



Semiconductor Physics

Syllabus

(Prerequisites : Intrinsic and extrinsic semiconductors, energy bands in conductors, semiconductors and insulators, semiconductor diode, I-V characteristics in forward and reverse bias)

Direct & indirect band gap semiconductor; Fermi level; Fermi-Dirac distribution; Fermi energy level in intrinsic & extrinsic semiconductors; effect of impurity concentration and temperature on Fermi level; mobility, current density; Hall effect; Fermi Level diagram for p-n junction (unbiased, forward bias, reverse bias);

Applications of semiconductors: LED, Zener diode and Photovoltaic cell

Learning Objectives

After reading this chapter, Learner should be able to :

- Understand direct and indirect band gap semiconductors
- Apply concept of Fermi level to intrinsic and extrinsic semiconductors
- Understand the effect of impurity concentration and temperature on Fermi level.
- Understand Hall effect and its applications
- Apply knowledge of semiconductors to LED, Zener diode, photovoltaic cell

3.1 Introduction

- Semiconductors have provided immense help in development of the present digital industry due to their unique characteristics especially electrical properties. Their large scale production has reduced cost like anything.
- In their purest form i.e. intrinsic for they are not so popular as the electrical properties are not that attractive but when it is doped with selected impurities in a very limited way, a drastic change is observed.
- In this chapter we will study the success path of semiconductors with necessary mathematics, the key points ranging from mobility to Hall effect and fundamental components like p-n junctions diodes.

3.2 Direct and Indirect Band Gap

- We have already seen classification of solids on the basis of value of forbidden energy band gap. We also know that semiconductors are broadly classified in terms of intrinsic and extrinsic semiconductors. Now we will learn about classification on the basis of recombination of electrons and holes.
- When energy $E = h\nu = E_g$ (forbidden gap) is applied to an electron-hole pair in valence band, an electron will be found in conduction band and there will be a corresponding hole in the valence band. Now electron will come back to valence band by releasing the energy which was used to send it to conduction band. This process is known as recombination. (Energy conservation takes place here.)



- When an electron (or hole) of mass m travels with velocity v , the momentum, $p = mv$.
- When electron is considered so small that it can exhibit wave nature as well, then quantum momentum

$$P = h k$$

Where h = Planck's constant

k = wave number (momentum)

$$\text{As } E = \frac{p^2}{2m}$$

$$= \frac{(hk)^2}{2m} = \frac{h^2}{2m} k^2$$

as h and m are constant.

$$E \propto k^2$$

i.e. It represents a parabola.

- The graph $E \rightarrow k$ which is of parabolic nature, is known an $E - k$ diagram. If we show $E - k$ diagram for conduction and valence band, it will be as shown in Fig. 3.2.1.

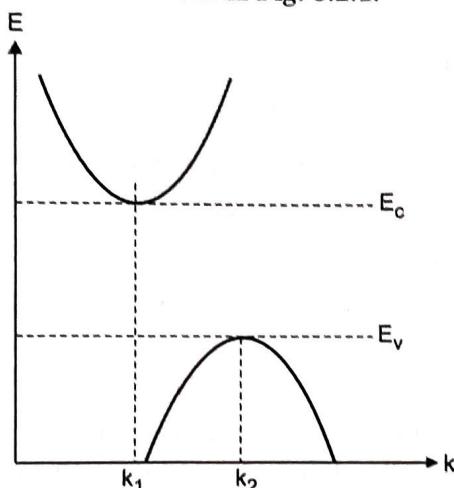


Fig. 3.2.1

- As electrons in conduction band and holes in the valence band possess different energies, they are bound to have different momentum as well ($\therefore E = \text{const } k^2$). Hence, we will have two different $E - k$ diagrams for conduction and valence bands.
- For recombination to take place, we must have momentum of hole (in valence band) and electron (in conduction band) to be equal. But as explained above, momentum of electrons and momentum of holes are different. We now have two options
 - (1) Momentum of electrons should be made equal to that of holes.
 - (2) Momentum of holes should be made equal to that of electrons
- Option number 2 is not possible as the mobility of holes is smaller than that of electrons.
- Hence, we will try to match momentum of electrons with holes.

- We consider trapped energy states available in particular semiconductors which act as agents for recombination. This means they try to hold electron for some time to make the hole recombine with it.
- Trapped energy states are as shown in Fig. 3.2.2.

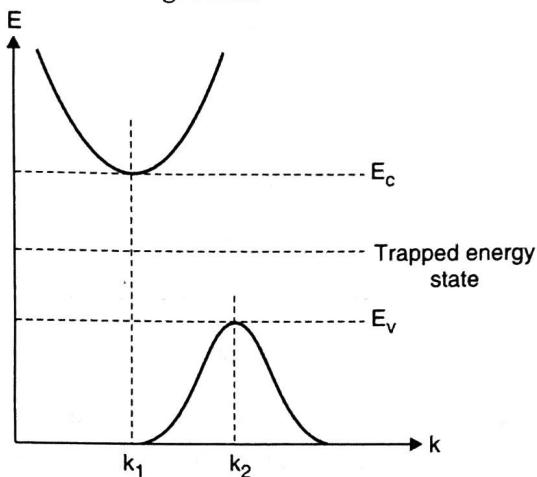


Fig. 3.2.2

- As it is clear from Fig. 3.2.2 that momentum for electron is k_1 and that for hole is k_2 (i.e. momentum are different). But in order to make momentum of the same value, a transition will take place as shown in Fig. 3.2.3.

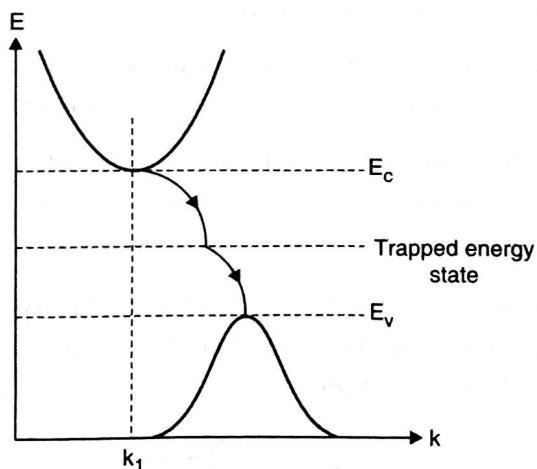


Fig. 3.2.3

i.e. the momentum becomes same not directly from conduction to valence band but indirectly through a trapped energy state available in forbidden gap.

- Such semiconductors are called indirect band gap semiconductors.
- Elemental semiconductors Si and Ge are of this type.
- Another possibility exists where the momentum of electron in conduction band and holes in valence band is the same.

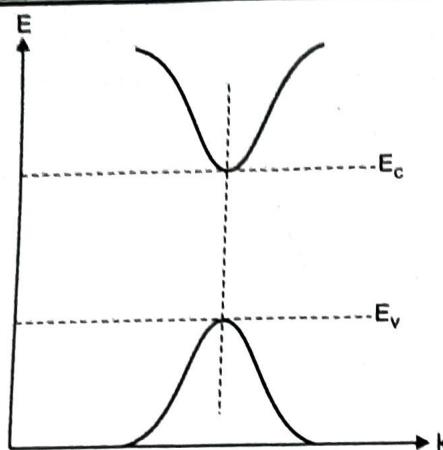


Fig. 3.2.4

- In such cases an electron can directly go to holes in the valence band for recombination. Such semiconductors are known as direct band gap semiconductors, for example GaAs.

3.3 Carrier Drift, Drift Velocity, Drift Current Mobility and Diffusion Current

MU - Dec. 13, May 15, May 16

Q. Define drift current, diffusion current and mobility of charge.

(Dec. 13, May 15, May 16, 3 Marks)

- When an electron (or a carrier) collides with the lattice, the direction to which it had confined its motion prior to the collision is abandoned and it starts moving in a different direction.
- Since this collision is a random process, the two directions do not have any interrelation. This is a kind of randomness in the motion of a conduction electron in the absence of an electric field.
- When an electric field is applied, though the randomness in its motion persists, there is overall shift in its position in the direction of the field with time. It means a net transportation of charge results in a current in the direction of the field.
- The net displacement in the electron's position per unit time caused by the application of an electric field becomes a constant at the steady state. The velocity of the electrons in the steady state in an applied electric field is called the **drift velocity**.

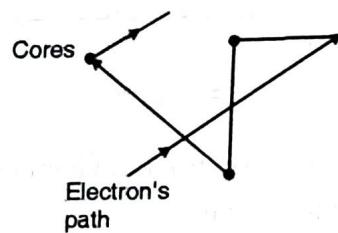


Fig. 3.3.1 : Electron random motion

- These velocities will not increase to large values because of electrical resistance due to thermal vibrations of ions (or atoms) at that temperature. For semiconductors, since we have electrons and holes, the drift velocities produce drift current in material.



Mobility of electrons

The mobility of electron is defined as the magnitude of the drift velocity acquired by the electrons in a unit field. Thus, if E is the applied electric field in which the electrons acquire a drift velocity v_d then the mobility of electrons μ is given by,

$$\mu = \frac{v_d}{E} \quad \dots(3.3.1)$$

The microscopic form of Ohm's law (Equation 3.3.1)

$$\begin{aligned} J &= \sigma E \\ \therefore \sigma &= \frac{J}{E} \quad \text{and} \quad J = \frac{I}{A} \\ \therefore \sigma &= \frac{I}{AE} \end{aligned}$$

Now current

$$\begin{aligned} I &= ne v_d A^* \\ \therefore \sigma &= \frac{nev_d A}{AE} = ne \mu_e \quad (\text{for electrons}) \\ \therefore \mu_n &= \frac{\sigma}{ne}, \quad \dots(3.3.2) \end{aligned}$$

for holes

$$\sigma_p = pe \mu_p$$

\therefore For semiconductor

$$\sigma = \sigma_n + \sigma_p$$

Typically mobility of electron = $1350 \text{ cm}^2/\text{V-s}$ and of hole is $480 \text{ cm}^2/\text{V-s}$

Mobility represents the ease with which the electrons could drift in a material under the influence of an electric field.

Mobility of electron is more than double that of holes, hence devices with electron as majority carriers are preferred.

$$\therefore I = ne v_d A$$

Diffusion current

Non-uniform concentration of charge carriers produces diffusion current. This kind of non-uniform concentration of charge carriers can be formed by thermal or radiation excitation of a part of the material or by injecting carriers into the material through surface.

