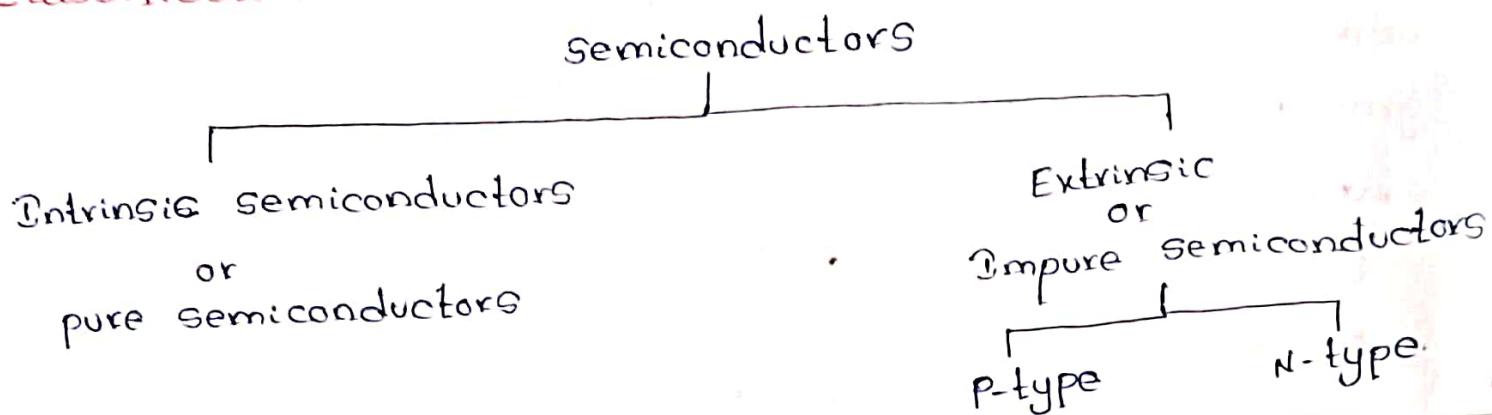


## 2. Semiconductors

### Introduction :

A substance which has conductivity in between conductors and insulators is known as semiconductor.

### Classification of Semiconductors :



Intrinsic Semiconductors	Extrinsic semiconductors
<ul style="list-style-type: none"><li>1. A semiconductor in an extremely pure form is known as intrinsic semiconductor.</li><li>2. conductivity is low.</li><li>3. No. of electrons is equal to no. of holes.</li><li>4. conductivity is due to both electrons and holes.</li><li>5. The current is of the order of microamperes.</li><li>6. Fermi level lies in between valence and conduction bands.</li><li>7. Resistivity is high.</li><li>8. There is no additional donor level and acceptor level.</li></ul>	<ul style="list-style-type: none"><li>1. chemically impure form of semiconductor is called an extrinsic semiconductor.</li><li>2. conductivity is high.</li><li>3. No. of holes is not equal to the no. of electrons.</li><li>4. conductivity is mainly due to majority charge carriers.</li><li>5. The current is of the order of milliamperes.</li><li>6. Fermi level lies near valence band in p-type and near conduction band in n-type.</li><li>7. Resistivity is low.</li><li>8. There is a donor level in N-type &amp; acceptor level in p-type extrinsic semiconductor.</li></ul>

**Doping** :- The process of adding impurity is called doping.

Two types of impure semiconductors :-

### i) N-type semiconductor :

When a small amount of pentavalent impurity is added to a pure semiconductor crystal during crystal growth, then the resulting crystal is called N-type extrinsic semiconductor.

→ Electron is available as a carrier of current.

→ Ex. of pentavalent atoms are - Bismuth ( $Z=83$ ), Antimony, ( $Z=51$ ), Arsenic ( $Z=33$ ), Phosphorous ( $Z=15$ ).

→ The pentavalent doping atom is known as donor atom because it donates one electron to conduction band of pure semiconductor.

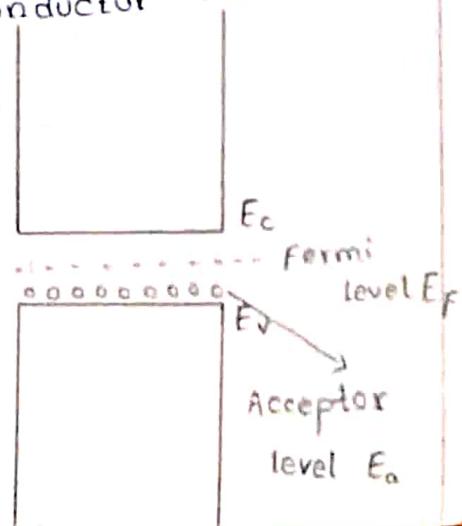
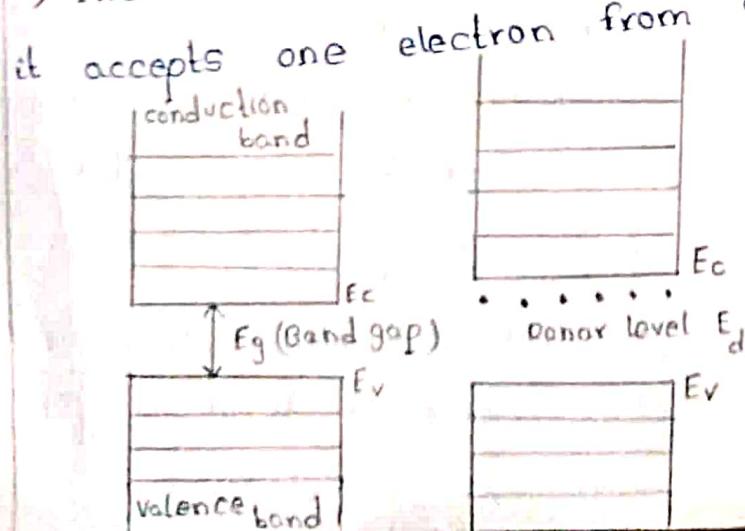
### ii) P-type semiconductor :

When a small amount of trivalent impurity is added to a pure crystal during the crystal growth, then the resulting crystal is called P type extrinsic Semiconductor.

