

Introduction

A semiconductor is a material that has a resistivity lies between that of a conductor and an insulator. The conductivity of a semiconductor material can be varied under an external electrical field. Devices made from semiconductor materials are the foundation of modern electronics, including computer, radio, telephones and many other devices.

In a metallic conductor, current is carried by the flow of electrons. In semiconductors, current can be carried by either flow of electrons or flow of holes or both. Germanium and Silicon are the best examples for semiconductor materials. Both are tetravalent (i.e. four valence electrons) and both have diamond crystal structure. At $T=0K$, the semiconductor acts as insulator.

Semiconductors are classified into two types, they are

1. Intrinsic semiconductor
2. Extrinsic semiconductor

1. Intrinsic semiconductor

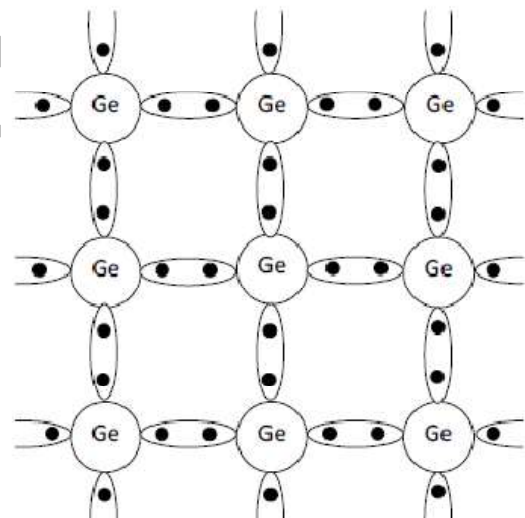
A pure semiconductor is called intrinsic semiconductor. A pure crystal of Germanium and Silicon is an example for intrinsic semiconductor. At $T=0K$, the semiconductor acts as insulator.

Germanium and silicon are tetravalent atoms (i.e. four valence electrons) and both have diamond crystal structure. In order to gain stability each germanium atom makes four covalent bonds with the four surrounding germanium atoms by sharing of their valence electrons as shown in figure.

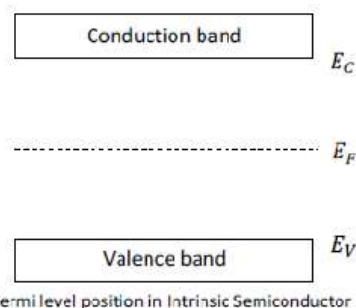
At $0K$, the semiconductor crystal acts as a perfect insulator since the covalent bonds are strong and no free electrons are available. At room temperature ($T>0K$) the semiconductor gives some conductivity since some of the covalent bonds are broken due to the thermal energy supplied to the crystals. The vacancy of an electron in the covalent is called hole. Thus the valence band has holes and conduction band has electrons

For silicon energy gap is $1.12eV$ and for germanium energy gap is $0.7eV$. In intrinsic semiconductor the electron concentration is equal to the hole concentration. In intrinsic semiconductors Fermi level is always lies between valence band and conduction band.

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



Intrinsic semiconductor



The law of mass action for intrinsic semiconductors is $np = n_i^2$

In intrinsic semiconductor the carrier concentration of electrons (n) and holes (p) is

$$n = N_c e^{\frac{-(E_c - E_F)}{KT}}$$

$$p = N_v e^{\frac{-(E_F - E_v)}{KT}}$$

2. Intrinsic carrier concentration

In intrinsic semiconductor

$$n = p$$

Hence $n = p = n_i$ is called intrinsic carrier concentration.

$$n_i^2 = N_c e^{\frac{-(E_c - E_F)}{KT}} \cdot N_v e^{\frac{-(E_F - E_v)}{KT}}$$

$$n_i^2 = N_c N_v e^{\frac{-(E_c - E_F)}{KT}} \cdot e^{\frac{-(E_F - E_v)}{KT}}$$

$$n_i^2 = N_c N_v e^{\frac{-(E_c - E_v)}{KT}}$$

Where $E_c - E_v = E_g$ is the forbidden gap.

$$n_i^2 = N_c N_v e^{\frac{-E_g}{KT}}$$

$$n_i = (N_c N_v)^{1/2} e^{\frac{-E_g}{2KT}}$$

The above equation shows the intrinsic carrier concentration.

3. Fermi level in intrinsic semiconductor

In intrinsic semiconductor $n = p$

$$N_c e^{\frac{-(E_c - E_F)}{KT}} = N_v e^{\frac{-(E_F - E_v)}{KT}}$$

$$\frac{N_v}{N_c} = \frac{e^{\frac{-(E_c - E_F)}{KT}}}{e^{\frac{-(E_F - E_v)}{KT}}}$$

$$\frac{N_v}{N_c} = e^{\frac{(2E_F - (E_c + E_v))}{kT}}$$

Taking logarithms on both sides

$$\log\left(\frac{N_v}{N_c}\right) = \frac{2E_F - (E_c + E_v)}{kT} \quad \because \log_e e^x = x$$

$$KT \log\left(\frac{N_v}{N_c}\right) = 2E_F - (E_c + E_v)$$

$$2E_F = (E_c + E_v) + KT \log\left(\frac{N_v}{N_c}\right)$$

$$E_F = \frac{KT}{2} \log \left(\frac{N_c}{N_v} \right) + \frac{(E_v + E_c)}{2}$$

If we assume that $N_c = N_v$

$$E_F = \frac{E_c + E_v}{2}$$

Thus the Fermi level in intrinsic semiconductor is always lies between the valence band and conduction band.

