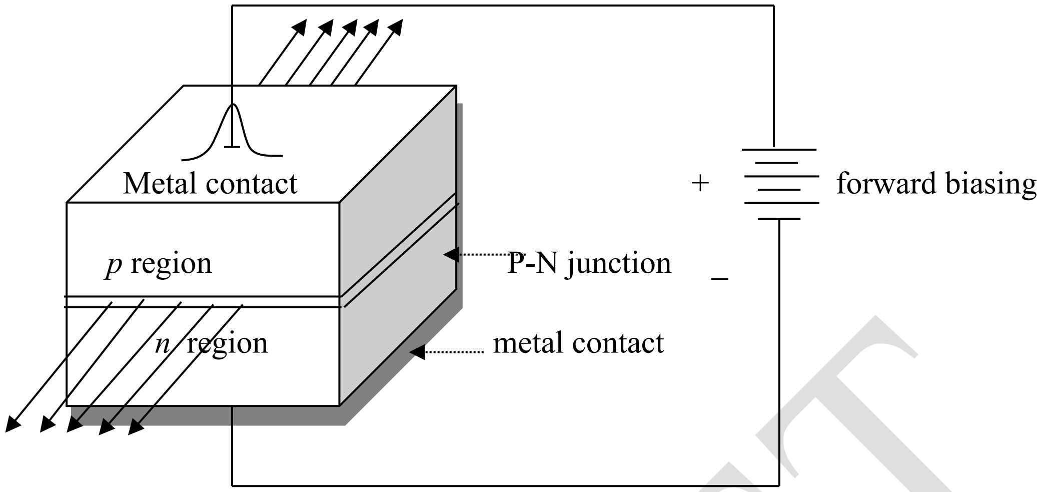
When a p - n junction diode is forward biased the electrons from n - region and the holes from p - region cross the junction and recombine with each other. During the recombination process the photons (light radiation) is released from direct band gap semiconductor (Eg: GaAs) which stimulates other electrons and holes to recombine and hence the stimulated emission takes place which produces the laser

Construction

The basic construction of a semiconductor homojunction diode is shown in the figure

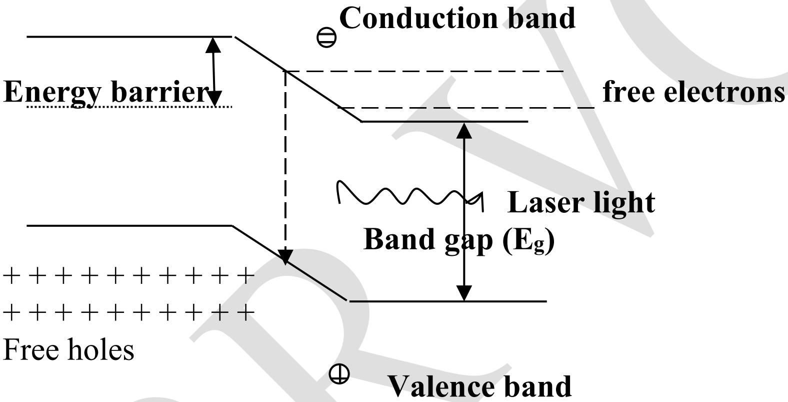
Laser output

The active medium is a *p* - *n* junction diode made from a single crystal of GaAs. This crystal is cut in the form a platelet of thickness 0.5mm.this platelet has an electrical (*n*-type) and hole conductivities (*p*-type) The photon emission is stimulated by a thin layer of PN junction. The potential difference is applied to the homojunction diode through the metal contact .the end faces of the junction are polished and made parallel to each other. They act as optical resonator (the diode has high refractive index) where the laser comes out.



Working

Figure shows the energy level diagram. When the diode is forward biased using the applied potential difference, the electron and holes are injected in to the junction where the concentration of holes in *p* – region and electrons in *n* - region strengthens. After the population inversion condition is achieved, the electrons and holes are recombined to produce a radiation in the form of light



When the forward biased voltage is increases, the emitted photon multiplies and triggers these recombining photons in phase. These photons moving at the plane of junction travels back and forth by reflection between two sides of the junction and grows in strength. After gaining enough strength it emits a laser beam of wavelength 8400A°. The wavelength of emitted radiation depends on (i) band gap & (ii) the concentration of donor & acceptor atoms. The wavelength of laser light is given by $E_g = h\upsilon$ (or) $\lambda = \frac{hc}{E_g}$ where E_g – band gap energy & $\upsilon = c / \lambda$

Characteristics

01.	Type	Solid state homojunction semiconductor laser
02.	Active Medium	PN junction GaAs diode
03.	Pumping Method	Direct conversion method
04.	Power output	1mW
05.	Nature of Output	Continuous (or) Pulsed
06.	Wavelength	8400 A°

Advantages

(i) It is small in dimension and compact
(ii) It exhibits high efficiency
(iii) The laser output can be increased easily by controlling junction current
(iv) It requires little auxiliary equipment

Disadvantages

(i) It is difficult to control mode pattern and structure of laser
(ii) Output beam has large divergence
(iii) Monochromacity is poorer than other type of laser
(iv) Threshold current density is large

Applications

(i) It is used in optical communication
(ii) It is used to heal the wounds by infrared radiation
(iii) It is used in CD writing and reading

