Semiconductor

By

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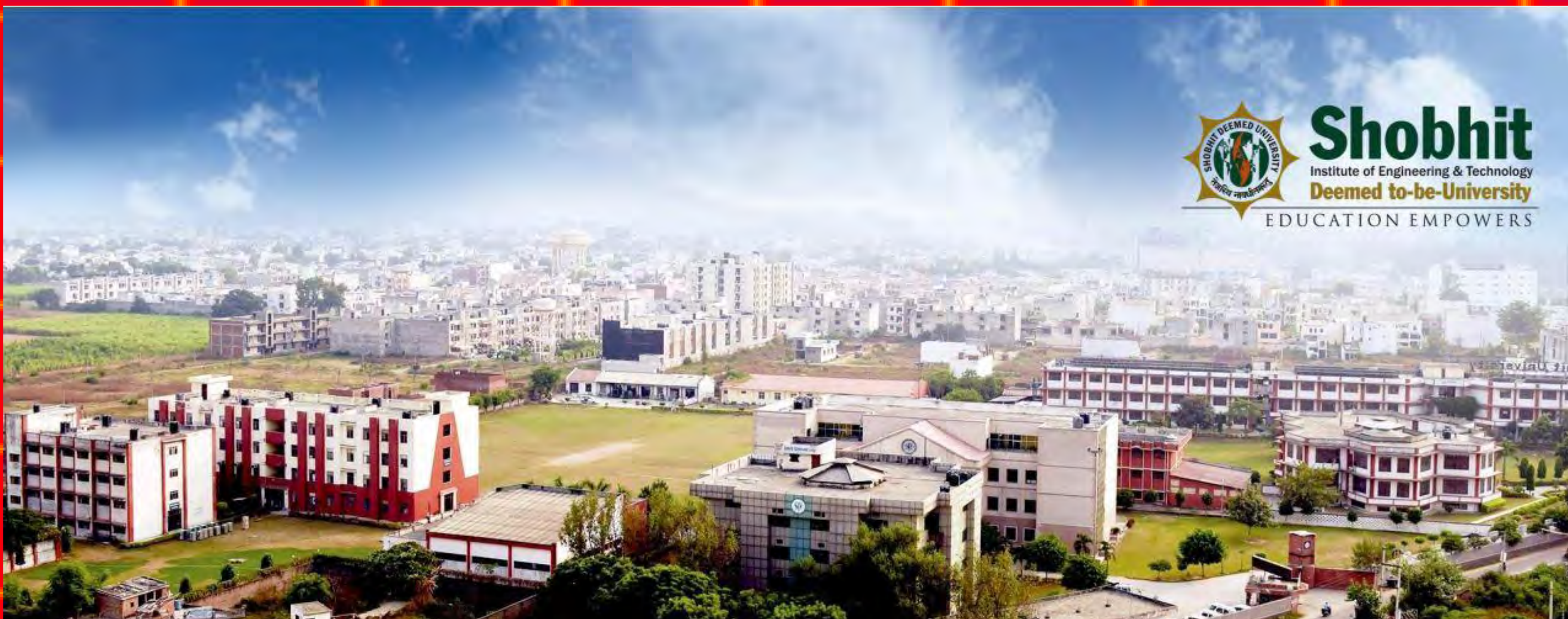


Chapter-1
Semiconductor

Conductor , Semiconductor & Insulators

Conductors: Semiconductors are those materials whose electrical conductivity is vary high ,through these materials electricity pass easily .The valence band and the conduction band overlap each other i.e. their is no forbidden energy gap (E_g=0). At absolute zero temperature ,large number of electrons remain in the conduction band. for example : copper , alluminium , gold etc.
Semiconductors: Semiconductors are those materials whose electrical conductivity is between conductors and insulators. The forbidden energy gap of a semiconductor is nearly same as insulator. The energy gap is narrower. The value of E_g =1.1eV for silicon crystal and E_g=0.7eV for germanium at ok. It can easily overcome due to thermal agitation or light. A semiconductor remains partially full valence band and partially full conduction band at the room temperature.
Insulator: Through these materials electricity cannot pass .Plastic, glass, wood etc are the examples of insulators. The valence band of these material remains full of electrons & the conduction band of these material remains empty. The forbidden energy gap between is widest i.e. is more than 10ev.

Intrinsic Semiconductors
An intrinsic semiconductor is a pure semiconductors .When an external voltage is applied to the instrinsic semiconductor, the free electrons flow toward the +ve battery terminal and the holes flow toward the negative terminal.
Two types of flow
Two types of carrier flow exist in an intrinsic semiconductor. First, there is the flow of free electrons through larger orbits (conduction band). Second, there is the flow of holes through smaller orbits(valence band)
Doping a Semiconductor
Doping is the process of control addition of impurity in pure semi conductor, it increases the conductivity of a semiconductor. A doped semiconductor is called extrinsic semiconductor. When an intrinsic semiconductor is doped with pentavalent (doner) atoms, it has more free electrons then holes. When an intrinsic semiconductor is doped with trivalent (acceptor) atoms, it has more holes then free electrons.

Two types of extrinsic semiconductors
In an n-type semiconductor the free electrons are the majority carrier, and the holes are minority carriers. In a p-type semiconductor the holes are the majority carriers, and the free electrons are the minority carriers.
pn Junction
It is a border between p-type & n-type semiconductor. The pn- junction itself forms the most basic semiconductor device called semiconductor diode, thus semiconductor diode and pn junction are one and the same.
Depletion layer
In pn junction diode the the free electrons on n side tend to diffuse across the junction ,when free electrons enters the p region, the free electrons recombines with hole in p region, and due to which hole disappears and free electron becomes valence electron.
Each time an electron diffuses across a junction , it creates a pair of ions , +ve ion on n side and -ve ion on p side, these pair of ions at junction is called a dipole. As no. of dipoles builds up, empty charge region is created know as depletion region.
Junction Potential width of depletion layer
Width of depletion layer is the distance measured from one side to the other side of the depletion region. Due to the presence of depletion region the electrons and holes do not i.e. depletion region acts as a

barrier. Due to the presence of immobile +ve(n-side) and –ve (p-side) ions on opposite sides of the junction an electric field is created across the junction . This electric field is known as junction potential also known as barrier potential. The barrier potential for silicon is 0.7 volt whereas for germanium is 0.3 volt at 25^0C.

Forward bias & Reverse bias

When an external voltage opposes the barrier potential, the diode is forward biased. If the applied voltage is greater than the barrier potential, the current flows. When an external voltage opposes the barrier potential, the diode is forward biased.

Diffusion of carriers in semiconductor : -

The movement of charge carriers from the region of high carrier concentration to the areas of low concentration, recombination of charge carriers occurs, the process is known as diffusion of carriers. The rate at which diffusion occurs depends on the velocity at which carriers move and on the distance between the carriers.

This diffusion current is proportional to the concentration gradient :

$$J_{nd} = q.D_n.\frac{\partial n}{\partial x}$$

$$J_{pd} = -\, q.D_p.\frac{\partial p}{\partial x}$$

Where D_n and D_p are the diffusion constant of p and n- type semiconductor, generally free electrons moves in conduction band & holes in valence band , valence band is more effected by electrostatic force so , we say mobility(it is the ease with which charge carriers flow) of electrons is higher then that of holes .