4. Intrinsic conductivity

In semiconductor, the electrons and holes will participate in electrical conductivity. To obtain an expression for electrical conductivity, we consider a rectangular bar of intrinsic semiconductor connected to a battery is shown in figure. When an electric field is applied along X-axis, the electrons move along negative X-axis and holes move along X-axis. Due to field, the charge carriers attain some constant velocity. This constant velocity is called drift velocity, represented by v_d .

$$v_d = \mu E \quad (1)$$

Let n be the concentration of electrons in semiconductor. Then the current density due to an electron is

$$J_e = nev_d \quad (2)$$

From equations (1) and (2) we get

$$J_e = ne \mu_e E$$

Similarly the, current density of hole is

$$J_h = pe \mu_h E \quad (3)$$

The total electric current density passing through the semiconductor is the sum of electron current density J_e and hole current density J_h .

$$J_{total} = J_e + J_h$$

$$J_{total} = ne \mu_e E + pe \mu_h E$$

$$J_{total} = e(n \mu_e + p \mu_h) E \quad (4)$$

From ohm's law

$$J = \sigma E \quad (5)$$

From equation (4) and (5)

$$\sigma_i = e(n \mu_e + p \mu_h) \quad (5)$$

Equation (5) represents the total electrical conductivity in semiconductor

In intrinsic semiconductor $n = p = n_i$

$$\sigma_i = e n_i (\mu_e + \mu_h) \quad (7)$$

Intrinsic carrier concentration

$$n_i = (N_c N_v)^{1/2} e^{\frac{-E_g}{2KT}} \quad (8)$$

Substituting equation (8) in equation (7) we get

$$\sigma_i = e (\mu_e + \mu_h) (N_c N_v)^{1/2} e^{\frac{-E_g}{2KT}}$$

$$\sigma_i = A e^{\frac{-E_g}{2KT}}$$

Where $A = e (\mu_e + \mu_h) (N_c N_v)^{1/2}$

5. Energy gap of a semiconductor

The energy gap between valence band and conduction band is called energy band gap or forbidden band gap.

In intrinsic semiconductor the resistivity of a semiconductor can be written as

$$\rho_i = \frac{1}{\sigma} = \frac{1}{B \cdot e^{\left(\frac{-E_g}{2KT}\right)}}$$

$$\rho_i = A e^{\left(\frac{E_g}{2KT}\right)}$$

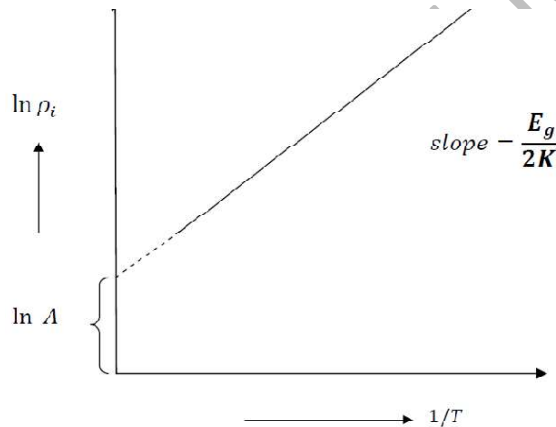
Taking ln on both side

$$\ln \rho_i = \ln \left(\frac{E_g}{2KT} \right) + \ln A$$

The energy gap of a semiconductor can be calculated by measuring slope of the graph $\ln \rho_i$ Vs $\frac{1}{T}$.

$$\frac{E_g}{2KT} = \frac{dy}{dx}$$

$$E_g = 2KT \frac{dy}{dx}$$



Graph between $\ln \rho_i$ versus $1/T$

6. Extrinsic semiconductor

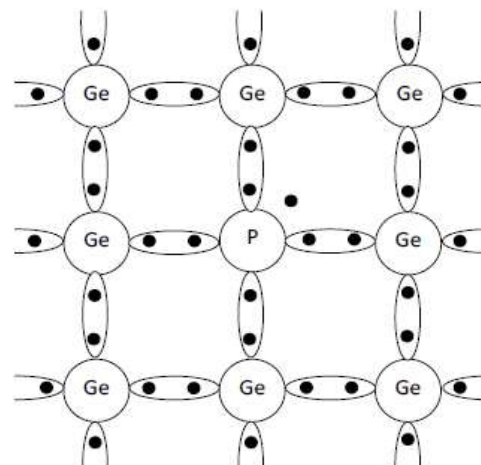
An impure semiconductor is called as extrinsic semiconductor. Depending upon on the type of impurity added to the intrinsic semiconductor, these are two types.