→ Hole is available as a carrier of current.

→ Ex. of trivalent atoms are - Boron ( $Z=5$ ), Aluminium ( $Z=13$ ), Gallium ( $Z=31$ ), Indium ( $Z=49$ ).

→ The trivalent atom is known as acceptor atom because it accepts one electron from semiconductor atom.

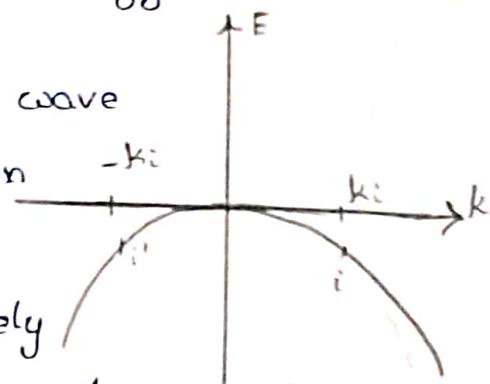


## charge carriers in Semiconductors:

There are two types of charge carriers, namely electrons and holes.

### Electrons and holes :-

- A Semiconductor is heated at  $0\text{K}$  to raise its temperature
- Electrons in valence band get sufficient thermal energy and crosses energy gap to reach conduction band.
- An empty state in the valence band is called a hole.
- When the hole & the conduction band electron are created due to the excitation of an electron from the valence band to the conduction band, it is called an electron-hole pair (EHP).
- The electron on reaching the conduction band is surrounded by a large no. of unoccupied energy states.
- As the large no. of empty states are available, the electrons move freely in the conduction band.
- In the valence band, all available energy states are occupied.
- Figure shows an electron  $i$  with a wave vector  $k_i$  and a corresponding electron  $i'$  with a wave vector  $-k_i$ .
- Since the two electrons are oppositely directed, they do not give rise to any net current.
- If the valence band has  $N$  electrons/ $\text{cm}^3$ , then for every electron moving with particular velocity, there exists another electron whose motion is exactly oppositely directed.
- Thus, for a filled valence band, the current density  $J$  can be written as,  $J = (-q) \sum_{i=1}^N v_i = 0 \rightarrow (i)$



→ Suppose, if a sufficient energy is given to  $j^{\text{th}}$  electron it gets excited to the conduction band.

→ The  $j^{\text{th}}$  electron does not now contribute to the current density, which becomes,

$$J = (-q) \sum_{i=1}^N v_i - (-q) v_j \rightarrow (\text{ii})$$

From equ (i), equ (ii) becomes,  $J = q v_j$ .

→ This current contribution is equal to +vey charged particles of velocity  $v_j$ .

→ The vacant states in the valence band can be treated as charge carriers with +ve charge & +ve mass.

→ The hole energy increases oppositely to the electron energy because the two carriers have opposite charge.

→ Holes seek the lowest energy states available at the top of the valence band as its energy increases downwards & conduction electrons found at bottom of conduction band as electron energy increases upwards.

### Effective Mass ( $m^*$ ) :-

→ If some magnitude of electric field is applied to both electrons in vacuum and inside the crystal, the electrons will accelerate at a different rate from each other due to the existence of different potentials inside the crystal.

→ The electrons inside the crystal has to try to make its own way. so the electrons inside the crystal has to try to move will have a different mass than that of the electrons in vacuum.

→ This altered mass is called an "effective mass".

To find effective mass,  $m^*$  -

taking the derivative of energy with respect to  $k$ :

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m} \Rightarrow \frac{d^2 E}{dk^2} = \frac{\hbar^2}{m}$$

changing  $m$  to  $m^*$ , then

$$m^* = \hbar^2 / \left| \frac{d^2 E}{dk^2} \right|$$

→ The sign of the effective mass is determined directly from the sign of the curvature of E-k curve.

→ Thus effective mass is an inverse function of the curvature of the E-k diagram; weak curvature gives large mass and strong curvature gives small mass.

→ The curvature of a graph at a minimum point is a +ve quantity and the curvature of a graph at a maximum point is a -ve quantity.

→ The curvature  $d^2 E/dk^2$  is +ve at the conduction band minima and -ve at valence band maxima.

→ Therefore, particles sitting near the minimum have a +ve effective mass and particles sitting near V.B maxima have -ve effective mass.

→ A -ve effective mass implies that a particle will go in the wrong way when an external force applied while moving in an electric field.

→ The electron and hole effective masses are denoted by  $m_e$  and  $m_h^*$  respectively.

### Drift and Diffusion:

The current that flows across a semiconductor has two components. 1. Drift current 2. Diffusion current

E-k diagram (band structure)

→ Shows characteristics of a particular semiconductor relation b/w energy and momentum of available states for electrons in the material.