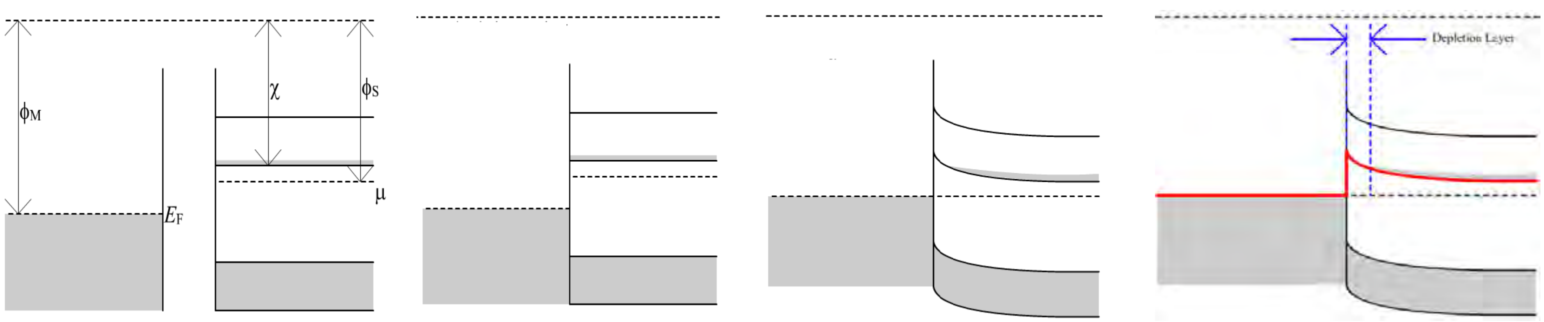
The mobility of electron being higher than that of holes, the Einstein relationship shows that, for a given concentration gradient, the diffusion current for electrons is higher than the diffusion current for holes.

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q}$$

Work function in metals and semiconductor junction:-

Energy required for an electron to move from Fermi level into the free space known as work function .The schematic below in fig. a shows a metal and an *n*-type semiconductor. The dashed line at the top represents the zero of energy of free space.

In fig. a, the work functions of metal & semi conductor denoted by Φ_M & Φ_S resp., E_F & μ indicates the fermi level of metal & semi conductor resp, χ i.e. electron effinity.



(a) (b) (c) (d)

When contact is made as shown in fig. b, electrons lower their energy by flowing from the semiconductor conduction band into the metal. This continues until the fermi energy level in the semiconductor as shown in fig. c reaches equilibrium with the fermi energy of the metal. The deformed band structure as shown in fig. d known as depletion layer forms a potential barrier.

The Energy Hill

The barrier potential of a diode looks like an energy hill. Electrons attempting to cross the junction need to have enough energy to climb this hill. An external voltage source that forward-bais the diode gives electrons the energy required to pass through the depletion layer.

Barrier Potential & Temperature

When the junction temperature increases, the depletion layer becomes narrow & the barrier potential decreases. It will decrease . It will decrease approximately 2.5 mV for each ^{0}C increase.

Field and capacitance of depletion layer

The two types of capacitances associated with a p-n junction diode are

1. Transition capacitance (C_T)
2. Diffusion capacitance (C_D)

The transient capacitance C_T referred to as space charge capacitance or barrier capacitance or depletion region capacitance. C_T is not constant, depends on the magnitude of reverse voltage. The value of C_T is inversely proportional to the width of depletion region and the width of depletion region is directly proportional the reverse voltage.

When the p-n junction diode is forward biased, a capacitance which is much larger then the transient capacitance is known as diffusion capacitance (C_D) or storage capacitance.

The diffusion capacitance (C_D) is given by,

$$C_D = \frac{dQ}{dV}$$

Forward A.C. and D.C. resistance of junction

The two types of resistance associated with a p-n junction diode are

1. DC resistance
2. AC resistance

The resitance offered by the diode to the DC operating conditions is called as "DC resistance or Static resistance " denoted by R_F **.**The DC resitance of a diode at operating point can be obtained by tacking the ratio of V_F & C_D

The resistance offered by the diode to the AC operating conditions is called as "AC resistance or Dynamic resistance" denoted by r_F. AC resistance is actually the reciprocal of the slope of the forward characteristics .

$$r_F = \frac{1}{Slope\ of\ the\ characteristics}$$

Reverse Breakdown

The maximum reverse bais voltage that can be applied to a p-n diode is known as reverse breakdown voltage. The breakdown in a reverse biased diode can take place due to following effects :

1. Avalenche effect
2. Zener effect

Once the breakdown voltage is reached, a large number of the minority carrier suddenly appears in a depletion layer and the diode conducts heavily.

Due to large reverse voltage the velocity of the minority carrier will increase & hence kinetic energy associated with them will also increase. While travelling, these high kinetic energy carriers will collide with the stationary atoms and impart some kinetic energy to the valence electrons present in the covalent bonds. Due to additionally acquired energy, these valence electrons collide with further atoms bounded with covalent bonds, generating more free electrons.

The process continues in the geometric fashion, until the reverse current becomes huge. The breakdown voltage of a diode depends on how heavily doped the diode is. Normal diodes has breakdown usually greater than 50V.

The Zener breakdown occurs in high doping diodes, where as avalanche breakdown occurs at low doping diodes. The breakdown voltage in Zener is lesser then Avelanche breakdown voltage.

Doping $\uparrow$ Breakdown voltage $\downarrow$

Doping $\downarrow$ Breakdown voltage $\uparrow$

The maximum reverse voltage that can be applied before entering the breakdown is called Peak inverse voltage (PIV) or Peak reverse voltage (PRV).

Derivations

1. $\frac{\Delta V}{\Delta T}$= -2.5mV/^{0}C
2. ΔV= (-2.5mV/^{0}C) * ΔT
3. % I_S= 100% for a 10^{0}C increase
4. % I_S= 7% per ^{0}C

Long & Short Questions

Q.1. Explain what is meant by mobility of charge carrier in a solid. Derive an expression for the conductivity of semiconductor containing both electrons & holes in terms concentration and mobilities of charge carriers.