*Expression of current I

Consider a conductor of uniform area of cross section A carrying current I . If v is the velocity of the electrons, then length traversed by the electron in unit time is v . Therefore in unit time they sweep the volume vA of the conductor. If n is the number of electrons/unit volume, then the number of electrons in volume vA = (nvA) . If e is the charge on each electron, then the quantity of charge crossing any section of conductor per second is $e(nvA)$. This also represents quantity of charge crossing any section per second or simply the current $\therefore I = e(nvA)$. The velocity acquired by the electron due to an applied electric field is drift velocity v_d .



- Whenever concentration of electrons or holes due to excitation is noticed, these excess carriers diffuse to less concentrated places.
- The rate of diffusion is proportional to concentration gradient and forms diffusion current.
- In semiconductor, total current is due to drift and diffusion currents.
- Electron motion in solid is a complex issue. Let us understand it by considering few terminologies.

1. Current density (J)
2. Electrical field (E)
3. Conductivity (σ)
4. Resistivity (ρ)

1. Current density (J)

- It is the current per unit area of cross section of an imaginary plane held normal to the direction of current in current carrying conductor.
- If I is the current and A is the area of cross-section, then the current density J is given by

$$J = \frac{I}{A} \quad \dots(3.3.3)$$

2. Electrical field (E)

- The potential drop per unit length of a conductor gives the electric field that exists across a homogeneous conductor.
- If L is the length of a conductor of uniform cross section and of uniform material composition, and V is the potential difference between its two ends, then the electric field E at any point inside is given by

$$E = \frac{V}{L} \quad \dots(3.3.4)$$

3. Conductivity (σ)

- It is the physical property that characterizes the conducting ability of a material.
- If R is the electrical resistance of uniform material of length L , and area of cross section A , then the electrical conductivity is given by

$$\sigma = \frac{1}{R} \left(\frac{L}{A} \right) \quad \dots(3.3.5)$$

Unit of conductivity is $(\text{ohm} - \text{m})^{-1}$

Now if we consider the product σE , then from equations (3.3.4) and (3.3.5) we get

$$\sigma E = \frac{V}{L} \frac{1}{R} \left(\frac{L}{A} \right) = \frac{V}{RA}$$

If we consider macroscopic form of Ohm's law we have

$$I = \frac{V}{R}$$

$$\therefore \sigma E = \frac{I}{A} = J$$

$$\therefore J = \sigma E \quad \dots(3.3.6)$$

This is known as **point form** or **microscopic form** of Ohm's law.



4. Resistivity (ρ)

Resistivity signifies the resistance property of the material and is given by the inverse of conductivity

$$\therefore \rho = \frac{1}{\sigma} \quad \dots(3.3.7)$$

Unit of resistivity is ohm-m.

3.3.1 Concept of Holes and Effective Mass

MU - May 14, Dec. 14

- Q.** Explain concept of hole in semiconductor. (May 14, 3 Marks)
- Q.** What is effective mass? Why is the effective mass of holes more than the effective mass of electrons? (Dec. 14, 4 Marks)

- An energy band which is completely filled carries no current. But if some of the electrons in a filled band are excited into a higher band, **the remaining electrons in it can contribute to the current**.
- The properties of a vacant state in an almost full band are exactly those of a particle with a positive charge in an otherwise empty band. This quasiparticle is known as a **hole**.
- Since a hole has positive charge, it moves in a direction opposite to that in which an electron moves when an external electrical field is applied. The motion of electrons in the valence band may be considered to be equivalent to the motion of the holes in the opposite direction.
- **The electric current in a semiconductor therefore consists of two components - one due to the motion of electrons in the Conduction Band (CB) and the other due to holes in the Valence Band (VB).**
- The quasiparticle which represents a vacancy needs detailed approach when we assign to it a status of particle and hence a mass.
- This mass is arrived at by band theory of solids. The motion of an electron in the solid subjected to an electric field is written as,

$$F = m_e a$$

- Provided a mass other than the rest mass m_e is used in this equation. **This mass is called the effective mass and it is denoted by m_e^*** . In order to remove the concept of negative mass in band theory, electron was withdrawn from band theory and it was replaced by a particle of positive effective mass.
- In CB energy levels are vacant. Hence electron can move freely. Whereas in VB energy levels are filled, hence holes cannot move freely. This shows effective mass of holes in VB is more than electrons in CB.
- Direct evidence of the existence of holes was furnished by the Hall effect experiment discussed later in this chapter Section 3.10.

3.4 Fermi-Dirac Statistics

MU - May 14, May 17

- Q.** What is Fermi level? Write Fermi-Dirac distribution function. (May 14, 3 Marks)
- Q.** With the help of diagram, explain the variation of Fermi level with temperature in n-type semiconductor. (May 17, 5 Marks)



"Overall behavior of a system of many particles is related to the properties of the particles themselves".

- As it is seen in formation of bands, it is now clear that there are a large number of energy levels available for occupation by large number of electrons. The branch of physics dealing with this area is called "statistical mechanics".
- It is not concerned with the actual motions or interactions of individual particles but with what is most likely to happen.
- While statistical mechanics cannot help us find the life history of one of the particles in a system, it is able to tell us for instance, the probability that a particle has a certain amount of energy at a certain moment.

Table 3.4.1 : Three statistical distribution functions

	Maxwell Boltzmann	Bose-Einstein	Fermi-Dirac
Applies to system of	Identical distinguishable particles	Identical indistinguishable particles	Identical indistinguishable particles
Applies to	Classical particles	Bosons	Fermions
Example	Molecules of a gas	Phonons in a solid	Free electrons in a metal.

- We will concentrate only on Fermi-Dirac statistics.
- According to Fermi-Dirac statistics, we make use of function $f(E)$ which determines the carrier occupancy of the energy. In other words, $f(E)$ governs the distribution of electrons among the energy levels as a function of temperature. It is given by

$$f(E) = \frac{1}{1 + \exp(E - E_F)/KT} \quad \dots(3.4.1)$$

Where, $f(E)$ = Probability that a particular energy

level E is occupied by an electron.

E_F = Fermi energy

K = Boltzmann constant

T = Temperature in Kelvin

3.5 Fermi Energy or Fermi Level

MU - May 12, Dec. 13, May 14

Q. What is Fermi level in semiconductor?

(May 12, Dec. 13, 5 Marks)

Q. What is Fermi level? Write Fermi-Dirac distribution function.

(May 14, 3 Marks)

- When the filling up of electrons is undertaken, the universal rule is that the lowest energy level gets filled first.
- However, there will be many more allowed energy levels left vacant as shown in Fig. 3.5.1.

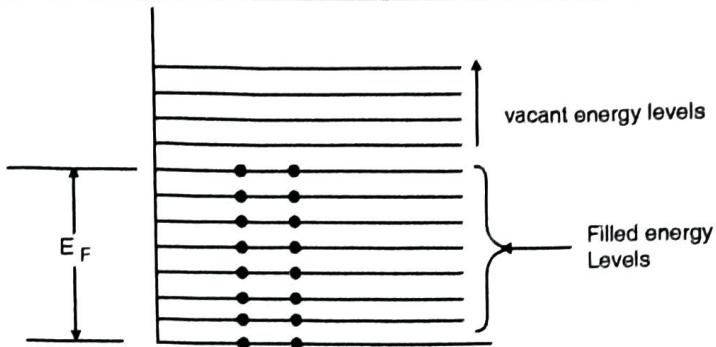


Fig. 3.5.1 : Fermi energy

- Here we define Fermi energy or Fermi level as -

The energy of the highest occupied level at zero degree absolute is called the Fermi energy, and the level is referred to as the Fermi level E_F .

- All the energy levels above the Fermi level at $T = 0^\circ K$ are empty and those lying below are completely filled. E_F may or may not be an allowed state. It provides a reference with which other energy levels can be compared.

3.5.1 Fermi Level in Conductor

MU - Dec. 13, Dec. 15

Q. What is Fermi level in semiconductor?

(Dec. 13, Dec. 15, 5 Marks)

As mentioned in classification the conductors have many free electrons. Let us see how Fermi function helps us understand their distribution.

(a) At $T = 0^\circ K$

- At $0^\circ K$ electrons occupy the lower energy levels in the conduction band leaving upper energy levels vacant.
- The band is filled up to a certain energy level E_F , therefore Fermi level may be regarded as the uppermost filled energy level in conductor at $0^\circ K$. Let us see some important conclusions from Equation (3.4.1).

At $T = 0^\circ K$, levels below E_F have $E < E_F$

$$\begin{aligned}\therefore f(E) &= \frac{1}{1 + e^{(E - E_F)/KT}} \\ &= \frac{1}{1 + e^{-\infty}} \\ &= \frac{1}{1 + 0} = 1\end{aligned}$$

$f(E) = 1$ means all the levels below E_F
are occupied by electrons.

At $T = 0^\circ K$, levels above E_F have $E > E_F$



$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}} = \frac{1}{1 + e^{\infty}}$$

$$= \frac{1}{1 + \infty} = 0$$

$\therefore f(E) = 0$ means all the levels above E_F are vacant.

At $T = 0^\circ K$, for $E = E_F$

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}} = \frac{1}{1 + e^0}$$

$\therefore f(E)$ is indeterminable.

This is summarized in Fig. 3.5.2.

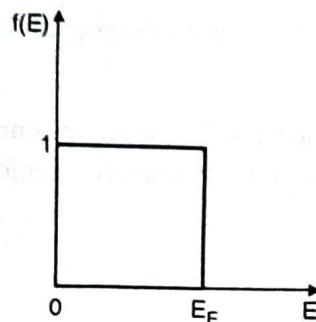


Fig. 3.5.2 : Fermi-Dirac distribution at $T = 0^\circ K$

(b) At $T > 0^\circ K$

- At temperature above $0^\circ K$, few electrons are excited to vacant levels above E_F . This happens to those electrons which are close to E_F hence probability to find an electron at $E > E_F$ will become greater than unity which was zero at $T = 0^\circ K$.
- Similarly, due to excitation of electrons, few levels just below E_F will become vacant and $f(E)$ will be slightly reduced which was unity at $T = 0^\circ K$.
- In a simple way one can understand that, what increase in $f(E)$ at $T > 0^\circ K$ above $E = E_F$ we get is equal to reduction in $f(E)$ below $E = E_F$. This is shown as below in Fig. 3.5.3.