$k$ -momentum,  $E$ -Energy  
 $d^2 E/dk^2$  is curvature.

## 1. Drift current :

- In a perfect crystal periodic electric field allows electrons and holes to move freely as if in a vacuum, but defects in crystals disturbs the electric field.
- For  $T > 0K$ , thermal energy can cause the lattice ions to vibrate.
- The flow of charge carriers, due to the applied voltage or electric field is called drift current.
- When the voltage is applied to a semiconductor, the free electrons move towards the +ve terminal of a battery and holes move towards the -ve terminal of a battery.
- The electrons always try to move in a straight line towards the +ve terminal, but due to continuous collision with the atoms they change the direction of flow.
- Each time the electron strikes an atom it bounces back in a random direction.
- The applied voltage does not stop the collision and random motion of electrons, but it causes the electrons to drift towards the +ve terminal.
- The average velocity that an electron or hole achieves due to the applied voltage or electric field is called "drift velocity."
- The drift velocity of electrons is given by  $V_n = \mu_n E$   
The drift velocity of holes is given by.  $V_p = \mu_p E$   
where,  $\mu_n$  and  $\mu_p$  are mobility of electrons and holes,  $E$ = applied electric field.
- The drift current density due to free electrons is given by,  $J_{n,p} = e n \mu_n E$  and

the drift current density due to holes is given by

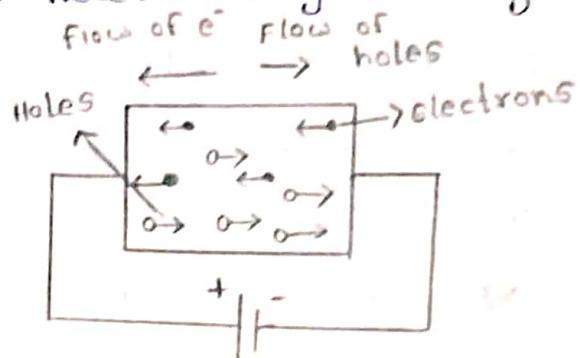
$$J_{P(\text{drift})} = e p \mu_p E$$

where,  $e$  = charge of electron

$$= 1.602 \times 10^{-19} \text{ coulombs}$$

$n$  = no. of electrons and

$p$  = no. of holes.



→ Then the total drift current density is,

$$J_{(\text{drift})} = J_{n(\text{drift})} + J_{p(\text{drift})}$$

$$= en\mu_n E + ep\mu_p E$$

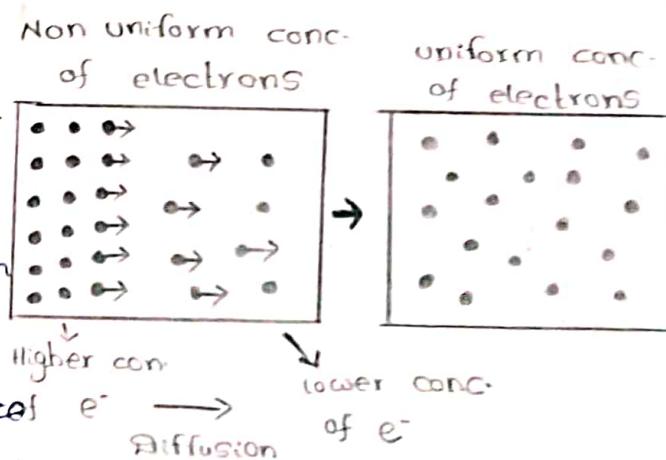
$$J_{(\text{drift})} = eE(n\mu_n + p\mu_p)$$

### Diffusion Current :-

→ The movement of charge carriers from the higher concentration area to the lower concentration area is termed as diffusion.

→ The no. of electrons present at left side of semiconductor is more.

→ As these electrons experience a repulsive force from each other will move from left side to right side to reach the uniform concentration of electrons.



→ These moved electrons constitute  $e^-$  current, this current is called the diffusion current.

→ Diffusion current occurs without an external voltage or without applied electric field.

→ The direction of diffusion current is same or opposite to that of the drift current.

→ The diffusion current density is directly proportional to the concentration gradient. Concentration gradient is the difference in concentration of electrons and holes in a given area.

→ If the concentration gradient is high, then diffusion current density is high, if it is low, concentration gradient is low.

→ The concentration gradient for n-type semiconductor is given by  $J_n \propto \frac{dn}{dx}$ .

The concentration gradient for p-type semiconductor is given by  $J_p \propto \frac{dp}{dx}$

where  $J_n$  &  $J_p$  are diffusion current densities due to electrons and holes.

→ The diffusion current density due to electrons is given by  $J_n = +e D_n \frac{dn}{dx}$ ,  $D_n$  = diffusion coefficient of electrons.

The diffusion current density due to holes is given by

$$J_p = -e D_p \frac{dp}{dx}, \quad D_p = \text{diffusion coefficient of holes.}$$

→ The overall density of the current of respective holes or electrons can be given by the sum of diffusion current and drift current.