Related Short Answer Questions

(i) Define mobility of charge carriers in a semiconductor [Kanpur 1993,2000]

(ii) What do you mean by diffusion & diffusion current ? [Kanpur 1995]

Mobility : This is a property of conductor defined as the ratio of drift velocity to applied electric field in a conductor denoted by μ. Let us assume that when unit electric field is applied across the piece of metal causing drift velocity of v meter /sec, since drift velocity is directly proportional to electric field , we have

$$\boldsymbol{v}\ \alpha\ E \implies v = \mu E$$

$$\therefore \quad \mu = \frac{v}{E}$$

$$\therefore \text{ unit of } \mu \text{ would be } \frac{metere^2}{volt-sec}$$

Conductivity : It is measure of the ease at which an current flows through the conductor. It is also defined as the inverse of resistivity denoted by σ:

$$\sigma = \frac{1}{\rho} \qquad (\rho\text{= resistivity})$$

$\therefore$ unit of σ is Siemens / meter

Also J= $\sigma E \implies \sigma = \frac{J}{E} = \frac{ne\mu}{E}$ (J= current density, n=no. of free electrons, e=electronic charge, E= electric field)

$$\therefore\ \sigma = \frac{J}{E} = \frac{1}{\rho}$$

In semiconductors, there are two types of charge carriers (electrons & holes) , therefore the conductivity of semiconductor due to conductivity of electrons(σ_e) & conductivity of holes(σ_h).

$$\sigma_e = \frac{J_e}{E} = \frac{nev_e}{E} = ne\mu_e$$

$$\sigma_h = \frac{J_h}{E} = \frac{pev_h}{E} = pe\mu_h$$

Total conductivity of a semiconductor

$\sigma = \sigma_e + \sigma_h = ne\mu_e + pe\mu_h$ (for intrinsic semiconductor $n = p = n_i$)

$\sigma_i = en_i(\mu_e + \mu_h)$.

Q.2. What are majority and minority charge carriers in n-type & p- type semiconductor ? Explain with diagram . What is doping ?

Minority & Majority Carriers

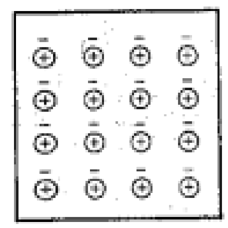


Fig.1 n-type semiconductors

- In n-type semiconductor there is excessive free electrons so the majority carriers are electrons & holes are minority carriers where as in p-type semiconductor there is excess of holes therefore majority carriers are holes & electrons are minority carriers.
- For intrinsic semiconductor no. of electrons is same as the no. of holes , therefore , there is no minority & majority carriers

Doping

- Doping is the process of control addition of impurity in pure semi conductor , due to which conducting properties of semiconductor changes. The doped semiconductor is known as Extrinsic semiconductor .
- The impurities may be of two types

  1. Donor impurity 2. Acceptor impurity

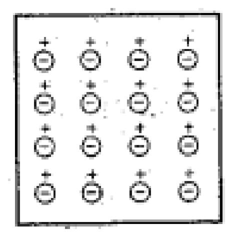


Fig. 2 p-type semiconductors

- Donor impurity(pentavalent atom) is used to manufacture n-type extrinsic-semiconductor.
- Acceptor impurity (trivalent atom) is used to manufacture p-type extrinsic- semiconductor.
- We visualized the pentavalent atoms and free electrons n- type semiconductors as shown in fig.1 . Each circled plus sign represents a pentavalent atom, and each minus sign is the free electron
- Similarly we visualized the trivalent atoms and free holes p- type semiconductors as shown in fig. Each circled plus sign represents a trivalent atom, and each plus sign is the hole.

Q.3. **Derive expression for the densities of free electrons and holes in an instrinsic semiconductor. Show that the Fermi level lies half way between the conduction and valence bands.**

Related Short Answer Questions		
(i)	Define and explain 'Fermi Level'	[Kanpur 2010]
(ii)	Define law of mass action	

- In an intrinsic semiconductor , concentration of free electrons and holes is equal. Theoretical analysis reveals that under thermal equilibrium the product of concentration of free electrons and holes is constant. This is known as **law of mass action.**

$$np = n_i^2$$

Where n_i is the intrinsic concentration and is the function of temperature. For an intrinsic semiconductor $n = p = n_i$

Fermi level

- Fermi level is simply a reference energy level. It is the energy level at which probability of finding electron n energy units above it in the conduction band is equal to probability of finding a hole n energy units below it in valence band.
- Let at any temp. T^0 K , no. of electrons in the conduction band be n_C, no. of electrons in the valence band be n_V and total no. of electrons in both band, $n = n_C + n_V$
- No. of electrons in conduction band, $n_C = nP(E_G)$

Where $P(E_G)$ represents the probability of an electron having energy E_G. Its value may be determined from Fermi-Dirac probability distribution function given as

$$P(E) = \frac{1}{1 + e^{\frac{E_G - E_F}{KT}}}$$

$P(E)$ is the probability of finding an electron having any particular value of energy E.

- The probability $P(0)$ of an electron being found in the valence band with zero energy is

$$P(0) = \frac{1}{1 + e^{\frac{0 - E_F}{KT}}} = \frac{1}{1 + e^{\frac{-E_F}{KT}}}$$

So $$n_V = \frac{1}{1 + e^{\frac{-E_F}{KT}}}$$

Similarly $$n_C = \frac{n}{1 + e^{\frac{E_G - E_F}{KT}}}$$

Now, total no. of electrons in both the bands,

$$n = n_C + n_V = \frac{n}{1 + e^{\frac{E_G - E_F}{KT}}} + \frac{1}{1 + e^{\frac{-E_F}{KT}}} \quad \{\text{if n=1}\}$$

$$\Rightarrow \qquad 1 - \frac{1}{1+ e^{\frac{-E_F}{KT}}} = \frac{1}{1+ e^{\frac{E_G - E_F}{KT}}}$$

$$\Rightarrow \qquad E_F = \frac{1}{2} E_G$$

Q. 4. Describe diffusion of carriers in semiconductor.

- The movement of charge carriers from the region of high carrier concentration to the areas of low concentration, recombination of charge carriers occurs, the process is known as diffusion of carriers.
- The rate at which diffusion occurs depends on the velocity at which carriers move and on the distance between the carriers.
- This diffusion current is proportional to the concentration gradient :

$$J_{nd} = q.D_n.\frac{\partial n}{\partial x}$$
$$J_{pd} = - q.D_p.\frac{\partial p}{\partial x}$$

Where D_n and D_p are the diffusion constant of p and n- type semiconductor.

- Generally free electrons moves in conduction band & holes in valence band , valence band is more effected by electrostatic force so , we say mobility(it is the ease with which charge carriers flow) of electrons is higher then that of holes .

- The mobility of electron being higher than that of holes, the Einstein relationship shows that, for a given concentration gradient, the diffusion current for electrons is higher than the diffusion current for holes.

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q}$$

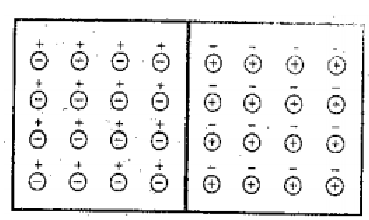
Q.5 What is p-n junction diode? How does a barrier field appear across a p-n junction ?

Or

Explain the pn junction at no bias

Related Short Answer Questions
(i) Explain the term diode .

Junction Diode



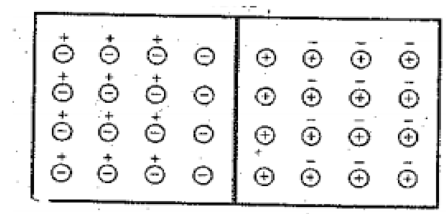
- The border b/w p-type and n-type semiconductor is called p-n junction, which has led to different inventions including diodes, transistors and integrated circuits.