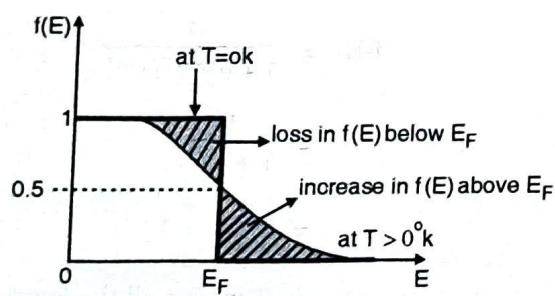


Fig. 3.5.3 : Electron occupancy at $T > 0^\circ K$

At $E = E_F$ for $T > 0^\circ K$

$$f(E) = \frac{1}{1 + e^0} = \frac{1}{1 + 1} = \frac{1}{2} = 0.5$$

3.5.2 Fermi Level In Semiconductor

- Once the concept of Fermi level is understood properly by considering conductors, it is proper to go to semiconductors.
- A semiconductor has conduction band and valence band separated by a small energy gap.
- At normal temperature, a significant number of electrons are excited to conduction band (CB) and from Valence band (VB) leaving behind same number of holes.
- Therefore $f(E)$ has non-zero probability above Fermi level and $f(E)$ reduces by same amount below E_F as shown in Fig. 3.5.4.

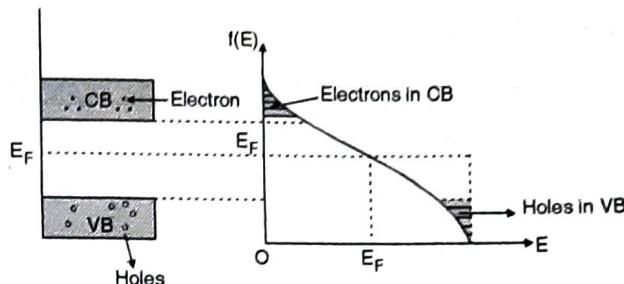


Fig. 3.5.4 : Fermi-Dirac distribution of semi conductor at $T > 0^\circ \text{K}$

Fermi level is halfway between CB and VB if it is intrinsic.

3.6 Intrinsic Semiconductors

- Pure semiconductors are called intrinsic semiconductors. In intrinsic semiconductors.

$$n_e = n_h = n_i \quad \dots(3.6.1)$$

where n_e = Number of electron per unit volume or electron density

n_h = Hole density

n_i = Intrinsic carrier concentration

Here n_e is given by

$$n_e = N \exp(-E_g / 2KT) \quad \dots(3.6.2)$$

where N = Possible states per unit volume

E_g = Forbidden energy gap

K = Boltzmann constant

- When thermal energy is applied, a few electrons from valence band jump into conduction band by leaving hole in valence band. That is the reason $n_h = n_e$.
- These electrons will move freely when electric field is applied. The motion of holes is imagined in the direction which is opposite to that of electron.
- The conduction in intrinsic semiconductor is due to thermally excited electrons and holes, so it is very small.



- The conductivity in intrinsic semiconductor is given by,

$$\sigma_{in} = n_e e \cdot \mu_e + n_h e \mu_h \quad \dots(3.6.3)$$

Where

n_e = Number of electrons

n_h = Number of holes

e = Charge of electron

μ_e = Mobility of electrons

μ_h = Mobility of holes

3.6.1 Fermi Level in Intrinsic Semiconductors

MU - Dec. 12, May 13, Dec. 13, Dec 14, May 15, Dec. 15, May 17, Dec. 17, May 19

- Q.** For an intrinsic semiconductor show that the Fermi level lies in the centre of the forbidden energy gap.
(Dec. 12, Dec. 15, 5 Marks, Dec. 17, 4 Marks, May 19, 3 Marks)
- Q.** Derive an expression for Fermi level for an intrinsic semiconductor. (May 13, 8 Marks)
- Q.** Show that in intrinsic semiconductor Fermi level always lies at the middle of forbidden energy gap. (Dec. 13, 5 Marks)
- Q.** Show that for intrinsic semiconductor, the Fermi level lies midway between the conduction band and the valance band. (May 15, 8 Marks)
- Q.** Explain the concept of Fermi level. Prove that Fermi level lies exactly at the centre of the Forbidden energy gap in intrinsic semiconductor. (May 17, 7 Marks)

- It can be shown for intrinsic semiconductors, Fermi energy level E_F lies midway between conduction and valence band. The proof is given below.
- At any temperature $T > 0^\circ K$,

n_e = Number of electrons in conduction band

n_v = Number of holes in valence band

$$\text{We have } n_e = N_C e^{-(E_C - E_F)/KT} \quad \dots(3.6.4)$$

Where N_C = Effective density of states in conduction band

$$\text{And } n_v = N_V e^{-(E_F - E_V)/KT} \quad \dots(3.6.5)$$

Where

N_V = effective density of states in valance band

For best approximation

$$N_C = N_V \quad \dots(3.6.6)$$

For intrinsic semiconductor

$$n_C = n_v$$

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

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

$$\therefore e^{-(E_C - E_F - E_F + E_V)/KT} = \frac{N_V}{N_C}$$

$$\therefore e^{-(E_C + E_V - 2E_F)/KT} = \frac{N_V}{N_C}$$

$$\text{as } N_V = N_C = 1$$

$$e^{-(E_C + E_V - 2E_F)/KT} = 1$$

∴ Taking \ln on both sides

$$\frac{-(E_C + E_V - 2E_F)}{KT} = 0$$

$$\therefore (E_C + E_V) = 2E_F$$

$$\therefore E_F = \frac{E_C + E_V}{2} \quad \dots(3.6.7)$$

Thus, the Fermi level in an intrinsic semiconductor lies at the center of forbidden energy gap.

3.7 Extrinsic Semiconductor

- **Intrinsic semiconductors have low conductivity** and serve only in limited applications. It is necessary to modify and control conductivity of intrinsic semiconductors to employ them in manufacturing useful devices.
- The conductivity of intrinsic semiconductor can be increased by adding impurities. A deliberate introduction of controlled quantities of impurities into pure semiconductor is called **doping**.
- The impurity added is called **dopant**. The doped semiconductor is called **extrinsic semiconductor**.
- The impurities to be used as dopants are selected from group III or group V elements because of the following reasons.
- These atoms are nearly of the same size as Si or Ge and substitute themselves easily into the host lattice by going into the place of some of the host atoms.
- The impurity is of substitutional type and the original crystal structure does not get distorted.
- Extrinsic semiconductors are of two types depending upon the impurity element introduced.

3.7.1 n-Type Semiconductors

- If a pentavalent impurity is added to a pure semiconductor it becomes n-type extrinsic semiconductor. The impurity added is called donor impurity.
- As shown in Fig. 3.7.1 antimony (Sb) added as an impurity has five valence electrons. Each Sb atom forms covalent bonds with the surrounding four Si atoms with the help of four of its five electrons and the fifth valence electron remains loosely bound to the parent impurity atom which becomes available as current carrier.

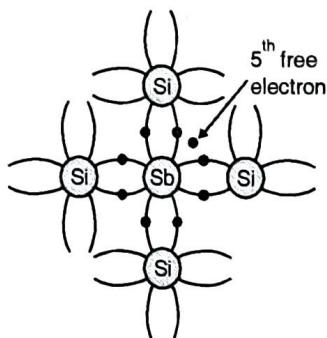


Fig. 3.7.1 : n-type semiconductor



- The energy required to remove the fifth electron is very small (0.05 eV). This energy is very small in comparison to 1.12 eV, which is the energy gap for Si, and it also represents the energy to break a covalent bond.
- So at modest temperatures the fifth electron can be detached from the impurity atom. The liberated electron is called **free electron**, and it can take part in conduction by entering into conduction band.
- Unlike the intrinsic semiconductors, by leaving fifth electron there is no hole created. Therefore at ordinary temperatures, there will be more electrons in the conduction band than holes in the valence band (holes are produced by intrinsic process). It means here electrons in conduction band come from two different ways.

- (i) By the donor atom
- (ii) By intrinsic process

- Therefore, the majority current carriers in n-type semiconductors are electrons and minority current carriers are holes.
- The addition of an impurity adds an allowed energy level E_D at a very small distance below the conduction band as shown in Fig. 3.7.2.

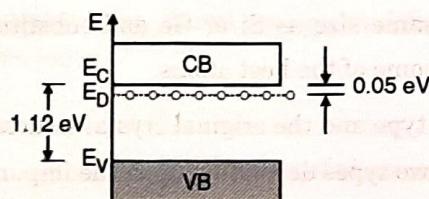


Fig. 3.7.2 : Donor level in n-type semiconductor

- This additional level lies in forbidden energy gap. An electron located at the donor level will have to acquire an energy equal to $(E_C - E_D)$ only, as against the energy $(E_C - E_V = E_g)$ required by an electron located in valence band, to go into conduction band at moderate temperatures.

As the conductivity is due to electrons, it is given by

$$\sigma_e = n \cdot e \cdot \mu_e \quad \dots(3.7.1)$$

The electron concentration will be governed by Boltzmann factor as

$$n \propto e^{-(E_C - E_D)/KT} \quad \dots(3.7.2)$$

and conductivity can be written as

$$\sigma_e = \sigma_0 e^{-(E_C - E_D)/KT} \quad \dots(3.7.3)$$

Position of Fermi level

In n-type semiconductors, as there are many free electrons in conduction band, the Fermi level gets shifted towards the conduction band. At 0°K it is between the bottom of conduction band and the level E_D .

3.7.2 p-Type Semiconductors

- If a trivalent impurity (Group III) is added to a pure semi-conductor, it becomes p-type extrinsic semiconductor. The impurity added is called as **acceptor impurity**.
- As shown in Fig. 3.7.3 boron (B) has been added as impurity which has three electrons. Each B atom tries to form covalent bonds with surrounding four Si atoms and falls short of one electron for completing four covalent bonds.
- As a result a vacancy is left in the bonding. This vacancy is not a hole. Originally, the environment in the crystal lattice is electrically neutral.

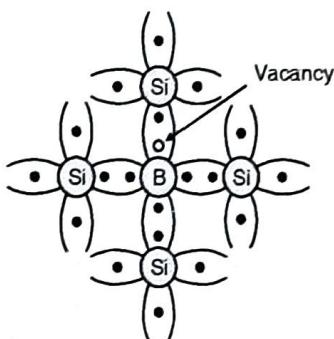


Fig. 3.7.3 : p-type semiconductor

- The introduction of impurity atom does not disturb the environment, and the vacancy arising due to the non-formation of bond is not a hole.
- However, when an electron from a neighbouring bond acquires energy and jumps into this vacancy, it leaves behind a positively charged environment in the broken bond. Therefore, a hole is generated there.
- The addition of an impurity adds an allowed level E_A at a very small distance above the top of the valence band as shown in Fig. 3.7.4

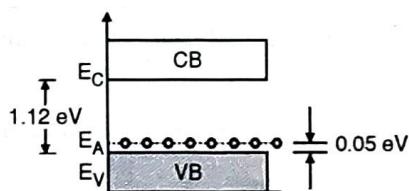


Fig. 3.7.4 : Acceptor level in p-type semiconductor

- At $T = 0^\circ\text{K}$ all acceptor levels at E_A are vacant as shown in Fig. 3.7.4 and valence band is full but the conduction band is empty.
- When the temperature increases, electrons from the valence band jump into acceptor level and leave holes behind. At moderate temperature all acceptor levels are filled and correspondingly for each acceptor atom one hole is created in the valence band.
- The generation of holes is not followed by the simultaneous generation of electrons. Therefore p-type semiconductor has holes as majority carriers and electrons as minority carriers, which results because of intrinsic process.