→ The overall current density w.r.t. electrons can be given as.  $J_{n(\text{total})} = J_n(\text{drift}) + J_n(\text{diffusion})$

$$J_n = e n \mu_n E + e D_n \frac{dn}{dx} \quad \text{and}$$

w.r.t. holes is given as  $J_{p(\text{total})} = J_p(\text{drift}) + J_p(\text{diffusion})$

$$J_p = e_p n_p \mu_p E - e D_p \frac{dp}{dx} \quad \therefore \text{The overall current density is } J = J_n + J_p.$$

## Differences between Drift current & Diffusion current:

Drift current	Diffusion current
1. The movement of charge carriers is because of the applied electric field is known as drift current.	1. The diffusion current can be occurred because of the diffusion in charge carriers.
2. It requires electrical energy for the process of drift current.	2. Some amount of external energy is enough for the process of diffusion current.
3. This current obeys ohm's law.	3. This current obeys Fick's law.
4. The direction of charge carriers in this semiconductor is reverse to each other.	4. For charge carriers, the densities of diffusion are reverse in symbol to each other.
5. The direction of drift current as well as the electric field, will be the same.	5. The direction of this current can be decided by the concentration of the carrier slope.
6. It depends on the permittivity.	6. It is independent of permittivity.
7. The direction of this current depends on polarity of the applied electric field.	7. The direction of this current mainly depends on the charge within the concentrations of carrier.

## Einstein's relation :-

The relation between Diffusion coefficient and mobility of charge carriers is called Einstein's relation, i.e  $\frac{D}{\mu} = \frac{k_B T}{q}$ ,  $k_B$  = Boltzmann constant,  $T$  = Temperature,  $q$  = charge.

## Generation and Recombination:

Generation is a process where electron hole pairs are created by exciting an electron from valence band to conduction band, creating a hole in valence band.

→ Recombination is the reverse process where electrons & holes from conduction band and valence band recombine and are annihilated.

→ There are 2 types of recombination processes - radiative recombination & non-radiative recombination.

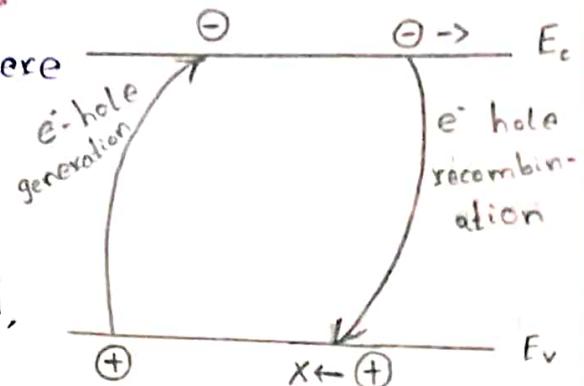
**Radiative Recombination:** the energy is emitted in the form of a photon.

**Non-radiative recombination:** the energy is given from one to one or more phonons.

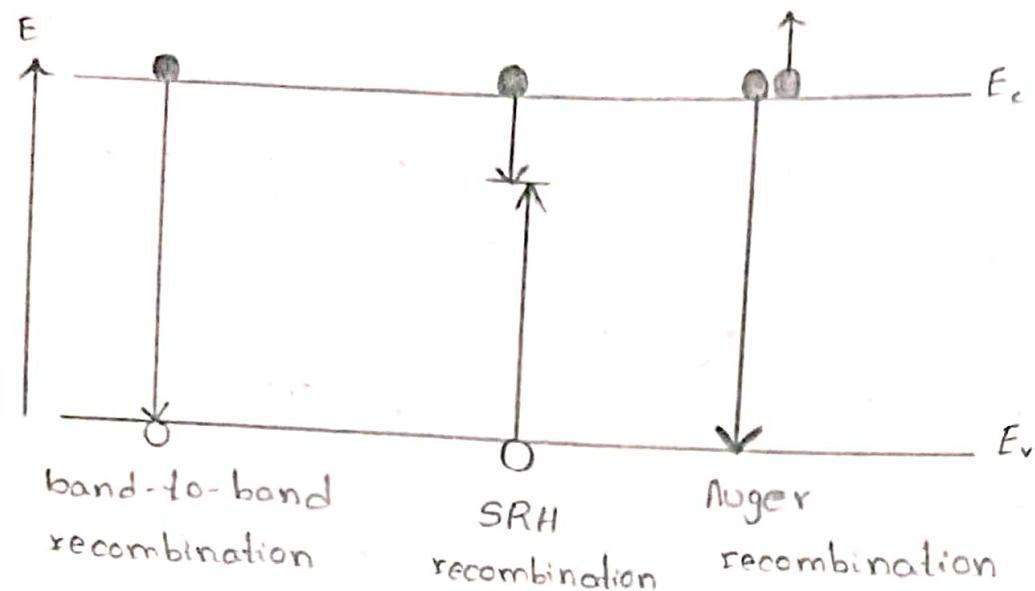
→ The recombination can happen in different process named, band-to-band recombination, shockley-read-hall (SRH) or trap assisted recombination and auger recombination.

**Band-to-band radiative recombination:** This occurs when an electron moves from its conduction band state into the empty valence band state associated with the hole.

**SRH or Trap assisted Recombination:** It occurs when an electron falls into a trap, an energy level within the bandgap caused by the presence of a foreign atom or a structural defect. once the trap is filled it cannot



Electron-hole generation and recombination.



accept another electron. The  $e^-$  occupying the trap is a 2<sup>nd</sup> step, moves into an empty valence band state thereby completing the recombination process. It is a two step transition of an  $e^-$  from the conduction band to valence band or the annihilation of the electron and hole, which meet each other in the trap.

**Auger Recombination:** A process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole. The involvement of a 3<sup>rd</sup> particle affects the recombination rate.