- We visualized the pentavalent atoms and free electrons n- type semiconductors as shown on the right side of fig. . Each circled plus sign represents a pentavalent atom, and each minus sign is the free electron it contributes to the semiconductor .
- A manufacturer can produce a single crystal with p-type material on one side and n-type on the other side ,the region where these materials meet known as junction diode.

Barrier Potential

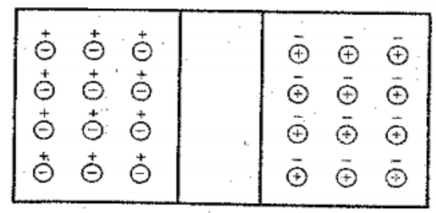
- The free electrons on n side tend to diffuse across the junction , when free electrons enters the p region, it recombines with hole, and due to which hole disappears and free electron becomes valence electron.
- Each time an electron diffuses across a junction , it creates a pair of ions , +ve ion on n side and -ve ion on p side, these pair of ions at junction is called a dipole. As no. of dipoles builds up, empty charge region is created know as depletion region.
- Each dipole has electric field b/w the +ve & -ve ions. Therefore , if additional free electrons enters the depletion region, the electric field tries to push these electrons back into the n region. The electric field b/w the ions is equivalent to difference of potential called the barrier potential.

Two types of semiconductors



Creation of ions at junction

Depletion layer

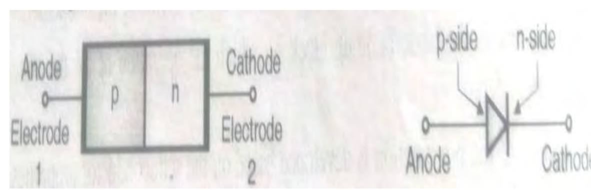


The pn junction

Diode

- The pn- junction itself forms the most basic semiconductor device called semiconductor diode. Thus semiconductor diode and pn junction are one and the same.
- The meaning of the term “diode” is the device having “two electrodes” (di-ode).
- As shown in fig., the diode has two electrodes one each for the two regions on each side of the junction.
- The two electrodes named as anode and cathode

The current will flow through the diode, if and only if an external voltage source is connected to it with appropriate polarities.



Q.6 **Explain with suitable diagrams, why the energy levels of an atom becomes energy band in solids and hence explain the behavior of conductors, semiconductors and insulators.**

or **[Kanpur 1992]**

What do you mean by energy band ? Distinguish clearly between a metal, semiconductors and insulator on the basis of energy bands in solids. **[Kanpur 1994,97]**

or

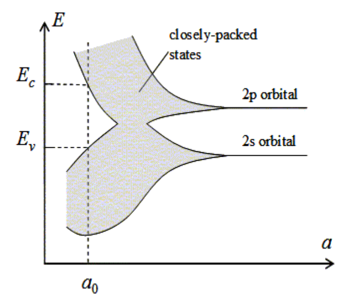
Why the energy levels of an atom become energy band in solids and hence explain the distinction between solid conductors, semiconductors and insulators. **[Kanpur 1995, 2002]**

Or

What do you mean by energy band in solids ? How are they formed ? How can you make a distinction between metal, insulators and semiconductor on the basis of these bands.

Related Short Answer Questions

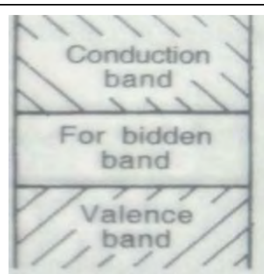
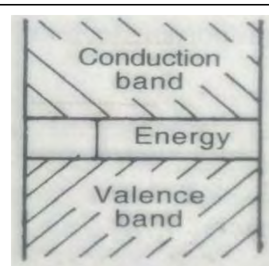
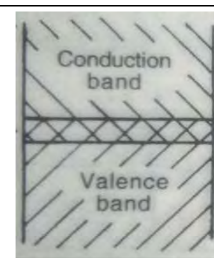
(i) Distinguish metals, insulators and semiconductors [Kanpur 2004]
(ii) Explain conduction and valance band [Kanpur 2009]



Distance b/w atoms

- In an isolated atom electrons are restricted to sets of discrete energy levels, with large gaps among them where no energy state is available for the electron to occupy.
- When these isolated atoms are brought together (interatomic spacing) to form a solid, various interactions (attraction and repulsion) occur between atoms, due to which same energy level has distinct value in different atom i.e. a same energy level has a band of energy.
- As interatomic spacing is decreased as shown in the fig., the energy band formed ,splits into two band separated by energy gap, known as forbidden gap.
- The higher energy band (upper band) is known as conduction band and the lower ener called valence band.

Conductor , Semiconductor & Insulators

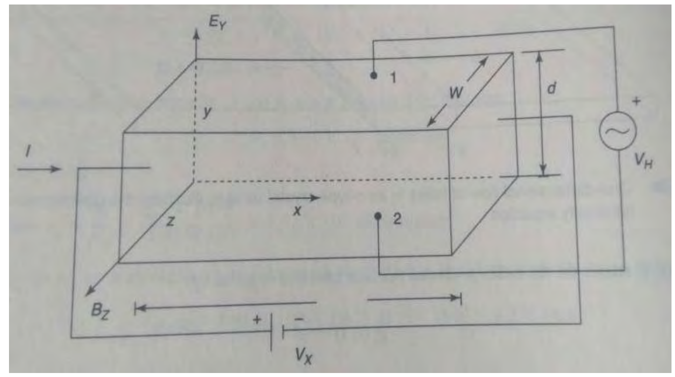
Characteristics	**Insulator**	**Semiconductor**	**Conductor**
Conductivity	Low	Moderate	Vary High
Resistivity	Vary High	Moderate	Vary Low
Electrons availability	small	moderate	large
Energy band diagram			
Temperature coefficient	Negative	Negative	Positive
Forbidden gap	Large	Small	No gap
Examples	Paper, Mica, glass	Silicon, Germinium	Matels, Aluminium, Copper

Q.7. What is hall effect ? Obtain expression for hall coefficient and hall voltage and describe method for its determination.

Related Short Answer Questions

(i) Define Hall co-efficient.
(ii) Why is Hall Potential developed ?

When a semiconductor sample carrying a current *I* is placed in a transverse magnetic field *B*, then an electric field E_0 is induced in the specimen , in the direction perpendicular to both *B* and *I* , this phenomenon is called the **HALL effect.**



- Hall effect may be used for determining whether a semiconductor is *n*-type or *p*-type .If a current *I* is applied in the +ve x-direction and magnetic field in +ve z-direction, a force will be exerted in the –ve y-direction of the current carriers.
- The current is carried by electron from side 1 to side 2, if the semiconductor is *n*-type. Therefore Hall voltage appers between surfaces 1 & 2 . The electric field developed in *y*-direction E_y is given by :

$$\frac{\mathrm{V_H}}{d} = \mathrm{E_y}$$

Where , d is the distance between surfaces 1 & 2 . In the equilibrium state the electric field $\mathrm{E_y}$ due to the Hall effect must exert force on the carrier, which just balances the magnetic force i.e.