n- type extrinsic semiconductor

p- type extrinsic semiconductor

n- type extrinsic semiconductor:-

Intrinsic semiconductor is doped with v group elements such as phosphorus (P), arsenic (As), and antimony (Sb), n – type semiconductor is formed. V group elements contain five valence electrons. When v group element is added to pure semiconductor, four valence electrons of impurity atoms makes four covalent bonds with the four surrounded intrinsic atoms and fifth electron is loosely bounded with the parent atom. When it received a small amount of energy, the fifth valence electron is excited into conduction band form acceptor level. As a result the donor levels get ionized.

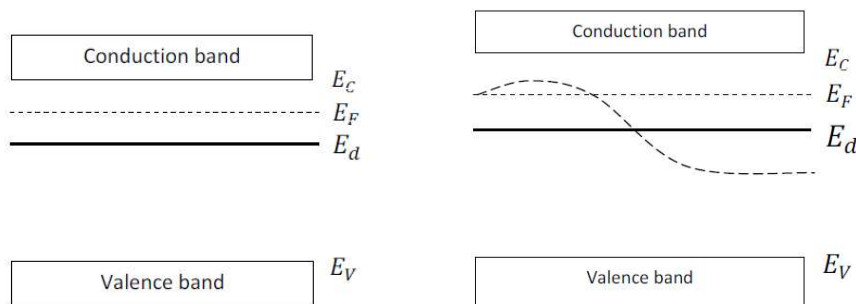


n- Type extrinsic semiconductor

These free electrons are responsible for electrical conduction. At higher temperature the electron hole pairs are created by breaking the covalent bond i.e. electron excited into the conduction band leaving the holes in the valence band. As a result, the concentrations of electrons are greater than holes. Hence electrons are the majority charge carriers and holes are minority charge carriers. The v group impurity atoms are also called donor impurity atoms.

In n-type semiconductors, the Fermi level always lies between conduction level and donor level at lower temperatures but at higher temperatures the Fermi level moves towards the intrinsic Fermi level.

$$E_F = \frac{(E_d + E_c)}{2} - KT \log\left(\frac{N_c}{N_d}\right)$$

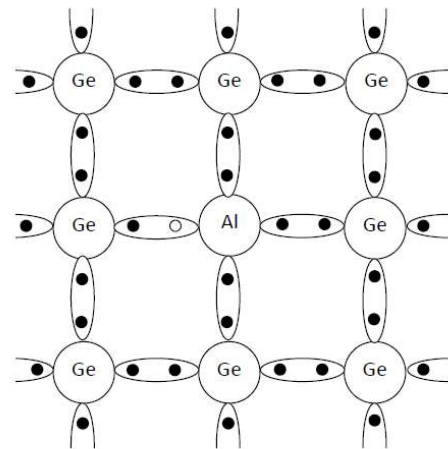


Fermi level position in n-Type Extrinsic Semiconductor

Variation of Fermi level with temperature in n-Type Semiconductor

p- Type extrinsic semiconductor:-

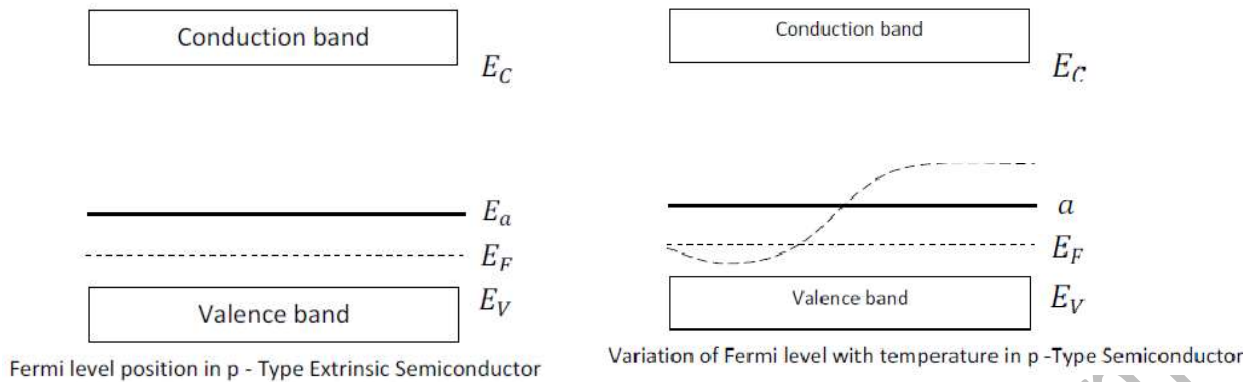
Intrinsic semiconductor is doped with III group elements such as Aluminium (Al), gallium (Ga), indium (In) p – type semiconductor is formed. III group elements contain three valence electrons. When III group element is added to pure semiconductor, three valence electrons of impurity atoms makes three covalent bonds with the three surrounded intrinsic atoms and one bond is left over with the deficiency of one electron. When the temperature is raised ($>0K$) the electrons from the valence band try to occupy the acceptor and it gets ionized creating the hole in the valence band. These holes are responsible for electrical conduction. At higher temperature the electron hole pairs are created by breaking the covalent bond i.e. electron excited into the conduction band leaving the holes in the valence band. As a result, the concentrations of holes are greater than electrons. Hence holes are the majority charge carriers and electrons are minority charge carriers. The III group impurity atoms are also called acceptor impurity atoms.