### Diffusion Length:

The diffusion length of a carrier in a material can be defined as the average distance that an excited carrier will travel before recombining.

The diffusion length can be defined as follows:

$L_d = \sqrt{D\tau}$ , where D is the diffusion coefficient and  $\tau$  is the life time of the excited carrier.

## The Fermi-level and Fermi-Dirac Distribution:

→ Electrons in solids obey fermi-dirac statistics (Particles obey pauli exclusion principle). The distribution of electrons in allowed energy levels at thermal equilibrium is given by the fermi-dirac distribution function,  $f(E)$  which is,  $f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$  where  $k$  is boltzmann's constant ( $k = 1.38 \times 10^{-23} \text{ J/K}$ ).

→ The function  $f(E)$  gives the probability that an available energy state at  $E$  will be occupied by an electron at absolute temperature  $T$ .

→ The quantity  $E_F$  in the function  $f(E)$  is called the fermi-level.

→ Let us put  $E = E_F$ , we get

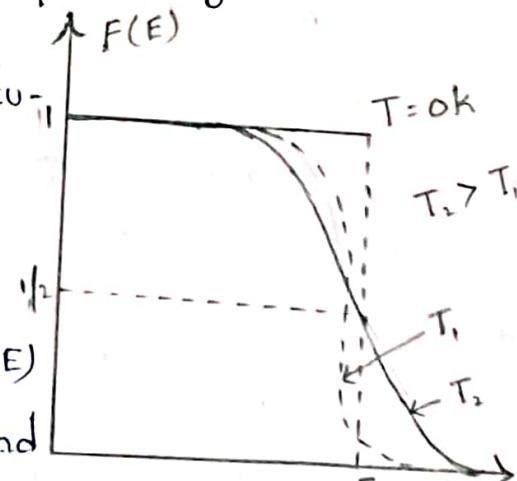
$$f(E_F) = [1 + e^{(E_F - E_F)/kT}]^{-1} \Rightarrow f(E_F) = \frac{1}{1+1} = \frac{1}{2}$$

Thus the fermi level  $E_F$  represents that energy which has a probability  $1/2$  is being occupied by an electron.

→ A plot of  $f(E)$  for some temperatures is shown in fig.

→ A few salient features of the function  $f(E)$  are-

i) At  $0\text{K}$ , the distribution function  $f(E)$  takes a simple rectangular shape and it implies that states upto  $E_F$  are filled with electrons & states above  $E_F$  are empty.



ii) At temperature greater than  $0\text{K}$ , some probability exists for states above the fermi level is filled with the electrons.

- iii) At any temperature  $T$ , there is a probability  $f(E)$ , says that, states above  $E_F$  are filled and corresponding probability  $[1-f(E)]$  exists that states below  $E_F$  are empty.
- iv) The fermi function is symmetric about  $E_F$  for all temperatures. Thus the probability of  $f(E_F + \Delta E)$  state above  $E_F$  is filled is equal to the probability  $[1-f(E_F - \Delta E)]$  state below  $E_F$  are empty.

→ The distribution function can have a finite value in the bandgap of a semiconductor, but there is no possibility of an electron existing within the band gap.