- The conductivity of a p-type semiconductor at ordinary temperature is given by

$$\sigma_p = p \cdot e \cdot \mu_h \quad \dots(3.7)$$

The hole concentration is governed by Boltzmann law as

$$n_p = e^{(E_V - E_A) / kT} \quad \dots(3.7.1)$$

The conductivity of a p-type semiconductor is given by

$$= \sigma_0 e^{(E_V - E_A) / kT} \quad \dots(3.7.2)$$

Position of Fermi level

In n-type semiconductor, as there are many free holes in valence band, the Fermi level gets shifted towards the valence band. At 0°K it is between top of valence band and the level E_A .

Table 3.7.1 : Difference between conduction for conductors and semiconductors

Sr. No.	Conduction	Semi-conduction
1.	Resistance depends upon temperature, impurity, type of material and ageing factor.	Semi-conduction depends upon temperature (for intrinsic) and on impurity atoms (for extrinsic type).
2.	And kind of material (a) single crystal (b) poly crystalline (c) alloys or (d) amorphous material can be used for conductor.	Only single crystal is used for semi-conduction.
3.	Resistance increases with temperature.	Resistance decreases with temperature.
4.	Charge carriers are only electrons.	Charge carriers are both electrons and holes.
5.	Resistivity and hence conductivity cannot be altered to a desired value.	Conductivity (for extrinsic) can be altered by addition of impurity atoms.
6.	Active components cannot be made out of conductor.	Active components like diodes and transistors can be made of semiconductors.
7.	Conductivity is due to loosely bound electrons (metallic bonds).	Conductivity is due to covalently bonded electrons.

Table 3.7.2 : Comparison between intrinsic and extrinsic semiconductors

Sr. No.	Intrinsic semiconductors	Extrinsic semiconductors
1.	This is a pure element crystal.	This is a single crystal with impurity.
2.	The charge carriers are electrons of the parent atom of crystal and holes formed in absence of that electron.	The charge carriers are electrons or holes of the impurity atoms fitted into the crystal of parent atoms.
3.	The charge carriers, electrons and holes are equal in numbers i.e. $n_e = n_h$	In n-type majority charge carriers are electrons and in p-type majority carriers are holes.



- The conductivity of a p-type semiconductor at ordinary temperature is given by

$$\sigma_p = p \cdot e \cdot \mu_h \quad \dots(3.7.4)$$

The hole concentration is governed by Boltzmann law as

$$\sigma_p = e^{(E_V - E_A) / KT} \quad \dots(3.7.5)$$

The conductivity of a p-type semiconductor is given by

$$= \sigma_0 e^{(E_V - E_A) / KT} \quad \dots(3.7.6)$$

Position of Fermi level

In n-type semiconductor, as there are many free holes in valence band, the Fermi level gets shifted towards the valence band. At 0°K it is between top of valence band and the level E_A .

Table 3.7.1 : Difference between conduction for conductors and semiconductors

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5.	Resistivity and hence conductivity cannot be altered to a desired value.	Conductivity (for extrinsic) can be altered by addition of impurity atoms.
6.	Active components cannot be made out of conductor.	Active components like diodes and transistors can be made of semiconductors.
7.	Conductivity is due to loosely bound electrons (metallic bonds).	Conductivity is due to covalently bonded electrons.

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1.	This is a pure element crystal.	This is a single crystal with impurity.
2.	The charge carriers are electrons of the parent atom of crystal and holes formed in absence of that electron.	The charge carriers are electrons or holes of the impurity atoms fitted into the crystal of parent atoms.
3.	The charge carriers, electrons and holes are equal in numbers i.e. $n_e = n_p$.	In n-type majority charge carriers are electrons and in p-type majority carriers are holes.

Sr. No.	Intrinsic semiconductors	Extrinsic semiconductors
4.	The charge carriers, say electrons, can be increased only by increase in temperature.	The majority charge carriers can be increased by slightly increasing the percentage of impurity atoms.
5.	More energy is needed for the electrons to cross E_g (compared to extrinsic).	Less energy is needed for the electrons (impurity atoms) to cross E_g (compared to intrinsic).

3.7.3 Effect of Temperature on n-type Material

MU - May 17, Dec. 17, May 18

- Q. With the help of diagram, explain the variation of Fermi level with temperature in n-type semiconductor. (May 17, 5 Marks)
- Q. With energy band diagram explain the variation of Fermi energy level with temperature in extrinsic semiconductor. (Dec. 17, May 18, , 5 Marks)
- Q. Draw the energy band diagram of p-n junction diode in forward and reverse bias condition. (Dec. 17, May 18, 3 Marks)

(i) **At low temperature :** When the temperature in the semiconductor is low, only few donor atoms get ionized and electrons move from the donor level to the conduction band.

Hence, Fermi level for n-type semiconductor at low temperature lies midway between the bottom of the conduction band and donor level.

(ii) **At moderate temperature :** At moderate temperature all donor atoms are ionized. So, the concentration of electrons in conduction band is equal to the concentration of donor atoms.

When the temperature increases up to moderate value, Fermi level slowly shifts away from the conduction band and moves towards the center of the forbidden gap.

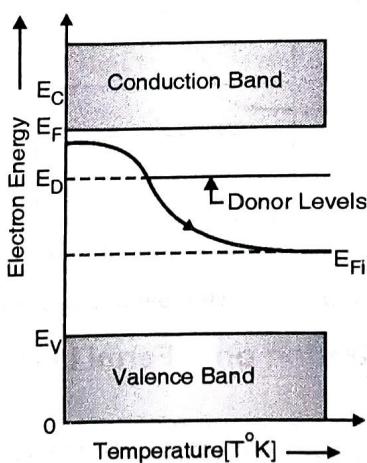


Fig. 3.7.5 Variation of E_F with temperature in n-type material

(iii) **At higher temperature :** At high temperature, the concentration of transfer of electrons from valence band to conduction band is more compared to concentration of electrons from donor atoms and Fermi level is shifted to middle of the forbidden gap.

The variation of Fermi level with temperature for n-type of material is shown in Fig. 3.7.5.

3.7.4 Effect of Temperature on p – type Material

MU - Dec.17, May 18

- Q. Draw the energy band diagram of p-n junction diode in forward and reverse bias condition. (Dec. 17, 3 Marks)
- Q. With energy band diagram explain the variation of Fermi energy level with temperature in extrinsic semiconductor. (Dec. 17, 5 Marks)
- Q. Draw the energy band diagram of p-n junction diode in forward and reverse bias condition. (May 18, 3 Marks)

(i) **At low temperature :** At low temperature only few acceptor levels are occupied, and simultaneously holes are produced in valence band.

So, Fermi level lies in the middle of the top of the valence band and the acceptor level.

(ii) **At moderate temperature :** At moderate temperature, all acceptor levels are filled.

So, at moderate temperature, Fermi level gradually moves up i.e. moves towards the middle of the forbidden gap.

(iii) **At higher temperature :** At very high temperature, the contribution of conduction band for the formation of holes in the valence band is more compared to acceptor impurity.

Hence, at very higher temperature, Fermi level approaches the middle of the energy gap i.e. the position of E_F for intrinsic semiconductor. The variation of E_F with temperature in p- type material is shown in Fig. 3.7.6

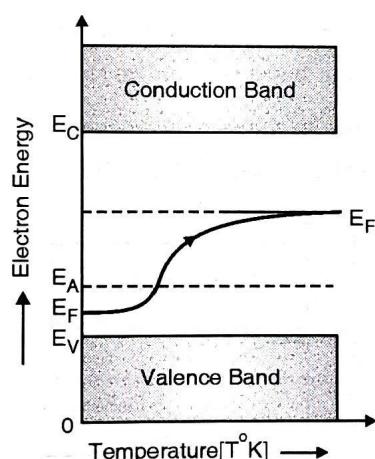


Fig. 3.7.6 Variation of E_F with temperature in p-type material

3.8 Effect of Impurity Concentration on Fermi Level

MU - Dec. 15, Dec. 16

- Q. Draw a neat labelled energy band diagram to show the variation of Fermi level with doping concentration in n-type semiconductors. (Dec. 15, 3 Marks)
- Q. How does the position of Fermi energy level change with increasing doping concentration in p-type semiconductors? Sketch the diagram. (Dec. 16, 5 Marks)

- We have seen the effect of temperature on Fermi level. The position of Fermi level is also affected by addition of impurity and by variation in the concentration of impurity.
- If a donor impurity is added to an intrinsic semiconductor, it results in n-type of semiconductor and a donor level comes into existence below the bottom of conduction band.

- At impurity concentrations, the impurity atoms are so spaced that they do not interact with each other. Once the concentrations are increased, interaction among them starts.
- The donor levels starts splitting and forms an energy band below the conduction band. The width of this band increases with increase in the impurity concentration. At one stage it overlaps with the conduction band.
- Due to broadening of the donor levels into band the width of forbidden energy gap reduces and the Fermi level is found moved upwards.
- With increase in concentration of donor impurity, the Fermi level continues shifting towards conduction band and enters into conduction band.

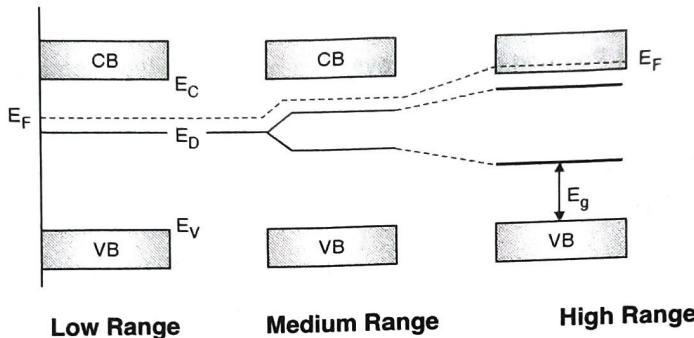


Fig. 3.8.1

- In the same way, for p-type semi conductors increase in the impurity concentration makes Fermi level shift into valence band.

3.9 P-N Junction

- The extrinsic semiconductors, individually, are of limited use. However, when a p-type and an n-type semiconductors are joined together such that crystal structure remains continuous at the metallurgical boundary, a p-n junction is formed.
- In practice it is formed by adding excessive acceptor impurities to a portion of n-type semiconductor or donor impurities to a p-type semiconductor.