2.10. Liquid Crystal Display

The action of the LCD of the field effect (twisted nematic) type is described below. In the twisted nematic configuration, the nematic phase is sandwiched between buffed glass plates that have transparent electrodes evaporated onto the buffed sides. The two plates are oriented with their buffing directions perpendicular to each other. As a consequence, the orientation of the molecules in nematic liquid crystal changes by 90° between the two plates (Fig. 1). The direction of the polarization of the light incident on the glass plate changes by 90°, because of the change in orientation of the molecules sandwiched between the two plates. Consequently, when placed between crossed polaroids the light passes through. It gets reflected by a mirror and retraces its path. Thus, the configuration looks bright when exposed to light. On applying an electric field between the plates, the molecules orient parallel to the field.
Now the incoming light from the polariser cannot pass through the analyzer and hence the configuration looks dark when exposed to bright light. Hence the device can be used to display characters. The display consists of two glass plates with a special liquid crystal (nematic fluid) in between [Fig. 2]. The bottom surface of the top plate has invisible semi-silvered shapes, where the segments or symbols are to be seen. The back glass plate is also metallized. A polariser (polaroid sheet) is kept over the top glass plate. Electrical contacts are made to the metallized back plate and each segment of the display in the top plate.
When an electric field is applied across a segment and the back plate, the liquid crystal under that segment has its molecules oriented in a particular direction. The effect is that the liquid crystal and the polariser at the top are brought in 'crossed' position and there is extinction of light in that segment, when the field is present. Other segments, under no field, remain invisible.

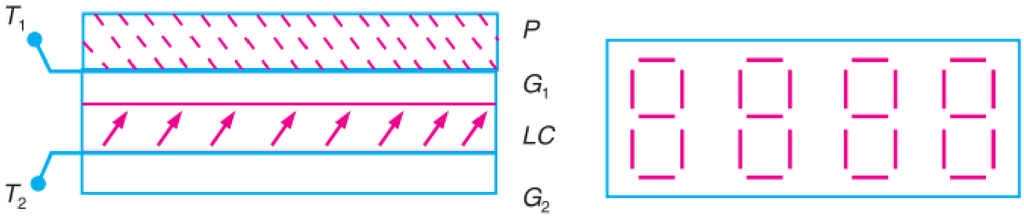


Figure 2

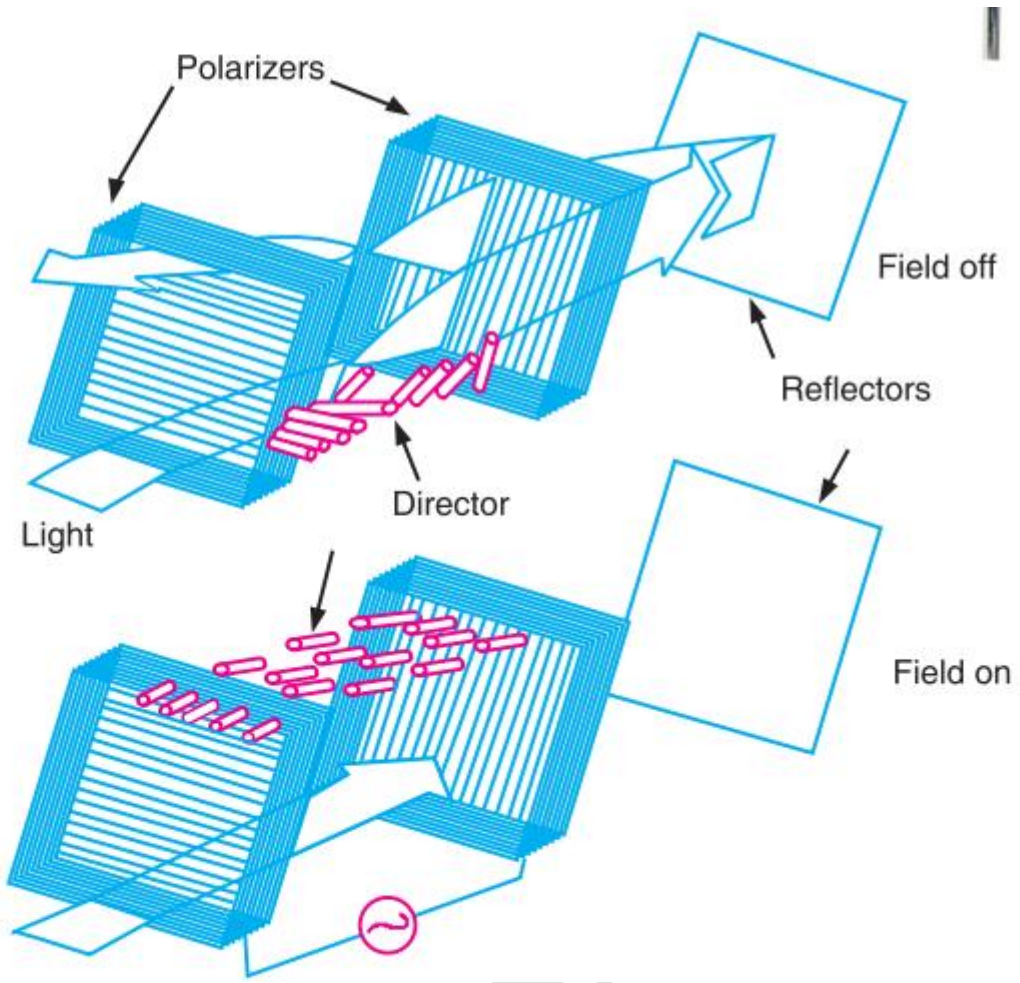


Figure 1