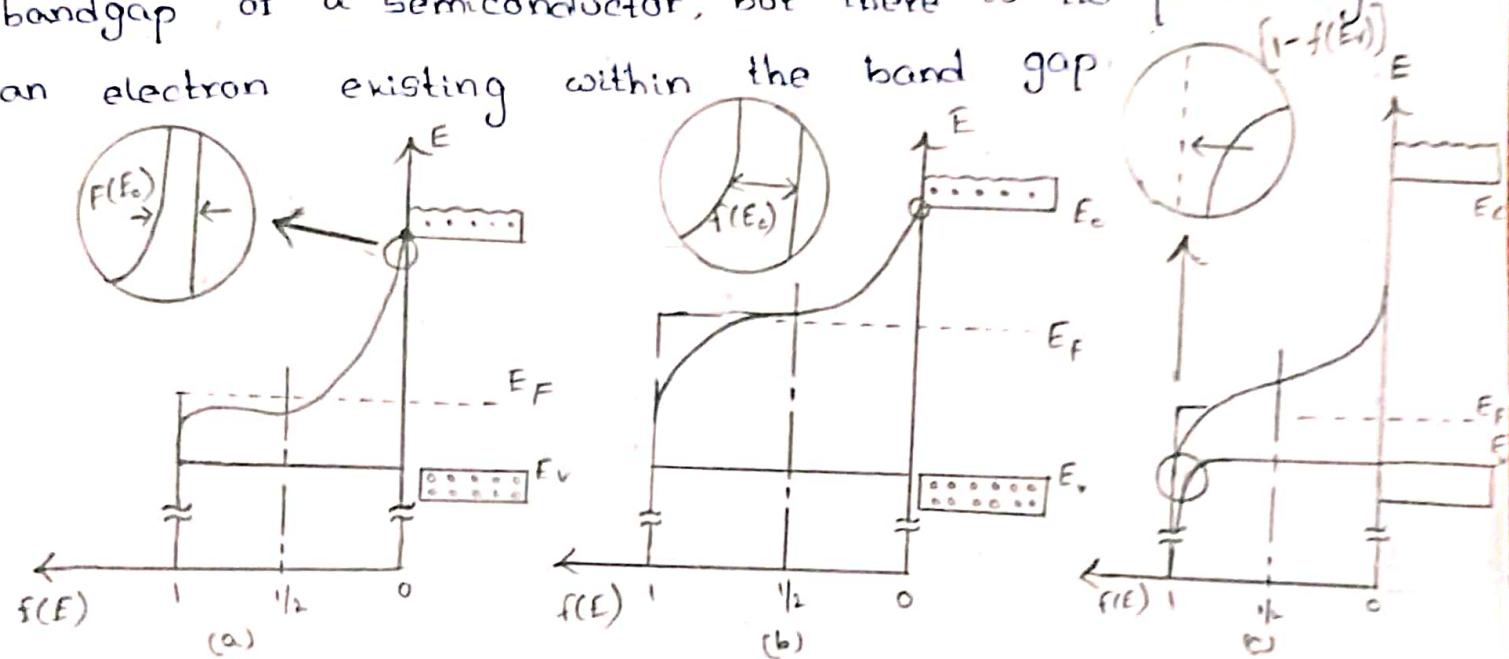


Fig: The fermi distribution function for a) intrinsic b)n-type & c) p-type materials.

→ As the concentration of holes in valence band is equal to concentration of electrons in the conduction band, the fermi level  $E_F$  must therefore lie at the middle of band gap in an intrinsic semiconductor.

→ Due to the function  $f(E)$  is symmetric about  $E_F$ , the electron probability tail of  $f(E)$  extending into the conduction band is symmetrical with the hole probability tail  $[1-f(E)]$  in the valence band. (fig-a)

→ The densities of available states at  $E_V$  and  $E_C$  are of

the order of  $10^{19} \text{ cm}^{-3}$ .

→ Small changes in  $f(E)$  can lead to significant changes in the free carrier concentration.

→ An n-type semiconductor has high concentration of electrons in the conduction band than concentration of holes in valence band, therefore the  $E_F$  is close to  $E_c$ .

→ As  $E_F$  moves closer to  $E_c$ , the values of  $f(E)$  for each energy level in the conduction band increases, this implies in total electron concentration. [fig. b]

→ For the p-type semiconductor, the tail  $[1-f(E)]$  below  $E_v$  is larger than the tail of  $f(E)$  above  $E_c$ .

→ The concentration of holes in the p-type material depends upon the difference  $(E_F - E_v)$ . Thus the position of  $E_F$  in band diagram at particular temperature indicates the concentration of electrons and holes.

### Electrons and holes in quantum well :-

Electrons and holes are charge carriers that are essential to the electronic behaviour of the semiconductor.

\* A quantum well is a nanostructure that confines charge carriers in a region with dimensions on the order of a few nanometers in atleast one direction. It is typically composed of semiconductor material.

\* In a quantum well, the energy levels for electrons and holes become quantized due to the confinement of their motion in the well. The energy levels form a discrete set of allowed states, similar to the energy levels in an atom.

**Electrons:** In a quantum well, electrons are confined within a narrow region along one dimension. Due to quantum confinement, the energy levels for electrons become discrete, with only certain allowed energy values. These energy levels are often referred to as subbands. The lowest energy subband is called the ground state and the higher energy subbands are referred to as excited states. The energy spacing between these subbands depends on the dimensions of the quantum well.

**Holes:** Holes are essentially the absence of an electron in a filled electronic band. In semiconductors, electrons in the valence band can leave behind a hole when they move to a higher energy level or excited by an external energy source. In a quantum well, holes also become confined due to quantum effects. Similar to electrons, the energy levels for holes become quantized, forming a set of discrete subbands.

Electrons and holes can have different effective masses in a quantum well. This change in effective mass arises due to quantum confinement and modified potential energy within the well. The effective mass determines how the carriers respond to external electric fields and influences their mobility & transport properties.

The interaction b/w electrons and holes in a quantum well is crucial for various optoelectronic devices. For example, when an electron & a hole recombine, they can emit a photon, leading to light emission in quantum well used in lasers & LED's.

## Charge of electron-hole concentration - Qualitative

### Analysis:

When analyzing the qualitative changes in electron-hole concentration, we refer to the behaviour of charge carriers in a semiconductor material. Here is a qualitative analysis of changes in electron-hole concentration:

**Doping:** Adding of impurities to semiconductor material to alter its electrical properties. Two types of dopants are used n-type and p-type.

In n-type doping, by adding elements from group V, extra electrons are introduced into the material. These electrons become the majority charge carriers, while the holes become the minority carriers. Therefore electrons concentration increases, while the hole conc. decreases.

In p-type doping, by adding elements of group III, holes are introduced in the material. Therefore, the majority charge carriers hole concentration increases & minority charge carriers electron concentration decreases.

**Temperature effects:** Increasing and decreasing the temperature of a semiconductor material affects the electron-hole concentration.

At higher temperatures, more electrons gain enough energy to break free from the valence band and become conduction band electrons. This leads to increase in the electron concentration & hole concentration decreases.

At lower temperatures, fewer electrons jump to the conduction band, resulting in decrease in electron concentration & increase in hole concentration.

**Illumination :** Illuminating a semiconductor with light can also impact the electron-hole concentration.

When a semiconductor absorbs photons with energies greater than its bandgap, electron-hole pairs are generated. The absorbed energy promotes valence band electrons to the conduction band, creating free electrons & leaving behind holes in the valence band. Therefore, both the electron and hole concentration increase.