p- Type extrinsic semiconductor

In p-type semiconductor, the Fermi level is always lies between valence level and acceptor level at lower temperatures but at higher temperatures the Fermi level moves towards the intrinsic Fermi level.

$$E_F = \frac{(E_v + E_a)}{2} + KT \log\left(\frac{N_v}{N_a}\right)$$



7. Law of mass action

According to law of mass action “the product of majority and minority charge carrier concentration at a particular temperature is equal to the square of intrinsic carrier concentration at that particular temperature.”

$$n_p p_p = n_i^2$$

In intrinsic semiconductor, expressions for the electron and hole concentrations are

$$n = N_C e^{-(E_C - E_F)/KT}$$

$$p = N_V e^{-(E_F - E_V)/KT}$$

In intrinsic semiconductor electron concentration is equal to the hole concentration.

$$n = p = n_i$$

$$np = n_i^2$$

$$n_i^2 = N_C e^{-(E_C - E_F)/KT} N_V e^{-(E_F - E_V)/KT}$$

$$n_i^2 = N_C N_V e^{-(E_C - E_V)/KT}$$

For n-type semiconductor, the law of mass relation can be written as

$$n_n p_n = n_i^2 \quad (1)$$

For p-type semiconductor, the law of mass relation can be written as

$$n_p p_p = n_i^2 \quad (2)$$

From equations (1) and (2) we observe that, the product of majority and minority charge carrier concentration at a particular temperature is equal to the square of intrinsic carrier concentration at that particular temperature.

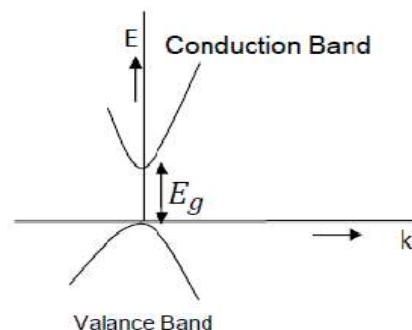
8. Direct and indirect band gap semiconductors

Direct band gap semiconductor

In direct gap semiconductors the band diagram between energy and wave vector (E-K curve) is shown in figure.

In direct band gap semiconductors the maximum of the valence band and minimum of the conduction band present at the same of k as shown in figure.

In direct band gap semiconductors, when an electron recombines with the hole, emits their energy in terms of light.



Direct band gap semiconductor

Life time (recombination time) of charge carriers is very less.

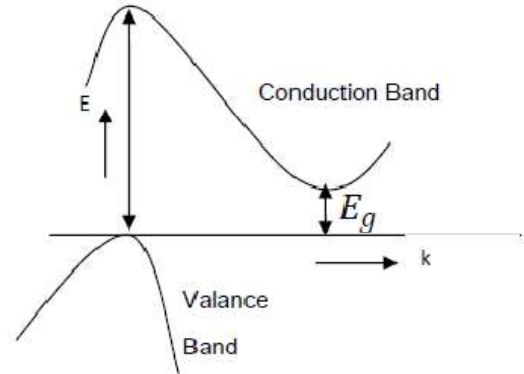
Compound semiconductors like GaAs and InP are examples for direct band gap semiconductors.

Band gap of InP =1.35eV and, GaAs=1.4eV. Direct band gap semiconductor is used to fabricate LEDs and laser diodes.

Indirect band gap semiconductor

In in-direct gap semiconductors the band diagram between energy and wave vector (E-K curve) is shown in figure.

In indirect band gap semiconductors, the maximum of the valance band and minimum of the conduction band present at the different values of k as shown in figure.



Indirect band gap semiconductor

In Indirect band gap semiconductors, when an electron recombines with the hole, emits their energy in terms of heat.

So indirect band gap semiconductors are not used in the preparation of semiconductor laser.

Life time (recombination time) of charge carriers is more.

Elemental semiconductors like germanium and silicon are examples for in-direct gap semiconductors.

Band gap of Ge=0.7eV and Si =1.12eV. . Indirect band gap semiconductor is used to fabricate diodes and transistors.