$$\mathrm{eE_y} = \mathrm{Bev_0}$$

where e is magnitude of charge of carriers , $\mathrm{v_0}$ is the drift velocity.
Current density *J* is given by :

$$J = \rho \mathrm{v_0} = \frac{\mathrm{I}}{Wd}$$

Where , ρ is the charge density & w is the width of the specimen in the direction of the magnetic field. Combing all the above relations, we have

$$V_H = E_y d = B v_0\ d = BJd/\rho = BI/\rho W$$

If the polarity of V_H is +ve at terminal 1 then the carrier must be an electron and $\rho = n_0 e$ where $\mathrm{n_0}$ is the electron concentration . If the terminal 2 becomes positively charged w.r.t. terminal 1 the semiconductor must be of p-type and $\rho = P_0 e$, where P_0 is the hole concentration:

$$R_H = \frac{l}{\rho}$$

Where R_H is the Hall coefficient.

$$R_H = \frac{\mathrm{V_H\ w}}{BI}$$

Conductivity σ is related to p mobility μ by : $\sigma = n_0 e\mu$

$$\sigma = \rho_0 \mu \qquad \Longrightarrow \frac{1}{\rho_0} = \frac{\mu}{\sigma}$$

$$\text{where, } \rho = n_0 e$$

If the conductivity is measured with Hall coefficient, mobility μ can be determined by :

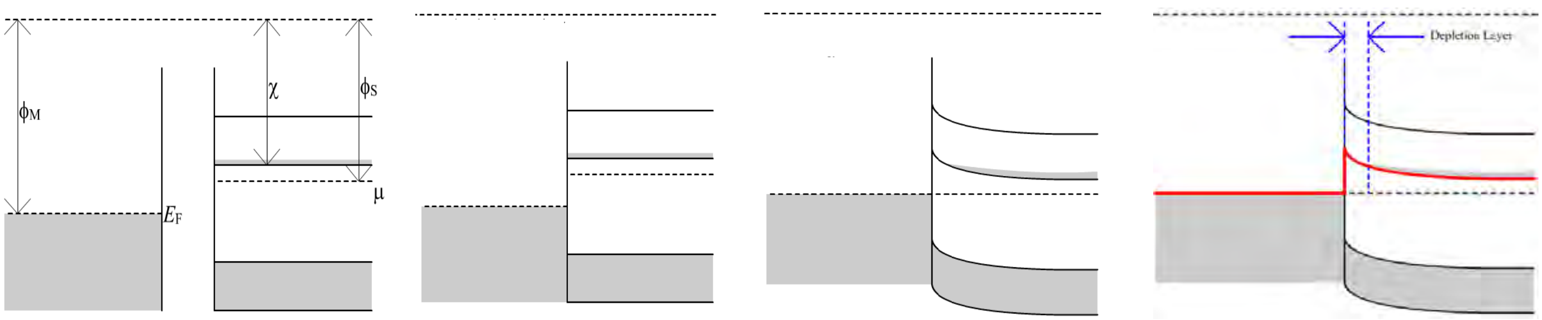
$$\because \quad J = \sigma E = \rho\mu E$$
$$\therefore \quad \frac{1}{\rho} = \frac{\mu}{\sigma} = R_H$$
$$\therefore \quad \mu = \sigma R_H$$

In the presence of scattering the mobility can be approximately be written as :

$$\mu = \frac{8\sigma}{3\pi} R_H$$

Q.8 Explain work function in metals and semiconductor junction.

- Energy required for an electron to move from Fermi level into the free space known as work function .
- The schematic below in fig. a shows a metal and an *n*-type semiconductor. The dashed line at the top represents the zero of energy of free space.
- In fig. a, the work functions of metal & semi conductor denoted by Φ_M & Φ_S resp., E_F & μ indicates the fermi level of metal & semi conductor resp, χ i.e. electron effinity.

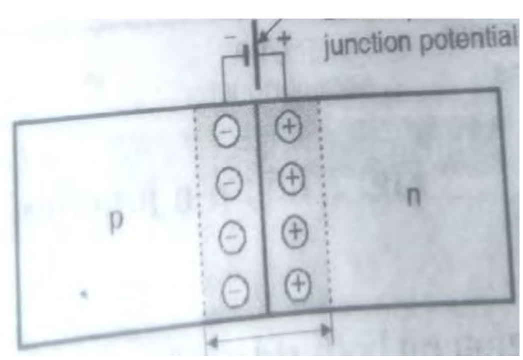


(a) (b) (c) (d)

- When contact is made as shown in fig. b, electrons lower their energy by flowing from the semiconductor conduction band into the metal.
- This continues until the fermi energy level in the semiconductor as shown in fig. c reaches equilibrium with the fermi energy of the metal.
- The deformed band structure shown in fig. d known as depletion layer forms a potential barrier.

Q.9 Explain junction potential width of depletion layer.

- Width of depletion layer is the distance measured from one side to the other side of the depletion region.



- Due to the presence of depletion region the electrons and holes do not i.e. depletion region acts as a barrier.
- Due to the presence of immobile +ve (n-side) and –ve(p-side) ions on opposite sides of the junction an electric field is created across the junction . This electric field is known as junction potential.
- Also known as barrier potential , as it act as a barrier to oppose the flow of electrons and holes across the junction.
- Barrier potential is measured in volts. The barrier

potential for silicon is 0.7 volt whereas for germanium is 0.3 volt at 25^0C.

- The built in potential V_{bi} at diode junction is

$$V_{bi} = \frac{\mathrm{KT}}{q} \ln \left(\frac{\mathrm{N_A}\,\mathrm{N_D}}{\mathrm{N_i^2}}\right)$$

where $\mathrm{N_A}$ = Acceptor [ ], $\mathrm{N_D}$ = Donor [ ] , $\mathrm{N_i}$ = instrinsic [ ] , K= Boltzmann constant

- The width d of depletion region is

$$d = \sqrt{\frac{2\xi_0}{q}} \left(\frac{1}{\mathrm{N_A}} + \frac{1}{\mathrm{N_D}}\right) V_{bi}$$

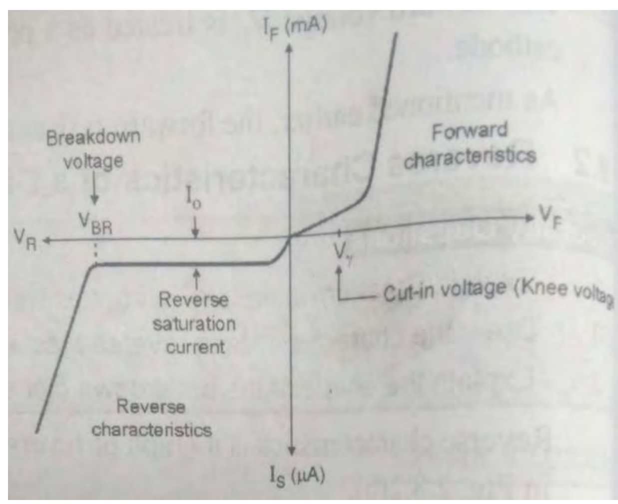
Q.10 Draw & explain the characteristic curve of P-N Junction diode

Or

Explain the effect of temperature on the reverse saturation current in a junction diode.