3.9.1 Depletion Layer and Potential Barrier

MU - May 13, Dec. 13, May 14, Dec. 14, Dec 15, Dec. 16

- | | |
|---|--------------------|
| Q. Draw the energy band diagram of an unbiased p-n junction and mark the barrier potential and depletion region. | (May 13, 3 Marks) |
| Q. Explain the formation of depletion layer in P-N junction. | (Dec. 13, 5 Marks) |
| Q. Explain the formation of barrier potential in P-N junction. | (May 14, 5 Marks) |
| Q. Explain the formation of depletion region in an unbiased p - n junction. | (Dec. 14, 3 Marks) |
| Q. Draw a neat labelled energy band diagram to show the variation of Fermi level with doping concentration in N-Type semi-conductors. | (Dec. 15, 3 Marks) |
| Q. How does the position of Fermi energy level change with increasing doping concentration in p-type semi-conductors? Sketch the diagram. | (Dec. 16, 5 Marks) |
| Q. Explain the formation of potential barrier across the unbiased p-n junction region. | (Dec. 16, 5 Marks) |

- In p-type of semiconductor, holes are majority carriers and its Fermi level is just above the top of acceptor level at room temperature (300°K). For n-type of semiconductor, electrons are majority carriers and its Fermi level is just below the donor level at 300°K .
- When p-n junction is being formed, both materials will find their Fermi levels non-aligned as shown in Fig. 3.9.1 and they must be aligned.

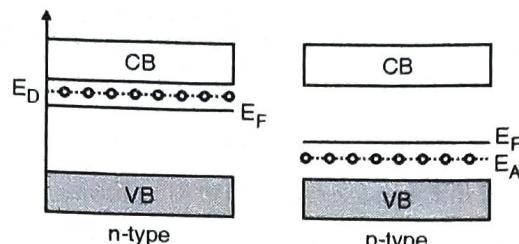


Fig. 3.9.1 : Position of Fermi-level in n-type and p-type semiconductor

- In order to obtain alignment, holes from p-type (majority carriers for a p-type) move towards n-type and at the same time electrons from n-type (majority carriers from n-type) move towards p-type. This is called **diffusion**.
- As the diffusion takes place across the junction the holes and the electrons combine to neutralise each other at the junction and produce a free space called **depletion layer** as shown in Fig. 3.9.2.
- At the junction due to the migration of a few holes from p-type to n-type region, the negative immobile ions are produced in p-region and in the same way positive immobile ions are produced in n-region as shown in Fig. 3.9.2.
- As the name suggest these ions are immobile in nature (fixed in lattice). Under equilibrium condition it can be assumed similar to a charged parallel plate capacitor and creates an electronic potential called potential barrier or junction potential which prevents further diffusion of majority charge carriers.

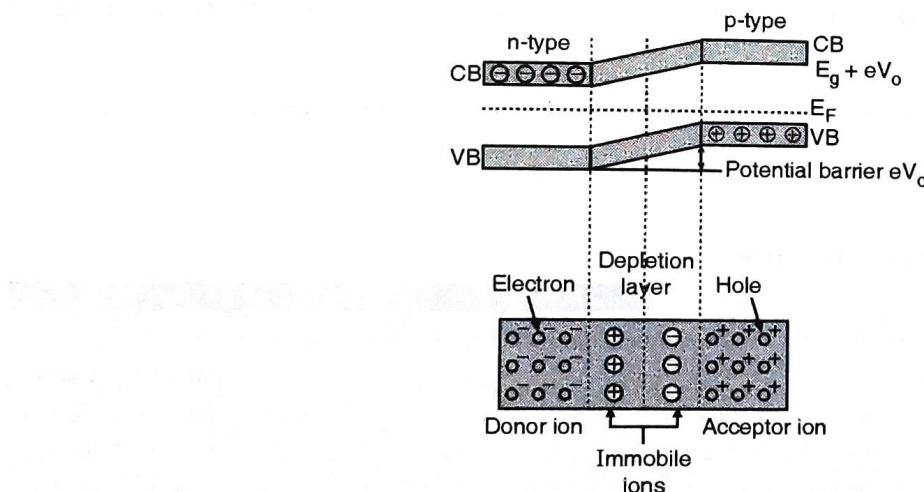


Fig. 3.9.2 : Unbiased p-n junction

3.9.2 Calculation of Potential Barrier

- The magnitude of potential barrier created can be estimated from the knowledge of the carrier densities in p and n-regions.



- The concentration of electrons in the conduction band on n-side is written as

$$n_n = N_C \exp [-(E_g - E_F) / KT] \quad \dots(3.9.1)$$

Similarly the concentration on p-side is written as

$$n_p = N_C \exp [-(\{E_g + eV_o\} - E_F) / KT] \quad \dots(3.9.2)$$

Dividing equation (3.9.1) by equation (3.9.2),

$$\frac{n_n}{n_p} = \exp [eV_o / KT] \quad \dots(3.9.3)$$

Taking natural logarithm on both sides of equation (3.9.3) we get

$$V_o = \frac{KT}{e} \ln \left(\frac{n_n}{n_p} \right) \quad \dots(3.9.4)$$

By rewriting equation (3.9.4) as

$$V_o = \frac{KT}{e} \ln \left(\frac{n_n}{n_p} \cdot \frac{p_n}{p_p} \right) \quad \dots(3.9.5)$$

Where p_p is hole concentration on p-side.

At room temperature, all impurities are ionised therefore

$$n_n = N_D = \text{Donor impurity concentration}$$

$$p_n = N_A = \text{Acceptor impurity concentration using relation,}$$

$$n_p \cdot p_p = n_i^2$$

Equation (3.9.5) can be modified as

$$V_o = \frac{KT}{e} \ln \left(\frac{N_D \cdot N_A}{n_i^2} \right) \quad \dots(3.9.6)$$

Taking

$$\frac{KT}{e} = \text{Constant} = V_T$$

$$V_o = V_T \ln \left(\frac{N_D \cdot N_A}{n_i^2} \right) \quad \dots(3.9.7)$$

3.10 Hall Effect and its Applications

MU - Dec. 12, Dec. 13, May 15, Dec. 15, May 16, May 18, Dec. 18, May 19

Q. What is Hall effect? Derive expression for Hall voltage with neat labelled diagram.	(Dec. 12, May 16, 5 Marks)
Q. Explain Hall effect in metal. Derive the formulae for density and mobility of electrons.	(Dec. 13, 8 Marks)
Q. State the Hall effect. Derive the expression for Hall voltage and Hall coefficient with neat diagram.	(Dec. 15, 3 Marks, Dec. 17, May 18, 7 Marks)
Q. Derive an expression for Hall voltage and Hall coefficient with neat labelled diagram.	(Dec. 18, 7 Marks)
Q. What is Hall effect? Derive an expression for Hall voltage. How can mobility be determined using Hall effect?	(May 15, May 19, 3 Marks)

- If a metal or semiconductor, carrying a current I is placed in a transverse magnetic field B , an electric field E is induced in the direction perpendicular to both I and B . This phenomenon is known as **Hall effect** and the electric field or voltage induced is called **Hall voltage (V_H)**. The physical process of Hall effect is as follows. Consider a specimen along positive x-direction (Fig. 3.10.1).



- The current flowing through the specimen is in the positive x-direction and the magnetic field is in the positive z-direction. The force exerted on charge carriers, that is, on electrons is downward. The electrons move downward and thus voltage V_H (Hall voltage) is developed along upper surface as positive and lower as negative

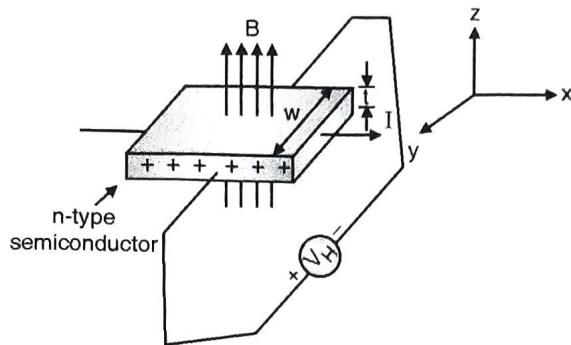


Fig. 3.10.1: Hall effect

3.10.1 Experimental Determination of Mobility

- If the specimen in Fig. 3.10.1 is assumed to be of n-type, then magnetic force experienced by electrons will be towards -Y direction as it is applied transversely
 \therefore Magnetic force $F = e v B$
- Holes present in specimen will experience the same force but in positive Y direction. Hence, electrons and holes will be separated.

This develops potential difference between both the surfaces, denoted by V_H , called Hall voltage.

$$\therefore E_H = \frac{V_H}{w} \quad \dots(3.10.1)$$

- The current in this case is given by

$$= n A e v \quad \dots(3.10.2)$$

(Where, v = drift velocity)

- In equilibrium condition, the force due to magnetic field B and the force due to electric field E_H acting on the charge are balanced.

$$\therefore e E_H = evB \quad \dots(3.10.3)$$

or

$$E_H = vB$$

Using equation (3.10.3) and (3.10.1)

$$V_H = Bvw$$

Using equations (3.10.1) and (3.10.2).

$$v = \frac{I}{enA} = \frac{J}{en}$$

where $J = \frac{I}{A}$

Hence, Hall voltage can be written as

$$V_H = \frac{IBw}{enA} = \frac{Bw}{en} \cdot J$$

It can be also modified by using, $A = w \times t$

$$V_H = \frac{IB}{en} \quad \dots(3.10.4)$$

By measuring V_H , I , B , and t , the charge density (n_{he} or $n_e e$) can be calculated.

Another important parameter is Hall coefficient R_H it is defined as,

$$\begin{aligned} R_H &= \frac{1}{pe} && \text{(for p-type semiconductor)} \\ &= \frac{1}{ne} && \text{(for n-type semiconductor)} \end{aligned}$$

From equation (3.10.4),

$$R_H = \frac{V_H t}{BI} \quad \dots(3.10.5)$$

$$As \sigma = \mu ne, \mu = \sigma R_H$$

\therefore If the conductivity and Hall coefficient are measured then the mobility and density of electron can be determined.

- With increase in temperature of the semiconductor, the carrier concentration is increased and R_H decreases.
- The net electric field E acting on the charge carrier is constant of the applied electric field E_x and Hall electric field E_H . The angle made by E with x-axis is called Hall angle, given by

$$\theta_H = \tan^{-1}\left(\frac{E_H}{E_x}\right)$$

Which can also be proved as,

$$\theta_H = \tan^{-1}(R_H \sigma B)$$

3.10.2 Applications

1. The Hall voltage V_H is proportional to magnetic field B , for the given current I , therefore Hall effect is used in magnetic field meter.
2. The charge carrier concentration can be determined.
3. The mobility of charge carriers can be determined.
4. The nature of semiconductor (p-type or n-type) can be determined.