9. Differences between direct and indirect band gap semiconductor

Direct band gap semiconductors	Indirect gap semiconductors
<p>1. In direct gap semiconductors the band diagram between energy and wave vector is shown in figure</p> <p><u>Direct band gap semiconductor</u></p>	<p>1. In in-direct gap semiconductors the band diagram between energy and wave vector is shown in figure</p> <p><u>Indirect band gap semiconductor</u></p>
<p>2. In direct band gap semiconductors the maximum of the valance band and minimum of the conduction band present at the same of k</p>	<p>2. In in-direct band gap semiconductors the maximum of the valance band and minimum of the conduction band present at the different values of k</p>

3. In direct band gap semiconductors, when an electron recombines with the hole, it emits their energy in terms of light.	3. In direct band gap semiconductors, when an electron recombines with the hole, it emits their energy in terms of heat.
4. Life time(recombination time) of charge carriers is very less.	4. Life time (recombination time) of charge carriers is more.
5. These are mostly form the compound semiconductors.	5. These are mostly form the elemental semiconductors.
6. Examples: InP, GaAs.	6. Examples: Germanium and silicon.
7. Band gap of InP=1.35eV and , GaAs=1.42eV	7. Band gap of Ge=0.7eV and Si=1.12eV
8. Direct band gap semiconductors are used to fabricate LEDs and laser diodes	8. Indirect band gap semiconductors are used to fabricate diodes and transistors

10. Drift current and diffusion currents

In case of semiconductors we observe two kinds of currents.

- I. Drift current
- II. Diffusion current

Drift current

Definition:- The flow of electric current due to the motion of charge carriers under the influence of external electric field is called drift current.

When an electric field E is applied across a semiconductor material, the charge carriers attain a drift velocity v_d .

So drift velocity $v_d = \mu \cdot E$ (1)

The relation between current density J and drift velocity v_d is

$$J = Nq v_d \quad (2)$$

Where N is the carrier concentration

q is the charge of electron or hole

From equations (1) and (2), we get

$$J^{drift} = Nq\mu E$$

μ is the mobility of charge carrier.

The above equation shows the general expression for drift current density.

Drift current density due to electrons is

$$J_e^{drift} = ne \mu_e E$$

Where n is the electrons carrier concentration and

μ_e is the mobility of electrons

Drift current density due to holes is

$$J_h^{drift} = pe \mu_h E$$

Where p is the carrier concentration of holes.

μ_h is the mobility of holes

\therefore Total drift current density

$$\begin{aligned} J^{drift}(total) &= J_e^{drift} + J_h^{drift} \\ &= ne \mu_n E + pe \mu_h E \\ &= eE (n\mu_e + p\mu_h) \end{aligned}$$

Diffusion current

Definition:-

The flow of electric current due to the motion of charge carriers under concentration gradient is called diffusion current

Or

The motion of charge carriers from the region of higher concentration to lower concentration leads to a current called diffusion current.

Let ΔN be the excess electron concentration. Then according to Fick's law, the rate of diffusion of charge carriers is proportional to concentration gradient $\left(-\frac{\partial(\Delta N)}{\partial x}\right)$

$$\begin{aligned} \text{Rate of diffusion of charge} &\propto -\frac{\partial(\Delta N)}{\partial x} \\ &= -D \frac{\partial(\Delta N)}{\partial x} \end{aligned}$$

Where D is the diffusion coefficient of charge carriers

The negative sign indicates decrease of N with increase of x

So, the diffusion current density J^{diffu} is

$$J^{diffu} = q \left[-D \frac{\partial(\Delta N)}{\partial x} \right] = -qD \frac{\partial(\Delta N)}{\partial x}$$

Where q is the charge of the charge carrier

Diffusion current density due to holes is

$$J_h^{diffu} = -e \cdot D_h \frac{\partial(\Delta p)}{\partial x}$$

Diffusion current density due to electrons is

$$J_e^{diffu} = e \cdot D_e \frac{\partial(\Delta n)}{\partial x}$$

$+e$ and $-e$ are the charges of holes and electrons respectively.

The expression for total diffusion current density is

$$\begin{aligned} J^{diffu}(total) &= J_h^{diffu} + J_e^{diffu} \\ &= -e \cdot D_h \frac{\partial(\Delta p)}{\partial x} + e \cdot D_e \frac{\partial(\Delta n)}{\partial x} \end{aligned}$$

The expression for total current density due to holes is

$$\begin{aligned} J_h(total) &= J_h^{drift} + J_h^{diffu} \\ &= pe \mu_h E - e \cdot D_h \frac{\partial(\Delta p)}{\partial x} \end{aligned}$$

The expression for total current density due to electrons is

$$\begin{aligned} J_e(total) &= J_e^{drift} + J_e^{diffu} \\ &= ne \mu_e E + e \cdot D_e \frac{\partial(\Delta n)}{\partial x} \end{aligned}$$

11. Einstein relation

The relation between mobility and diffusion coefficient of charge carriers in a semiconductors is known as Einstein relation.