The V-I characteristics of p-n junction diode is a graph of voltage across the diode versus the current flowing through it . The V-I characteristics can be dived into two parts i.e. forward & reverse characteristics. The right side & left side of graph is forward & reverse characteristics respectively.

Forward characteristics



- When the external voltage is applied on germanium (Ge)/silicon (Si)diode, is less then 0.3/0.7 volts , the Ge/Si diode allows negligible current to flow through it know as cut in voltage & the Cut off region of V-I characteristics.
- When the external voltage is applied on germanium (Ge)/silicon (Si)diode, is more above cut in voltage, current through the diode increases suddenly.
- The voltage at which the forward diode current increases rapidly is known as cut in voltage or Knee voltage. Knee voltage for Ge is 0.3V & for Si is 0.7V.
- The Forward characteristics of Si diode shifts to the left at a rate of 2.5mV per ^{0}C increase in temperature.

Reverse characteristics

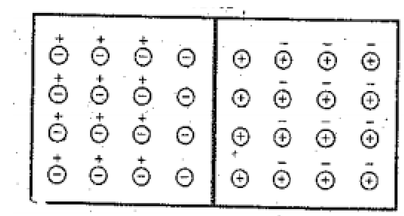
- Current flowing through a diode in the reverse biased state is known as reverse saturation current.

- As the reverse voltage is increased but below breakdown voltage(V_{BR}) , the reverse saturation current remains constant, if the temperature is constant . However when the reverse voltage is above (V_{BR}) , the large current flows
- The reverse saturation current in Si increases 100 % for each 10^0C rise in temperature i.e. approximately equal to 7 % for each ^{0}C rise in temperature.

Q.11 Discuss the meaning of potential barrier &Junction capacitance of a P-N junction diode

or

Explain field and capacitance of depletion layer.

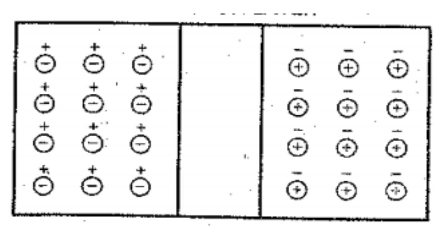


Creation of ions at junction

Barrier Potential

- The free electrons on n side tend to diffuse across the junction , when free electrons enters the p region, it recombines with hole, and due to which hole disappears and free electron becomes valence electron.
- Each time an electron diffuses across a junction , it creates a pair of ions , +ve ion on n side and -ve ion on p side, these pair of ions at junction is called a dipole. As no. of dipoles builds up, empty charge region is created know as depletion region.
- Each dipole has electric field b/w the +ve & -ve ions. Therefore , if additional free electrons enters the depletion region, the electric field tries to push these electrons back into the n region. The electric field b/w the ions is equivalent to difference of potential called the barrier potential.

Depletion layer



The pn junction

The two types of capacitances associated with a p-n junction diode are

1. Transition capacitance (C_T)
2. Diffusion capacitance (C_D)

- The **transient capacitance** C_T referred to as space charge capacitance or barrier capacitance or depletion region capacitance.
- C_T is not constant, depends on the magnitude of reverse voltage.
- The value of C_T is inversely proportional to the width of depletion region and the width of depletion region is directly proportional the reverse voltage.
- When the p-n junction diode is forward biased, a capacitance which is much larger then the transient capacitance is known as **diffusion capacitance** (C_D) or storage capacitance.
- The diffusion capacitance (C_D) is given by ,

$$C_D = \frac{dQ}{dV} = \frac{dI(V)}{dV} T_F \text{ , where } T_F = transist\ time$$

Q.12 Explain how you will determine the static & dynamic resistance of p-n junction.

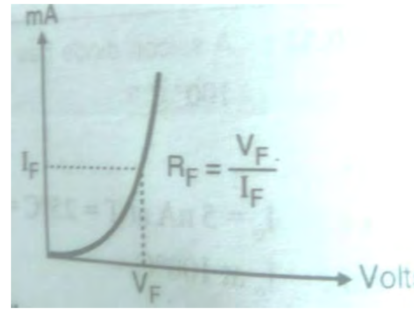
Or

Differentiate between static & dynamic resistance of a diode.

Or

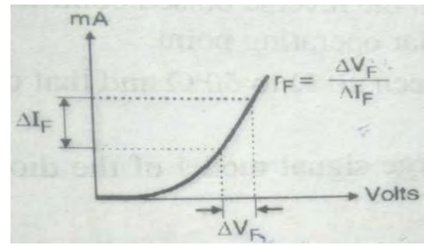
Discuss A.C. and D.C. resistance of junction

two types of resistance associated with a p-n junction diode are



1. DC resistance
2. AC resistance

- The resitance offered by the diode to the DC operating conditions is called as "DC resistance or Static resistance " denoted by R_F
- The DC resitance of a diode at operating point can be obtained by tacking the ratio of V_F & C_D



- The resistance offered by the diode to the AC operating conditions is called as "AC resistance or Dynamic resistance" denoted by r_F.
- AC resistance is actually the reciprocal of the slope of the forward characteristics .

$$r_F = \frac{1}{Slope\ of\ the\ characteristics}$$

Q.13. Discuss the different types of junction breakdown that can occur in a reverse biased diode.

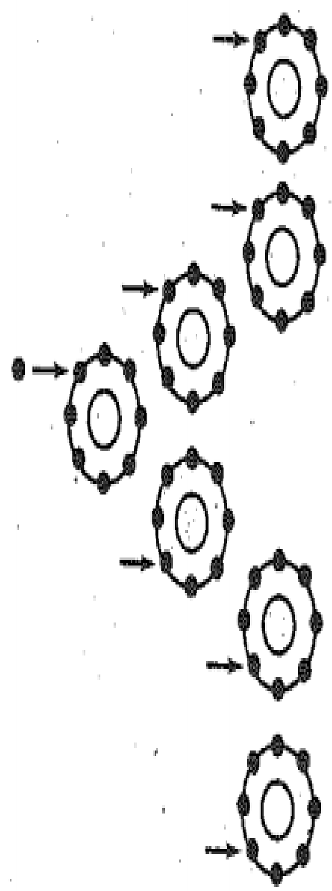
Or

What do you mean by Zener & Avalanche breakdown in the barrier layer of a semiconductor ?

Or

Explain the two breakdown mechanisms of a reverse bias diode.

- The maximum reverse bais voltage that can be applied to a p-n diode is known as **reverse breakdown voltage**.
- The breakdown in a reverse biased diode can take place due to following effects :
  1. Avalenche effect
  2. Zener effect



- Once the breakdown voltage is reached , a large number of the minority carrier suddenly appears in a depletion layer and the diode conducts heavily.
- Due to large reverse voltage the velocity of the minority carrier will increase & hence kinetic energy associated with them will also increase.
- While travelling, these high kinetic energy carriers will collide with the stationary atoms and impart some kinetic energy to the valence electrons present in the covalent bonds.
- Due to additionally acquired energy, these valence electrons collide with further atoms bounded with covalent bonds, generating more free electrons.
- The process continues in the geometric fashion , until the reverse current becomes huge.
- The breakdown voltage of a diode depends on how heavily doped the diode is. Normal diodes has breakdown usually greater than 50V.
- The Zener breakdown occurs in high doping diodes, where as avalanche breakdown occurs at low doping diodes.
- The Zener breakdown voltage is lesser then Avelanche breakdown voltage.
- Doping $\uparrow$ Breakdown voltage $\downarrow$

Doping $\downarrow$ Breakdown voltage $\uparrow$

- If the breakdown occurs at -4v it is zener breakdown, but if the breakdown occurs above -6v it is avalanche breakdown , however if breakdown occurs between -4v to -6v , it may be avelance or zener breakdown.