If the incident light has energies lower than the bandgap, the semiconductor does not absorb the photons, so the electron-hole concentration remains unaffected.

**Electric field :** Applying an external electric field can alter the concentration of electrons and holes in a material. In a strong electric field, electrons and holes can be separated and moved in opposite directions, resulting in an imbalance in their concentrations.

**Magnetic Field :** A magnetic field can influence the behavior of charge carriers in a material, affecting the concentration of electrons and holes.

**Strain :** Mechanical strain or stress applied to a material can affect its electronic properties. Strain can alter the energy band structure, leading to changes in the concentration of electrons and holes.

**Surface Effects :** The presence of a surface or interface can impact the concentration of charge carriers. Surface states or traps can capture or release electrons & holes,

leading to changes in their concentrations near the surface.

**chemical reactions:** chemical reactions occurring at the surface or within the material can alter the conc. of electrons.

Many factors other than electric, magnetic field such as quantum confinement, defects and impurities present in material can also alter the concentration of charge carriers.

**Temperature dependency of carrier concentration:**

The carrier concentration in a semiconductor is also affected by temperature. The intrinsic carrier concentration is governed by,

$$n_i(T) = \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} \exp\left(\frac{-E_g}{2kT}\right) \rightarrow (1)$$

where the exponential temperature dependence dominates  $n_i(T)$ . To determine the total carrier concentration, we must also consider space-charge neutrality : (2)

$$n(T) = N_D^+(T) - N_A^+ + \frac{n_i(T)}{n(T)} \quad \& \quad p(T) = N_A^-(T) - N_D^-(T) + \frac{n_i(T)}{p(T)}$$

For a doped semiconductor, the temperature dependence of electron concentration can be seen in fig. At very low temperatures (large  $1/T$ ), negligible intrinsic electron-hole pairs (EHPs) exist ( $n_i$  is very small) and the donor electrons are bound to the donor atoms. This is known

the ionization (or freeze-out) region. As the temperature is raised, increased ionization occurs and at about 100K all of the donor atoms are ionized, at which point the carrier concentration is determined by doping. The region where every available dopant has been ionized is called the extrinsic (or saturation) region. In this region, an increase in temperature produces no increase in carrier concentration.

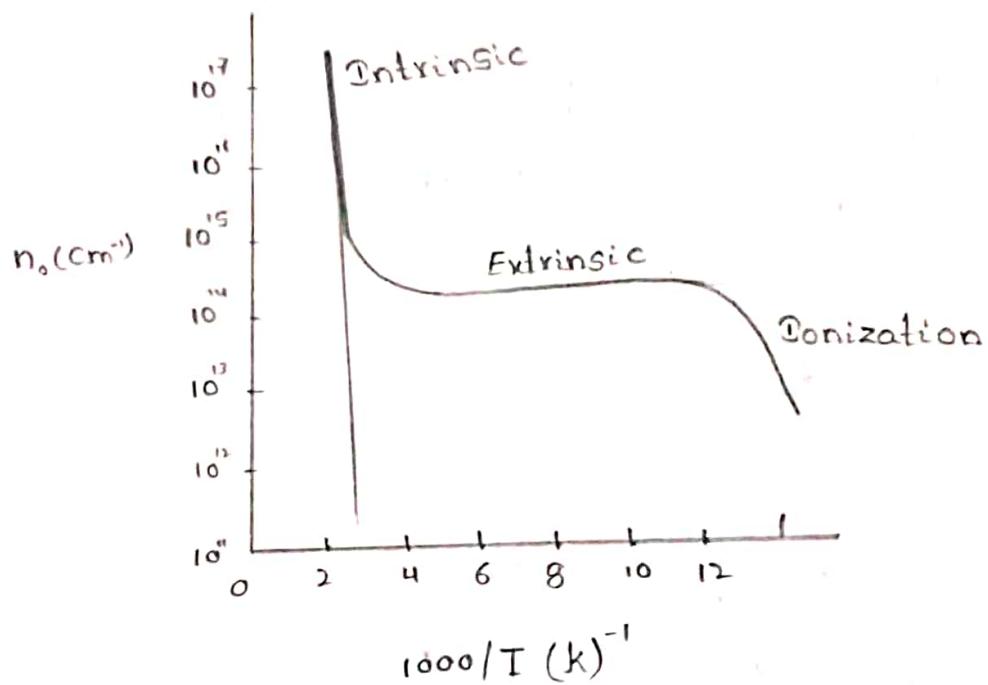


Fig :

Referring to equ (2), this is the region where  $N_D^+(T) = N_D$ ,  $N_A^-(T) = N_A$ , and  $n_i(T) \ll |N_D - N_A|$ .

At high temperatures, the thermally generated intrinsic carriers outnumber the dopants ( $n_i > |N_D - N_A|$ ). In this intrinsic region, carrier concentration increases with temperature as shown in equ (3) because  $n_i$  has become the dominant term of equ (2).

## Conductivity and Mobility :

### Conductivity :

A property of charge carriers describing its capacity of conduction.

Doping or impurity concentration enhances the number of charge carriers and hence the electrical conductivity of semiconductors.

It is similar to the conductivity of metals. But conductivity for semiconductors depends upon entirely different parameters. The conductivity of semiconductor is directly proportional to the following factors:

- charge carriers ( $\tau$ )
- The concentration of carriers ( $n$ )
- Mobility of carriers ( $u$ )

$$\text{conductivity } \sigma = qnu$$

SI units of  $\text{S/m}$  - Siemens per meter.