At equilibrium conducting condition, the drift and diffusion currents must be equal and opposite in direction. Any disturbance in equilibrium leads to diffusion of charge carriers resulting in diffusion current which creates an internal electric field. This field causes the drifting of charge carriers resulting in a drift current. Then at equilibrium the drift and diffusion currents balance each other.

Let Δn be the excess electrons concentration of a semiconductors. Then

$$\Delta n e \mu_e E = e D_e \frac{\partial(\Delta n)}{\partial x} \quad (1)$$

The force on excess electrons restoring equilibrium is equal to the product of excess charge and the electric field, i.e.,

$$F = \Delta n e E \quad (2)$$

From equations (1) and (2)

$$F = e \frac{D_e}{\mu_e} \frac{\partial(\Delta n)}{\partial x} \quad (3)$$

From kinetic theory of gasses, the force on charge carriers can be written as

$$F = KT \frac{\partial(\Delta n)}{\partial x} \quad (4)$$

From equations (3) and (4)

$$\frac{D_e}{\mu_e} = \frac{KT}{e}$$

Similarly for holes we get

$$\begin{aligned} \frac{D_h}{\mu_h} &= \frac{KT}{e} \\ \frac{D_e}{\mu_e} &= \frac{D_h}{\mu_h} \\ \frac{D_h}{\mu_h} &= \frac{D_e}{\mu_e} \end{aligned}$$

This is called Einstein relation.

12. Hall Effect

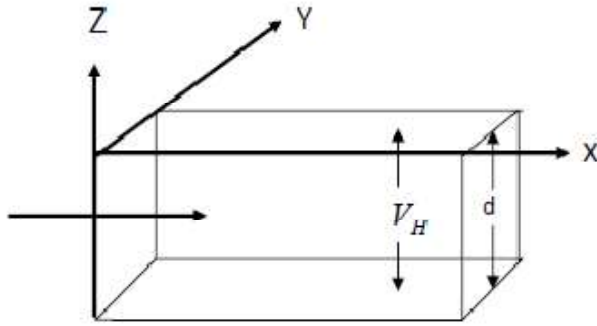
Statement:-

Hall Effect was discovered by E.H hall in 1879. When a magnetic field is applied perpendicular to the current carrying semiconductor, a potential difference of electric field is developed between two points on the opposite sides of the semiconductor in direction perpendicular to the both current and magnetic field. This phenomenon is known as Hall effect.

Let a current i is passed in the conductor along X axis and a magnetic field B is applied along Y axis. Due to the magnetic field, the charge carriers experience a force F perpendicular to X-Y plane i.e., along Z axis. The direction of force is given by the Flemings left hand rule. Due to the displacement of the charge carriers, some transverse field known as hall electric field E_H is developed across the two faces

$$\text{Magnetic deflection force} = q v_d B \quad (1)$$

$$\text{Hall electric deflecting force} = q E_H \quad (2)$$



At the equilibrium $qv_d B = qE_H$

$$E_H = v_d B \quad (3)$$

We know drift velocity $v_d = \frac{J}{Nq}$

(4)

Where N is the number of charge carriers per unit volume.
So from equations (3) and (4)

$$E_H = \frac{J}{Nq} B \quad (5)$$

Then the hall voltage V_H at the equilibrium is

$$E_H = \frac{V_H}{d} \quad (6)$$

Hall coefficient (R_H)

The ratio of the hall electric field to the product of current density and magnetic induction is known as Hall coefficient.

$$R_H = \frac{E_H}{JB} \quad (7)$$

Substitute the value of E_H from equation (5) in equation (7). We get

$$R_H = \frac{E_H}{JB} = \frac{1}{Nq}$$

Hall coefficient for n-type semiconductors is

$$R_H = \frac{-1}{ne} \quad (\text{since for electron } q = -e \text{ and } N = n)$$

Hall coefficient for p-type semiconductors is

$$R_H = \frac{1}{pe} \quad (\text{since for holes } q = e \text{ and } N = p)$$

The hall coefficient is negative when the charge carriers are electrons and positive when the charge carriers are holes.

Applications of Hall Effect

1. Hall Effect gives the information about the sign of the charge carriers.
2. Hall Effect can be used to measure the drift velocity of the charge carriers. $v_d = \frac{J}{nq}$
3. Strong magnetic fields can be measured by using Hall Effect.
4. The mobility of the charge carrier can be measured by the conductivity of the material and Hall coefficient.
5. Hall Effect can be used to measure the number of charge carriers per unit volume.

13. Photo diode

Silicon photo diode is a light sensitive device. It is also called as photo detector. Photo diode converts light signals into electrical signals. It is always operated in reverse biased condition.