Q.14 Define mobility of charge carriers in a semiconductor. Derive expressions for their drift conduction and diffusion conduction.

Or

What do you mean by diffusion & diffusion current ? Find an expression for the total electron current and hole current in a semiconductor.

Mobility : This is a property of conductor defined as the ratio of drift velocity to applied electric field in a conductor denoted by μ. Let us assume that when unit electric field is applied across the piece of metal causing drift velocity of v meter /sec, since drift velocity is directly proportional to electric field , we have

$$\boldsymbol{v} \,\alpha\, E \implies v = \mu E$$

$$\therefore \quad \mu = \frac{v}{E}$$

$\therefore$ unit of μ would be $\frac{metere^2}{volt-sec}$

The Current flowing through the semiconductor due to diffusion of carriers is known as **diffusion Conduction**, the diffusion current density is directily proportional to concentration gradient

$$J_n \;\alpha\; \frac{dn}{dx}. \implies J_n = qD_n \frac{dn}{dx}.$$

$$J_p \;\alpha\; \frac{dp}{dx}. \implies J_n = -qD_p \frac{dp}{dx}.$$

Where D_n & D_p are diffusion constants for n-type & p-type semiconductors

Einstein rel^n

$$D_n \;\alpha\; \mu_n$$

$$D_p \;\alpha\; \mu_p$$

$$\frac{D_n}{D_p} = \frac{\mu_n}{\mu_p} = V_T = \frac{KT}{q}$$

Current flowing through the semiconductor under the applied E-field called **Drift current**

$$J_n = qn\mu_n E$$

$$J_p = qn\mu_p E$$

Numerical

Q.1 Find the conductivity (σ) & resistivity (ρ) of an instrinsic semiconductor at temp. of 300^0K. It is given that n_i=2.5 x 10^{13}/cm^3, μ_n=3,800cm^2/sV, μ_p=1,800cm^2/sV , q= 1.6 x10^{-19} C.

Exp: As n_i=2.5 x 10^{13}/cm^3

μ_n=3,800cm^2/sV,

μ_p=1,800cm^2/sV ,

q= 1.6 x10^{-19} C

∵ Conductivity of instrinsic semiconductor (σ_i)= n_i e(μ_n + μ_p)

∴ σ_i = 2.5 x 10^{13} x1.6 x10^{-19} (3,800+ 1800) = 0.0224 S/cm Ans

∵ ρ_i= 1/ σ_i = 1/0.0224 = 44.64 Ω-cm Ans

Q.2. The instrinsic carrier concentration for silicon at room temperature (300^0K) is 1.5x 10^{10}/cm^3. If the mobility of electrons and holes are 1300cm^2/sV & 450cm^2/sV resp. what is the conductivity of silion at 300^0K ? If silicon is doped with 10^{18} boron atoms /cm^3, what is its conductivity ?

Exp: Given n_i=1.5x10^{10}/cm^3

μ_n=1300cm^2/sV,

μ_p=450cm^2/sV

∵ Conductivity of instrinsic semiconductor (σ_i)= n_i e(μ_n + μ_p)

∴ σ_i = 1.5x10^{10} x1.6 x10^{-19} (1300+ 450)=4.2 x 10^{-6}

∵ N_A= 10^{18} / cm^3

∴ Conductivity of a resulting P-type silicon semiconductor, σ_p =e N_A μ_p= 1.6 x10^{-19} x10^{18} x450

= 72S/cm Ans

Q.3. If germanium is doped with 2x 10^{21}atoms /m^3 atoms of aluminium then determine (i) Hole concentration (ii) concentration of free electrons (iii) conductivity at room temperature. Given μ_n=0.17 m/sec/v/m, E_g=0.7eV.

Exp: If we assume that all the acceptor atoms contributes to conduction then

Hole concentration = 2x 10^{21}atoms /m^3

The free electron density in intrinsic semiconductor

$n_i = N_C e^{-(E_c - E_f)/KT}$, where $N_C = 2(2\pi m_e kT/h^2)^{3/2}$

$= 2*\left(\frac{2*3.14*9.1x10^{-31}*1.38x10^{-23}*300}{6.6*10^{-34}}\right)^{\frac{3}{2}} e^{\frac{-0.7*1.6*10^{-19}}{2*1.38*10^{-23}}}$

$= 2.4x\ 10^{19}$ electron /cm^3

∴ The no. of free electrons $n = (n_i)^2/p = (2.4x\ 10^{19})^2/2x\ 10^{21} = 2.8\ x\ 10^{17}$

Conductivity $\sigma = ep\ \mu_n = 1.6\ x10^{-19} x\ 2x10^{21} x0.17 = 54.4$mhv.

Q.4. In an N-type semiconductor, the Fermi level lies 0.5 eV below the conduction band. If the concentration of doner atoms is tripled, find the new position of the fermi level, taking the value kT=0.3eV.

Exp: $E_C - E_F = 0.5eV$ at a given conc^n (let it be N_D)

New conc^n $(N'_d) = 3*\ N_D$

Let new fermi levl position be E'_f

We know that $n = n_d = N_e e^{\frac{E_f - E_C}{kT}}$

$$\frac{N'_d}{N_d} = \frac{e^{\frac{E'_f - E_C}{kT}}}{e^{\frac{E_f - E_C}{kT}}}$$

$\Longrightarrow$ $3 = \frac{e^{\frac{0.5}{kT}}}{e^{\frac{E_f - E_C}{kT}}}$ (taking ln both sides)

$\Longrightarrow$ $\ln 3 = \frac{0.5 + (E_f - E_c)}{0.03}$ (kT=0.03eV)

$\Longrightarrow$ $E_C = E_C - 0.5eV.\ \ln 3$ Ans

Q.5 A sample of intrinsic germanium at room temperature has a carrier concentration of 2.4 * $10^{19/}m^3$. It is doped with anitimony at a rate of one antimony atom / 10^8 atom of germanium atom. If the concentration of germanium atom is $4*10^{28}$ atoms/m^3, find the hole concentration and conductivity of the semiconductor. Mobility of electron $\mu_n = 0.35m^2$/V-sec.