The conductivity of semiconductor can be influenced by various factors, including temperature, impurities, presence of electric fields and exposure to light. It plays a crucial role in numerous electronic devices, including transistors, diodes, solar cells and integrated circuits.

### Mobility :

Mobility refers to a movement of an electron or holes through a metal or semiconductor in presence of an electric field.

The capability of movement is connected with drift velocity i.e. when an external electric field is applied across a piece of semiconductor, free electrons and holes are accelerated by the electric field and acquire this velocity component.

Drift velocity ( $V$ ) is directly proportional to the electric field ( $E$ ).  $V = uE$

where,  $u$  = mobility, units are -  $\text{m}^2/\text{Vs}$

- Mobility depends upon temperature, electric field, impurity concentration, defect concentration, electron & hole concentration.
- Electrons are faster particles than holes.
- At higher temperatures, mobility decreases because of inelastic collisions.
- Mobility increases as electric field intensity decreases.
- Higher mobility leads to better performance in electronic devices.

**Effects of temperature and doping on mobility :-**

There are two basic types of scattering mechanisms that influence the mobility of electrons and holes in a semiconductor: lattice scattering and impurity scattering. In lattice scattering a carrier moving through the crystal is scattered by a vibration of the lattice. Lattice vibrations cause the mobility to decrease with increasing temperature.

The mobility of the carriers in a semiconductor is also influenced by the presence of charged impurities.

(22)

Impurity scattering is caused by crystal defects such as ionized impurities. At lower temperatures, carriers move more slowly, so there is more time for them to interact with charged impurities. As a result, as the temperature decreases, impurity scattering increases, and the mobility decreases.

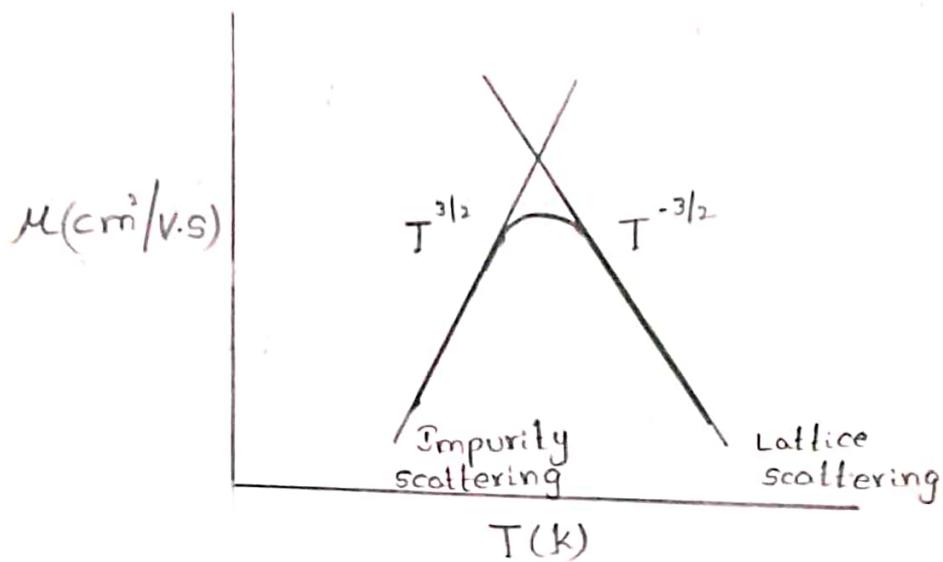


Fig: Approximate temperature dependence of mobility with both lattice and impurity scattering.

The total mobility is the sum of the lattice-scattering mobility and the impurity-scattering mobility.

Figure shows how the total mobility has a temperature at which it is a maximum.

The approximate temperature dependence of mobility due to lattice scattering is  $T^{-3/2}$ , while the temperature dependence of mobility due to impurity scattering is  $T^{3/2}$ .

Impurity scattering is typically only seen at very low temperatures. In the temperature range we will measure only the influence of lattice scattering.

## High-field effects :

High field effects in semiconductors refer to the phenomena that occur when the electric field applied to a semiconductor material exceeds a certain threshold. At high electric field strengths, various interesting phenomena emerge, such as impact ionization, velocity saturation and avalanche breakdown.

### Impact Ionization :

Impact ionization is a phenomenon that occurs when electrons gain enough energy from the electric field to collide with atoms in the crystal lattice, causing the generation of electron-hole pairs. This process can lead to a significant increase in the number of charge carriers in the material, resulting in an increase in current.

### Velocity saturation :

In a semiconductor, the drift velocity of charge carriers typically increases linearly with the applied electric field. However, at high electric fields, the velocity of the charge carriers saturates and no longer increases linearly. This velocity saturation effect occurs due to scattering mechanisms such as carrier-carrier scattering, phonon scattering or impurity scattering. Velocity saturation limits the maximum achievable current density in a semiconductor device.

## Avalanche Breakdown:

Avalanche breakdown occurs when the electric field in a semiconductor becomes so high that it causes a rapid multiplication of charge carriers through impact ionization. This results in a sudden increase in current and if not controlled, can lead to permanent damage to the semiconductor device. Avalanche breakdown is often avoided or controlled by incorporating appropriate device structures, such as pn junctions with well-defined doping profiles.

These high field effects are crucial in the design and operation of semiconductor devices & the use of advanced device structures improve device performance and reliability.