Symbol

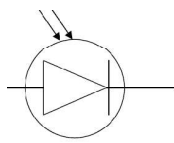
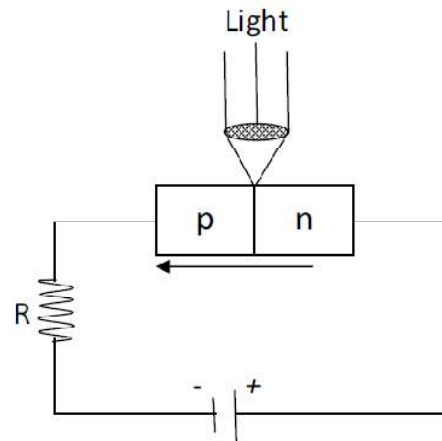


Photo diode symbol

Construction

The diode is made of semiconductor pn junction kept in a sealed plastic casing. The cover is so designed that the light rays are allowed to fall on one surface of junction and the remaining sides of the casing are painted to restrict the penetration of light rays. A lens permits light to fall on the junction.



Construction of Photo diode

Working

When light falls on the reverse biased $p-n$ photo diode junction, hole-electron pairs created by breaking of covalent bondings. The magnitude of photo current depends on the number of charge carriers generated and on the light falling of diode element. The current is also affected by the frequency of the light falling on the diode element. The magnitude of current under large reversed bias is given by

$$I = I_S + I_0 \left(1 - e^{-V/\eta V_T} \right)$$

Where I_S = short circuit current which is proportional to the light intensity

I_0 = Reverse saturation current

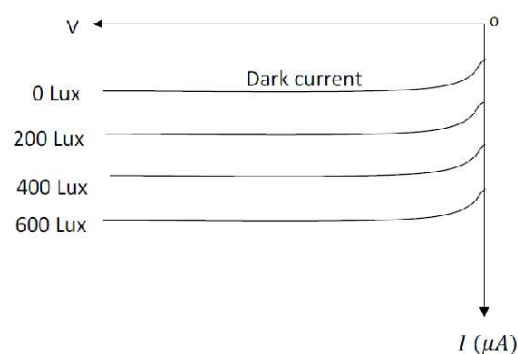
V = Voltage across the diode

V_T = Volt equivalent of temperature

η = Parameter, 1 for Ge, 2 for Si

Characteristics

The Characteristics of photo diode are shown in figure. The reverse current increases in direct proportion to the level of light. Even no light is applied, there is minimum reverse leakage current called dark current, flowing through the diode. Germanium has higher dark current than silicon.



Applications

Photo diodes are used as

Light detectors,

Demodulators,

Encoders.

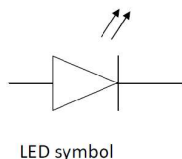
Optical communication system

High speed counting and switching circuits.

14. LIGHT EMITTING DIODE (LED)

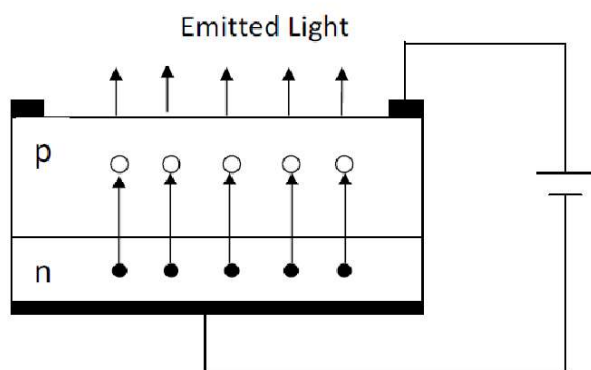
Light emitting diode is a pn junction device. It is always operated in forward biased condition. LED converts electrical energy into light energy. In the fabrication of LED's direct band gap semiconductors like GaP, GaAsP are used. In direct band gap semiconductors most of the energy is emitted in the form of light when hole and electron recombination takes place.

Symbol



Construction

The basic structure and of an LED is shown in figure. In LED, an N-type layer is grown on a substrate and a p type is deposited on it by diffusion. A metal (gold) coating is applied to the bottom of the substrate for the reflection of light and also to provide cathode connection. The metal anode connections are made at the outer edges of the p-layer.



Construction of LED

Working

When an LED is forward biased the electrons and holes move in towards the junction and recombination takes place. As a result of recombination the electrons lying in the conduction band of an n- region fall into the holes lying in the valence band of a p -region. The difference of energy in the valence band and conduction band is radiated in the form of light energy. Here their excess energy is transferred to the emitted photon. The brightness of emitted light is directly proportional to the forward bias current.