3.10.3 Light Emitting Diodes (LED)

MU - Dec. 15, Dec. 18

Q. Explain the principle, construction and working of a LED.

(Dec. 15, Dec. 18, 5 Marks)

- In this section, let us discuss about one of the important light sources which is the Light Emitting Diode (LED).
- An LED emits light when electrical energy is applied to it. LED is a two-terminal device. The terminals are named as anode (A) and the other as cathode (K).



- A p-n junction is formed between the anode and cathode. So, LED is basically a p-n junction diode.
- For proper operation, it is necessary to forward bias the LED as shown in Fig. 3.10.2(a) and the symbol of LED is shown in Fig. 3.10.2(b). This shows that the symbol is same as that of a p-n junction diode with two arrows indicating that it emits light.

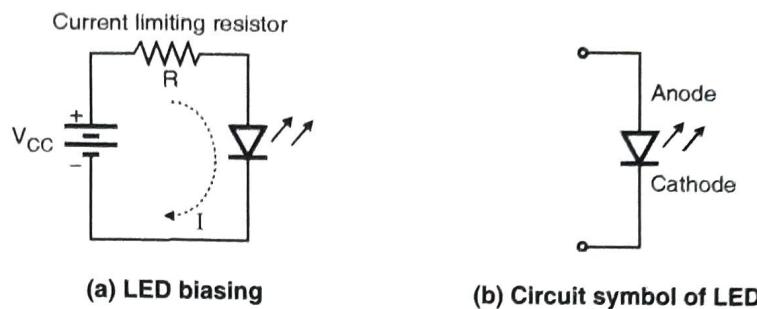


Fig. 3.10.2

Construction of LED

- One of the popular methods of LED construction is to deposit three semiconductor layers on the substrate as shown in Fig. 3.10.2 (c).
- The active region exists between the p and n regions. The light emerges from the active side in all the directions when electron-hole pairs recombine.
- The disadvantage of this structure is that the LED emits light in all directions. This problem can be solved by placing the basic structure of Fig. 3.10.2 (c) inside a small reflective cup, so as to focus the light in the desired direction.
- Such a structure is called as a cup-type construction and it is shown in Fig. 3.10.2(d).

Circuit symbol

- The circuit symbol of an LED is as shown in Fig. 3.10.2(b). This shows that the symbol is identical to a p-n junction diode with two arrows indicating that it emits light.

Semiconductor materials used

- LEDs are made of Gallium Arsenide (GaAs), Gallium Arsenide Phosphide (GaAsP) and Gallium Phosphide (GaP).
- Silicon and germanium are not used because they are essentially heat producing materials and are very poor in producing light.

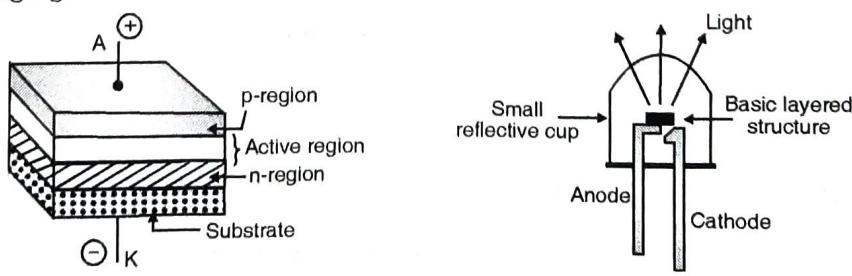


Fig. 3.10.2

Principle of LED Operation

- When the LED is forward biased, the electrons in the n-region will cross the junction and recombine with the holes in the p-type material.
- These free electrons reside in the conduction band, and hence at a higher energy level than the holes in the valence band.
- When the recombination takes place, these electrons return back to the valence band which is at a lower energy level than the conduction band.
- While returning back, the recombining electrons give away the excess energy in the form of light. This is shown in Fig. 3.10.2(e) This process is called as **electroluminescence**. In this way, an LED emits light. This is the principle of operation of LED.

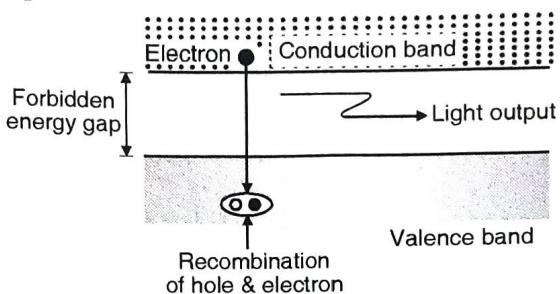
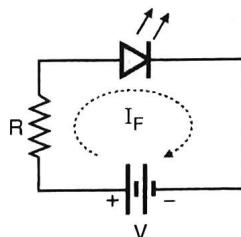


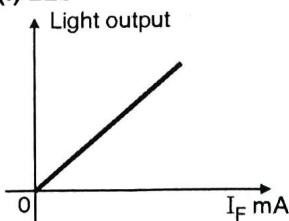
Fig. 3.10.2 (e) : Principle of operation of LED

Output Characteristics of LED

- The graph of Fig. 3.10.2 (g) shows the output characteristics of the LED. It shows the linear dependence of light output on the forward LED current.
- However, it is not possible to increase I_F indefinitely. Typically, the maximum value of I_F is 80 mA.



(f) LED is forward biased



(g) Relation between forward current and light output

Fig. 3.10.2

3.10.4 Zener Diode

- In p-n junctions, we have studied forward current but accepted that a very small reverse current is ignored.



- Under reverse-bias condition a very small current flows through diode but only up to certain voltage applied.
- Beyond that a breakdown occurs and a high current flows. This has been regarded as destructive in general.
- This current need not be destructive if the current is such that the diode does not become overheated. But suitably controlling the amount of impurity and making the p-n junction capable enough to make breakdown very distinctly sharp.
- This type diodes are called Zener diode and it is represented by the symbol shown Fig. 3.10.3(a).
- The Zener diode is used in reverse biased condition. It has its own specific application.



Fig. 3.10.3(a)

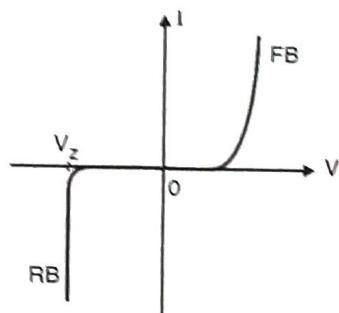


Fig. 3.10.3(b)

- Here it is seen that, once the diode has broken down, very little change in voltage across the diode results from a change in current through the diode. Thus a Zener diode of known breakdown voltage can be used as a reference voltage when operated in the reverse biased condition and can be used to regulate voltage.

3.10.5 Photovoltaic Cell

MU - May 13, Dec. 14, May 15, Dec. 17, May 18

- | | |
|--|--|
| Q. How is a p-n junction diode used to generate a potential difference in a photovoltaic solar cell? (May 13, 5 Marks) | |
| Q. Explain how a voltage difference is generated in a p-n junction when it is used in a photovoltaic solar cell. (Dec. 14, May 15, 5 Marks) | |
| Q. What is photovoltaic effect? Explain the principle and working of solar cell. (Dec. 17, May 18, 5 Marks) | |

- When suitable light falls on a p-n junction, a potential difference is produced across it. This voltage is capable of driving a current through an external circuit. This important phenomenon is called the 'photovoltaic effect'.
- This photovoltaic effect was first invented by E. Becquerel in 1839. He found that certain materials would produce very small amount of electric current when exposed to light. On continuous effort, Bell laboratories in 1954 constructed the first photovoltaic cell, known as a solar battery. Due to the energy crisis, presently photovoltaic technology is becoming the main source of electrical power for many industrial and domestic applications.



- A device is so constructed in which solar energy is converted into electrical energy. Therefore, this device is called as photovoltaic cell or solar cell. In the solar cell, semiconductor material is used. When light energy falls on it, electrons from the semiconductor material get free from the atom in the semiconductor. Further, these electrons are made free to move through the semiconductor by applying external potential or voltage. Finally, due to this arrangement electric current is observed in the electrical circuit. The current produced is found to directly depend on light intensity falling on the semiconductor materials. The following section describes the details of solar cell.

Solar Cell

MU - Dec. 12, Dec. 13, May 14, May 17

- | | |
|--|-----------------------------------|
| Q. Explain with neat diagram construction and working of solar cell. | (Dec. 12, May 14, 5 Marks) |
| Q. Explain the use of P-N junction as solar cell. | (Dec. 13, 3 Marks) |
| Q. What is the principle of a solar cell? Write its advantages and disadvantages. | (May 17) |

(a) Principle

- A solar cell works on the principle of photovoltaic effect. It is a device that directly converts the energy in light into electrical energy.
- It was first developed by French physicist Antoine-César Becquerel. He observed the photovoltaic effect while experimenting with a solid electrode in an electrolyte solution when he saw a voltage developed when light fell upon the electrode.

(b) Construction and working

- From construction point of view, generally crystalline silicon (Si) has been used as the light-absorbing semiconductor in most solar cells, even though it is a relatively poor absorber of light and requires a considerable thickness (several hundred microns) of material.
- Presently two types of crystalline silicon are used for production of solar cell namely

 - 1) **Monocrystalline** - It is produced by slicing wafers (up to 150mm diameter and 350 microns thick) from a high-purity single crystal.
 - 2) **Multicrystalline** - It is made by sawing a cast block of silicon first into bars and then wafers.

- For both mono and multicrystalline Si, a semiconductor homojunction is formed by diffusing phosphorus (an n-type dopant) into the top surface of the boron doped (p-type) Si wafer. Construction of the solar cell is as shown in Fig. 3.10.4(a).
- Screen-printed contacts are applied to the front and rear of the cell, with the front contact pattern specially designed to allow maximum light exposure of the Si material with minimum electrical (resistive) losses in the cell.
- The **most efficient production cells** use monocrystalline Si with laser grooved and buried grid contacts for maximum light absorption and current collection.
- Each Si cell generates about 0.5V, so about 36 cells are usually soldered together in series to produce a module with an output to charge a 12V battery.
- The cells are hermetically sealed under tough, high transmission glass to produce highly reliable, weather-resistant models that may be warranted for up to 25 years.