Exp: Given $n_i = 2.4 * 10^{19}$, $N = 4*10^{28}$

$N_D/N = 1: 10^8$

∴ $N_D = 4*10^{28}/10^8 = 4*10^{22}$ doners/m^3

$n \sim N_D = 4*10^{22}$ electrons / m^3

∴ $p = n_i^2 / N_D = (4*10^{28})^2/4*10^{22} = 1.4 * 10^{16}$holes /$m^3$

Q.6. Calculate the conductivity & resistivity of a p-type Ge crystal which is mixed by acceptor atoms of concentration $2*10^{17}$atoms/ cm^3 & all acceptor atoms are active , given that μ_h=1900cm^2/volts-sec, e=1.6*10^{-19}coulomb [

Exp: Given $n_h = 2*10^{17}$atoms/ cm^3= $2*10^{23}$ atoms/m^3 ,

μ_h=1900cm^2/volts= 0.19 m^2/volts

$\because \sigma_p = e\, n_h * \mu_h$

$\therefore \sigma_p = 1.6*10^{-19}*2*10^{23}*0.19 = 6080$ mho /m

$\because \rho_p = 1/\sigma_p$

$\therefore \rho_p = 1/6080\ \Omega$-m

Q.7. A silicon bar is doped with donor impurities N_D = 2.25 x 10^{15} atoms / cm^3. Given the intrinsic carrier concentration of silicon at T = 300 K is n_i = 1.5 x 10^{10} cm^{-3}. Assuming complete impurity ionization, find the equilibrium electron and hole concentrations .

Exp: As per the given data

$N_D = 2.25 \times 10^{15}$ Atom / cm^3

$n_i = 1.5 \times 10^{10}$ / cm^3

Since complete ionization taken place,

$n_0 = N_D = 2.25 \times 10^{15}$ / cm^3

$\because P_0 \,.\, n_0 = n_i^2$

$\therefore P_0 = n_i^2/n_0 = (1.5 \times 10^{10})^2/2.25 \times 10^{15} = 1*10^5/cm^3$ Ans

Q.8 Assume electronic charge q = 1.6×10^{-19} C, kT/q = 25 mV and electron mobility μ_n = 1000 cm^2/V-s. If the concentration gradient of electrons injected into a P-type silicon sample is 1×10^{21}/cm^4, find the magnitude of electron diffusion current density (in A/cm^2) .

Exp: Given q = 1.6×10^{-19} C, kT/q = 25 mV, μ_n = 1000 cm^2/V-s.

From Einstin relation ,

$$\frac{D_n}{D_p} = \frac{\mu_n}{\mu_p} = V_T = \frac{KT}{q}$$

$$\Rightarrow D_n = 25mV * 1000cm^2/v - s = 25cm^2/s$$

Diffusion current Density $J = q\, D_n \frac{dn}{dx}$

$= 1.6 \times 10^{-19} \times 25 \times 1 \times 10^{21}$

$= 4000$ A / cm^2 Ans

Q.9 When a silicon diode having a doping concentration of $N_A = 9 \times 10^{16}$ cm^{-3} on p-side and $N_D = 1 \times 10^{16}$ cm^{-3} on n-side is reverse biased, the total depletion width is found to be 3 µm. Given that the permittivity of silicon is 1.04 × 10^{-12} F/cm, find the depletion width on the p-side and the maximum electric field in the depletion region.

Exp: Given $N_A = 9 \times 10^{16}$ / cm^3 ; $N_D = 1 \times 10^{16}$ / cm^3

Total depletion width, $x = x_n + x_p = 3$ µm.

$\in = 1.04 \times 10^{-12}$ F / cm

Since $\frac{X_n}{X_p} = \frac{N_A}{N_D}$= = $(9 \times 10^{16})/(1 \times 10^{16})$

$X_n = 9X_p$

$\because$ x= $x_n + x_p$=3 μm.

9 $x_p + x_p$ =3 μm.

$\therefore$ x_p = 0.3 μm

Max. Electric field, E= $qN_AN_D / \in = (1.6*10^{-19} * 9 \times 10^{16} * 1\times10^{16}) / (1.04 \times 10^{-12})$

$= 4.15 \times 10^5$ V / cm Ans

Q.10 A diode has a power rating of 5W. if the diode voltage is 1.2 V and the diode current is 17.5 A, what is the power dissipation ? will the diode be destroyed ?

Exp: $\because P_D = V_D I_D$

$\therefore P_D$= (1.2V)(1.75A)=2.1W

$\because P_D < 5W$ so the diode will not destroyed.

Q.11. Find the dynamic resistance of a P-N junction diode at a forward current of 2mA. Assume kT/q= 25mV.

Exp: Given , forward current = 2mA= 0.002A

Volt equivalent of temp. , V_T= **kT/q= 25mV**

$\because$ Dyamic resistance (r) = $\eta V_T/I$ (η=1)

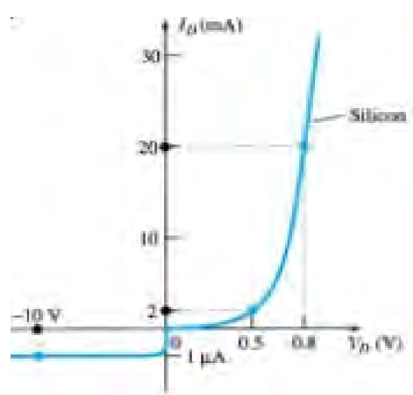
$\therefore$ r = 0.025/0.002= 12.5 Ω.

Q.12 Determine the dc reistance levels for the diode shown in fig. at

(a) $I_D = 2mA$

(b) $I_D = 20mA$

(c) $V_D = -10V$



Exp: (a) At $I_D = 2mA, V_D = 0.5\ v$(from the curve)

$\therefore$ $R_D = V_D/I_D$ =0.5v/2mA= 250 Ω

(b) At $I_D = 20mA, V_D = 0.8\ v$(from the curve)

$\therefore$ $R_D = V_D/I_D$ =0.8v/20mA = 40 Ω

(c) At $V_D = -10V, I_D = -1\mu A$ (from the curve)

$\therefore$ $R_D = V_D/I_D$ =-10v/- $1\mu A$ = 10 MΩ

Q.13 Assuming the barrier potential of 0.7V at an ambient temperature of 25^0C , What is the barrier potential of a silicon diode whwn the junction temperature is 100^0C ? At 0^0C ?

Exp: When the Junction temp. is 100^0C , the change in barrier potential is

ΔV= (-2.5mV/^{0}C) ΔT = (-2.5mV/^{0}C)(**100^0C - 25^0C**)= -187.5mV

$\therefore$ The barrier potential will decrese by 187.5mV

i.e. V_B= 0.7V – 0.18V = 0.52 V Ans

When the Junction temp. is 0^0C , the change in barrier potential is

$\Delta V = (-2.5mV/^0C)\ \Delta T = (-2.5mV/^0C)(\ \mathbf{0^0C - 25^0C}) = 62.5mV$

$\therefore$ The barrier potential will increase by 62.5mV

i.e. $V_B = 0.7V = 0.0625 = 0.7625$ V Ans

Q.14. A Silicon diode has a saturaration current of 5nA at 25^0C . What is the saturation current at 100^0C ?

Exp: The change in temp

$\therefore \Delta T = 100^0C - 25^0C = 75\ ^0C$

$\because$ there is seven doubling between 25^0C to 95 ^{0}C

$\therefore \quad I_S = (2^7)(5nA) = 640nA$

$\because$ there is 5 ^{0}C rise in temp from 95^0C to 100 ^{0}C

$\therefore \quad I_S = (1.07^5)(640nA) = 898nA$ Ans