Applications

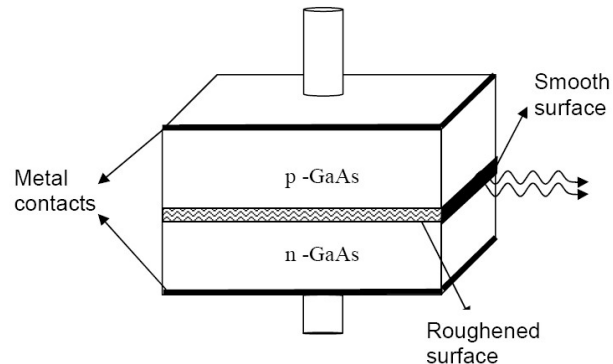
LEDs are used in
For instrument display
In calculators
Digital clocks
For indicating power ON/ OFF
For optical switching application
In optical communication system

15. Laser Diode:

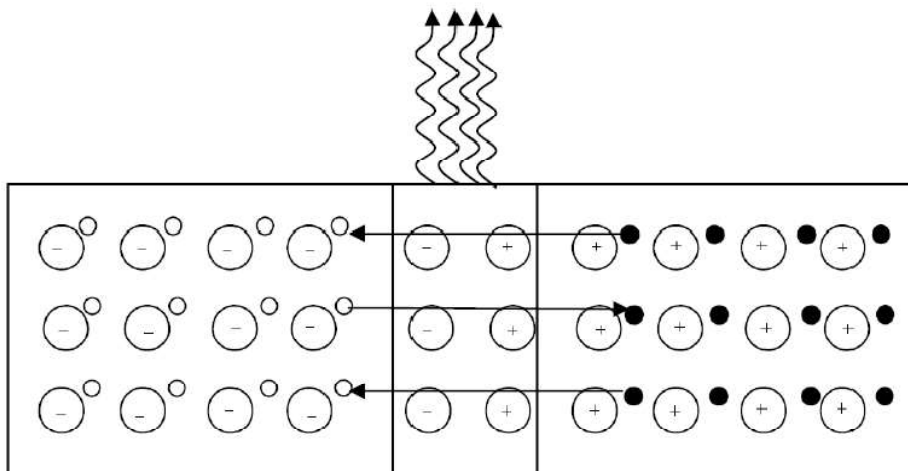
Direct band gap semiconductors are preferred in the fabrication of laser diodes because they emit energy in terms of light when an electron and hole recombination takes place. These are operated at forward biased condition. Compound semiconductors like *GaAs* and *InP* are examples for direct band gap semiconductors.

Construction

In this laser system, the active is a p-n junction diode made from crystalline gallium arsenide. The p-region and n-region in the diode are obtained by heavily doping germanium and tellurium respectively in GaAs. The thickness of the p-n junction is very narrow so that the emitted radiation has large divergence and poor coherence. At the junction two sides are roughed to avoid laser emission and the remaining two faces one is partially polished and the other is fully polished. The laser emission takes place from the partially polished face. To provide bias two metal contacts are provided in the top and bottom of the diode as shown in figure.

**Working**

The semiconductor laser device is always operated in forward bias condition. Electrons and the holes are the minority charge carriers in p-region and p-region semiconductors. When a huge current (10^4 Amp/mm²) is passing through the p-n junction, p-region is positively biased, holes are injected into n-region from p-region and n-region is negatively biased electrons are injected into p-region from n-region as shown in figure.



The continuous injection of charge carriers creates the population inversion of minority carriers in n and p sides' respectively. The electrons and holes recombine and release of light energy takes place in or near the junction as shown in figure 1. The emitted photons increase the rate of recombination of injected electrons from the n-region and holes in p-region by inducing more recombinations.

For GaAs semiconductor $E_g = 1.4\text{eV}$

from Planck's law $E_g = h\nu = h\frac{c}{\lambda}$

$$\lambda = \frac{hc}{E_g} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{1.4 \times 1.6 \times 10^{-19}} = 8874\text{\AA}$$

The wave length of emitted radiation depends up on the concentration of donor and acceptor atoms in GaAs. In case of GaAs homo-junction which has an energy gap of 1.44eV gives a laser beam of wave length around 8874 \AA . The efficiency of the laser emission is increases when we cool the GaAs diode.

16. Variation of Fermi level with temperature in intrinsic semiconductor

For intrinsic semiconductor

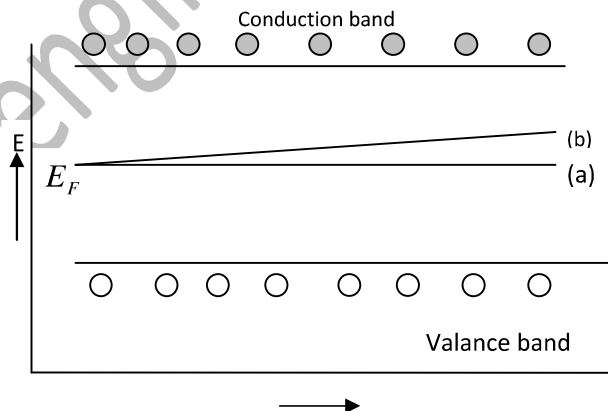
$$E_F = \frac{kT}{2} \log\left(\frac{N_C}{N_V}\right) + \frac{(E_v + E_C)}{2}$$

at T= 0K

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

Curve (a) The variation of Fermi level at T= 0K (b) The variation of Fermi level with temperature

The Fermi level is located half way between the valence band and conduction bands and its position is independent of temperature. Since m_h^* is greater than the m_e^* , E_F is just above the middle, and rises slightly with increasing temperature.



17. Working of p-n junction

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