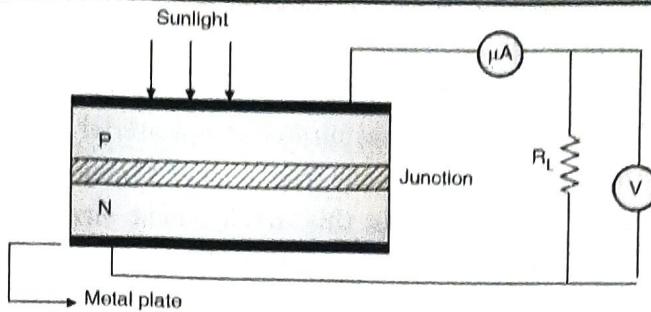


Fig. 3.10.4 : (a) Working of a solar cell

- (1) Production and development of pairs of positive and negative charges (electron-hole pairs) in the solar cell by absorbed solar radiation
- (2) Distance between positive and negative charges by a potential gradient within the cell

First it is essential to select the material or prepare the material which can absorb the energy associated with the photons of sunlight. This can be done using following relation

$$E = \frac{hc}{\lambda} \quad \dots(3.10.1)$$

Where,

E = Energy of a photon

and

λ = Wavelength of the radiation

h = Planck's constant = 6.62×10^{-27} ergs

c = Velocity of light = 3×10^8 m/s

Hence above relation becomes $E = \frac{1.24}{\lambda}$, in which E is the energy in electron-volt (eV) and λ is in nanometer.

Thus above relation is used to design a solar cell.

- The only materials suitable for absorbing the energy of the photons of sunlight are semiconductors like silicon, cadmium sulphide, gallium arsenide, etc.
- Generally in a semiconductor, the electrons occupy either valence band or the conduction band.
- The valence band has electrons at a lower energy level and is fully occupied, while the conduction band has electrons at a higher energy level and is not fully occupied.
- The difference between the energy levels of the electrons in the two bands is called the band gap energy E_g . It is necessary that photons of sunlight having energy E greater than the band gap energy E_g .
- Here, photons of sunlight having energy E which is greater than E_g is absorbed by the cell material. Therefore, excitation of the electrons takes place.
- Such excited electrons jump across the band gap from the valence band to the conduction band, but they leave behind holes in the valence band. In this way electron-hole pairs are created, it is as shown Fig. 3.10.4(b).
- Thus, electrons in the conduction band and the holes in the valence band become mobile. They can be separated and made to flow through an external electronic circuit.
- According to the photovoltaic effect, a potential gradient is developed within the cell.

In the case of silicon, the potential gradient is obtained by making the cell as a sandwich of two types of silicon, i.e. p-type and n-type. Thus, when a composite of the two types of silicon is formed, a jump in energy levels occurs at the junction interface. (See Fig. 3.10.4 (b))

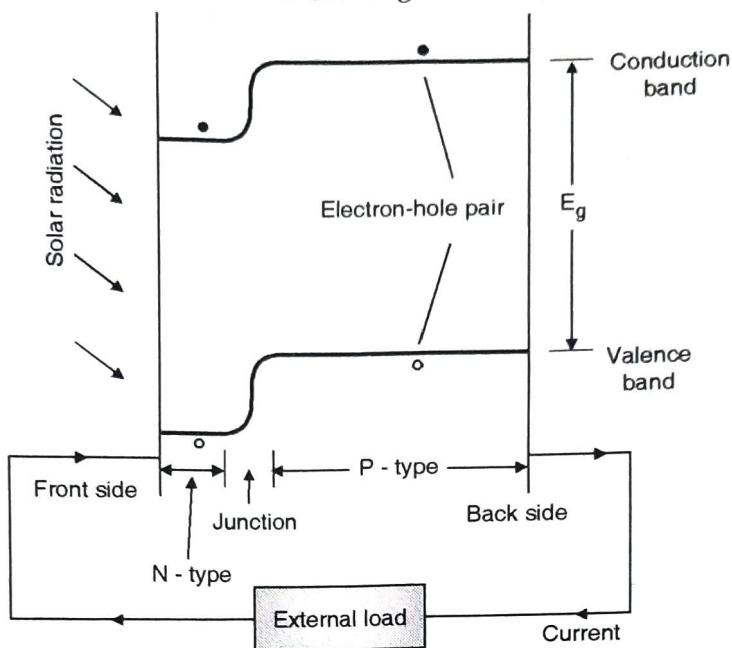


Fig. 3.10.4(b) : Band structure of solar cell

- In this way, the developed potential gradient is adequate to separate the electrons and holes, and hence produces a direct electric current to flow in the external circuit with load.

(c) Advantages of solar cell

- Raw material i.e. amount of solar energy is available at no cost for operation of the solar cell. Hence, it is more useful in satellite communication.
- It is pollution free. It is not harmful to human life.
- It is most useful in remote areas where traditional transmission may be difficult.
- They are portable as compared to other electronic energy transmission devices.

(d) Disadvantages of solar cell

- Operation in the night is not possible.
- It has low efficiency hence presently it is not economical.
- It is a dilute source.

3.11 Solved Problems on Mobility, Conductivity and Resistivity

Ex. 3.11.1 : The resistivity of Cu is 1.72×10^{-8} ohm-m. Calculate the mobility of electrons in Cu given that number of electrons per unit volume is $10.41 \times 10^{28} \text{ m}^{-3}$.

Soln. :

Given :

$$\rho = 1.72 \times 10^{-8} \Omega \cdot \text{m},$$

$$\sigma = \frac{1}{\rho} = 58.1 \times 10^6 \text{ mho/m}$$



$$n = 10.41 \times 10^{28} \text{ m}^{-3}$$

Formula :

$$\mu = \frac{\sigma}{ne} = \frac{58.1 \times 10^6}{10.42 \times 10^{28} \times 1.6 \times 10^{-19}}$$

$$\therefore \mu = 3.488 \times 10^{-3} \frac{\text{m}^2}{\text{volt sec.}}$$

...Ans.

Ex. 3.11.2 : Find the resistivity for Cu assuming that each atom contributes one free electron for conduction.**Soln. :****Given :**

$$\text{Density} = 8.96 \text{ g/cm}^3, \text{ Atomic weight} = 63.5$$

$$\text{Avogadro's number} = 6.02 \times 10^{23} / \text{g-mole}$$

$$\text{Mobility of electron} = 43.3 \text{ cm}^2 / \text{V-sec.}$$

Formula :

$$\sigma = n\mu e$$

$$\text{And } \rho = \frac{1}{\sigma}$$

$$\therefore \rho = \frac{1}{n\mu e}$$

∴ Calculation of n

$$\text{Atomic density} = \frac{6.023 \times 10^{23} \times 8.96}{63.5} = 8.4985 \times 10^{22} / \text{cm}^3$$

$$\therefore n = 1 \times \text{Atomic density} = 1 \times 8.5 \times 10^{22} / \text{cm}^3$$

$$\therefore \rho = \frac{1}{8.5 \times 10^{22} \times 1.6 \times 10^{-19} \times 43.3}$$

$$\therefore \rho = 1.698 \times 10^{-6} \text{ ohm-cm}$$

...Ans.

Ex. 3.11.3 : Find the resistivity of intrinsic Ge at 300°K given the density of carriers as $2.5 \times 10^{19} \text{ m}^{-3}$.**Soln. :****Formula :**

$$\sigma_{in} = n_e e \cdot \mu_e + n_h e \cdot \mu_h$$

For intrinsic semiconductor

$$n_e = n_h = n_i$$

$$\therefore \sigma = n_i e (\mu_e + \mu_h)$$

Using standard values of μ_e and μ_h

$$\therefore \sigma_{in} = 2.5 \times 10^{19} \times 1.6 \times 10^{-19} [0.39 + 0.19] = 2.32 (\text{ohm.m})^{-1}$$

$$\therefore \rho_i = \frac{1}{\sigma_i} = 0.43 \text{ ohm.m}$$

...Ans.

Ex. 3.11.4 : In an intrinsic semiconductor the energy gap E_g of an intrinsic semiconductor is 1.2 eV. Its hole mobility is much smaller than electron mobility and is independent of temperature. What is the ratio between conductivity at 600°K and that at 300°K? Comment on the result.**Soln. :**Since $\mu_e \gg \mu_h$, for intrinsic semiconductor equation (3.6.3) can be rewritten as,

$$\begin{aligned}\sigma_i &= n_i \cdot e \cdot \mu_e \quad (\text{as } n_i = n_e = n_h) \\ \therefore n_e &= N \exp [-E_g / 2KT] \\ \therefore \sigma_i &= e \cdot \mu_e \cdot N \exp [-E_g / 2KT]\end{aligned}$$

All the pre-exponential terms are independent of temperature. We can put a constant

$$\begin{aligned}\sigma_0 &= \mu_e \cdot e \cdot N \\ \therefore \sigma_i &= \sigma_0 \exp \left[\frac{-E_g}{2KT} \right] \\ \text{Now, } \sigma(600^\circ\text{K}) &= \sigma_0 \exp \left[\frac{-1.2}{2 \times K \times 600} \right] \\ \sigma(300^\circ\text{K}) &= \sigma_0 \exp \left[\frac{-1.2}{2 \times K \times 300} \right]\end{aligned}$$

Taking K, the Boltzmann constant in eV as $K = 8.62 \times 10^{-5}$ eV/K and solving we get

$$\frac{\sigma(600^\circ\text{K})}{\sigma(300^\circ\text{K})} = 1 \times 10^5 \quad \dots\text{Ans.}$$

Comment : The conductivity of an intrinsic semiconductor is greatly influenced by temperature.

Ex. 3.11.5 : Predict the effect on the electrical properties of a silicon at room temperature if every millionth silicon atom is replaced by an atom of indium. Comment on results.

Given :

$$\text{Concentration of Si atoms} = 5 \times 10^{28} \text{ m}^{-3}$$

$$\text{Intrinsic conductivity of Si} = 4.4 \times 10^{-4} \text{ mho.m}^{-1}$$

$$\text{Mobility of holes } \mu_h = 0.048$$

Soln. :

As indium belongs to group III, holes will remain as majority carrier. Concentration of Si atoms = $5 \times 10^{28} \text{ m}^{-3}$

Concentration of impurity atoms

$$n = 5 \times 10^{28} \times 1 \times 10^{-6} = 5 \times 10^{22} \text{ m}^{-3}$$

$$\therefore \sigma_p = \mu_h \cdot e \cdot n = 0.048 \times 1.6 \times 10^{-19} \times 5 \times 10^{22}$$

$$\therefore \sigma_p = 384 \text{ mho.m}^{-1} \quad \dots\text{Ans.}$$

Comment : Intrinsic conductivity for Si at room temperature is $4.4 \times 10^{-4} \text{ mho.m}^{-1}$ and when trivalent impurity of indium at one part per million is added, the conductivity becomes 384 mho.m^{-1} which is increased by almost six orders of magnitude.

Ex. 3.11.6 : An impurity of 0.01 ppm (particles per million) is added into Si. The semiconductor has a resistivity of 0.25 ohm.m^{-1} at 300°K . Calculate the hole concentration and its mobility. Also comment on result.

Given : Atomic weight of Si = 28.1 and

$$\text{density of Si} = 2.4 \times 10^3 \text{ kg/m}^3$$

Soln. :

$$\begin{aligned}\therefore \text{Number of Si atoms / m}^3 &= \frac{\text{Avogadro number} \times \text{Density}}{\text{Atomic weight}} \\ &= \frac{6.024 \times 10^{26} \times 2.4 \times 10^3}{28.1}\end{aligned}$$



$$= 5.14 \times 10^{28} \text{ atoms / m}^3$$

Impurity level is 0.01 ppm i.e. 1 atom at every 10^8 atoms of Si

\therefore Number of impurity atoms

$$= \frac{5.14 \times 10^{28}}{10^8} = 5.14 \times 10^{20}$$

Each impurity introduces one hole

$$\text{i.e. holes/m}^3 = 5.14 \times 10^{20} = n_h$$

$$\therefore \mu_p = \frac{1}{e.p.n_h}$$

$$= \frac{1}{1.6 \times 10^{-19} \times 0.25 \times 5.14 \times 10^{20}}$$

$$\therefore \mu_p = 0.0486 \text{ m}^2/\text{volt. sec}$$

...Ans.

Comment: On addition of trivalent impurity the mobility of Si remains the same but the concentration of holes increases.

Ex. 3.11.7 : The resistivity of intrinsic InSb at room temperature is $2 \times 10^{-4} \Omega \text{ cm}$. If the mobility of electron is $6 \text{ m}^2/\text{V-sec}$ and mobility of hole is $0.2 \text{ m}^2/\text{V-sec}$. Calculate its intrinsic carrier density. MU - Dec. 13, 5 Marks

Soln. :

Given

$$\rho_i = 2 \times 10^{-4} \Omega \text{ cm} = 2 \times 10^{-6} \Omega \text{ m}$$

$$\mu_n = 0.2 \text{ m}^2/\text{V-sec},$$

$$\mu_e = 6 \text{ m}^2/\text{V-sec.}$$

Formula :

$$\sigma_{in} = n_e e \mu_e + n_n e \mu_n$$

For intrinsic semiconductor

$$n_e = n_n = n_i$$

$$\therefore \sigma_{in} = n_i e (\mu_e + \mu_n)$$

$$\rho_{in} = \frac{1}{\sigma_{in}} = \frac{1}{n_i e (\mu_e + \mu_n)}$$

$$\therefore n_i = \frac{1}{\rho_{in} e (\mu_e + \mu_n)}$$

$$= \frac{1}{2 \times 10^{-6} \times 1.6 \times 10^{-19} (6 + 0.2)}$$

$$\therefore n_i = 5.04 \times 10^{23}$$

...Ans.

Ex. 3.11.8 : Calculate electron and hole concentration in intrinsic silicon at room temperature if its electrical conductivity is $4 \times 10^{-4} \text{ mho/m}$. Given that mobility of electron = $0.14 \text{ m}^2/\text{V-sec}$ and mobility of holes = $0.04 \text{ m}^2/\text{V-sec}$.

MU - May 14, May 17, Dec. 18, 3/5 Marks

Soln. :

For intrinsic semiconductor $n_e = n_h = n_i$.

and

$$\sigma_{in} = n_i e (\mu_n + \mu_e)$$

$$n_i = \frac{\sigma_{in}}{e(\mu_n + \mu_e)} = \frac{4 \times 10^{-4}}{1.6 \times 10^{-19} (0.14 + 0.4)}$$

$$n_i = 1.388 \times 10^{16}$$

...Ans.

Ex. 3.11.9 : Determine the concentration of conduction electron in a sample of silicon if one in every million silicon atoms is replaced by a phosphorous atom. Assume every phosphorous atom to be singly ionized. Si has a molar mass of 0.028 kg/mole and density of 2300 kg/m³

MU - Dec. 14, 5 Marks

Soln. :

Given :

$$\text{Molar mass} = 0.028 \text{ kg/mole}$$

$$\text{Density} = 2300 \text{ kg/m}^3$$

As the molar mass is given, number of silicon per m³ is given by

$$\begin{aligned} &= \frac{\text{Density}}{\text{Molar mass}} \times \text{Avogadro number} \\ &= \frac{2300}{0.028} \times 6.023 \times 10^{26} = 4.947 \times 10^{31} \end{aligned}$$

As every millionth atom is replaced by phosphorous hence number of phosphorous atoms per m³ is 4.947×10^{25}

Also, phosphorous is singly ionized, each atom contributes i.e.

$$\therefore \text{Concentration of electron} = 4.947 \times 10^{25}/\text{m}^3$$

... Ans.

Ex. 3.11.10 : Calculate conductivity of a germanium sample if donor impurity atoms are added to the extent of one part in 10^6 germanium atoms at room temperature.

Assume that only one electron of each atom takes part in conduction process.

Given : Avogadro's number : 6.023×10^{23} atoms / g-mole

Atomic weight of Ge = 72.6

Mobility of electrons = $3800 \text{ cm}^2/\text{volt-sec}$. Density of Ge = 5.32 g/cm^3

MU - Dec. 16, 3 Marks

Soln. :

$$\text{Atomic weight} = 72.6$$

$$\text{Density} = 5.32 \text{ g/cm}^3$$

$$\frac{5.32}{72.6} \times 6.023 \times 10^{23} = \frac{\text{Number of atoms}}{\text{cm}^3}$$

$$= 4.413 \times 10^{22}$$

Since Ge is doped with a donor impurity, it will become n-type. For impurity added one part in Ge

$$\frac{\text{Number of donor atoms}}{\text{cm}^3} = 4.413 \times 10^{16}$$

Every atom provides one electron.

$$\therefore \text{Concentration of electron} = 4.413 \times 10^{16} = n$$



$$\begin{aligned}\text{Conductivity } \sigma &= n e \mu_e \\ &= 4.413 \times 10^{16} \times 1.6 \times 10^{-19} \times 3800 \\ &= 26.831 \text{ mho.cm}^{-1}\end{aligned}$$

...Ans.

Ex. 3.11.11 : Calculate the current produced in a Ge sample of cross section 1 cm^2 and thickness of 0.01 m when potential difference of $2V$ is applied across it. The concentration of free electrons in Ge is $2 \times 10^{19}/\text{m}^3$ and mobilities of electron and holes are $0.36 \text{ m}^2/\text{V-sec}$ and $0.17 \text{ m}^2/\text{volt-sec}$. respectively.

MU - Dec. 16, 3 Marks

Soln. :

Ge is an intrinsic semiconductor.

$$\begin{aligned}\therefore \text{Conductivity } \sigma &= ne(\mu_n + \mu_e) \\ &= 2 \times 10^{19} \times 1.6 \times 10^{-19} \\ &\quad (0.36 + 0.17) \\ &= 1.696 \text{ mho m}^{-1}\end{aligned}$$

∴ Resistivity

$$\rho = \frac{1}{\sigma} = \frac{1}{1.696} = 0.5896 \text{ ohm-m}$$

Now

$$R = \frac{\rho l}{A} = \frac{0.5896 \times 0.01}{1 \times 10^{-4}} = 58.96 \text{ ohm.}$$

$$\therefore I = \frac{V}{R} = \frac{2}{58.96} = 0.034 \text{ Amp.}$$

3.12 Solved Problems on Fermi Level

Ex. 3.12.1 : What is the probability of an electron being thermally excited to conduction band in silicon at 27°C ? The band gap energy is 1.12 eV .

MU - Dec. 17, May 18, Dec. 18, 5/7 Marks

Soln. :

$$f(E_c) = \frac{1}{1 + \exp [(E_c - E_v) / KT]}$$

Remember

$$\begin{aligned}K &= \text{Boltzmann constant} \\ &= 1.38 \times 10^{-23} \text{ J/K}\end{aligned}$$

In eV it is given by

$$K (\text{in eV}) = \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}} = 86.25 \times 10^{-6} \text{ eV}$$

Also for intrinsic semiconductor

$$E_c - E_v = E_g / 2 = \frac{1.12}{2} = 0.56 \text{ eV}$$

$$\begin{aligned}\frac{E_c - E_v}{KT} &= \frac{0.56}{86.25 \times 10^{-6} \times (27 + 273)} \\ &= 21.64\end{aligned}$$

$$\therefore f(E_c) = \frac{1}{1 + e^{21.64}}$$

$$\therefore f(E_c) = 3.99 \times 10^{-10}$$

...Ans.

Ex. 3.12.2 : In a solid the energy level lies 0.012 eV below Fermi level. What is the probability of this level not being occupied by an electron?

Given : $T = 300^\circ \text{K}$, $k = 1.38 \times 10^{-23} \text{ J/K}$.

MU - Dec. 15, May 17, 5 Marks

Soln. :

$$\text{Here, } E_F - E = 0.012 \text{ eV}$$

$$kT = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}}$$

$$= 0.02587 \text{ eV}$$

\therefore The probability of an energy level not being occupied by an electron is $1 - f(E)$

$$1 - f(E) = 1 - \frac{1}{1 + \exp(E - E_F)/kT}$$

$$= 1 - \frac{1}{1 + \exp\left(\frac{0.012}{0.02587}\right)}$$

$$= 0.614$$

...Ans.

Ex. 3.12.3 : Explain the concept of Fermi level. What is the probability of an electron being thermally excited to conduction band in silicon at 20°C ? The band gap energy is 1.12 eV.

Given :

Boltzmann constant $1.38 \times 10^{-23} \text{ J/K}$.

MU - May 12, 4 Marks, Dec. 12, 3 Marks

Soln. :

$$f(E) = \frac{1}{[1 + \exp(E_C - E_V)/kT]}$$

$$K (\text{in eV}) = \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}} = 86.25 \times 10^{-6} \text{ eV}$$

For intrinsic semiconductor,

$$E_C - E_V = E_g/2 = \frac{1.12}{2} = 0.56 \text{ eV}$$

$$\begin{aligned} \therefore f(E_C) &= \frac{1}{1 + \exp\left[\frac{0.56}{86.25 \times 10^{-6} \times (20 + 273)}\right]} \\ &= \frac{1}{1 + \exp\left[\frac{0.56}{22.15956}\right]} \\ &= 2.37 \times 10^{-10} \end{aligned}$$

...Ans.

Ex. 3.12.4 : Fermi level in potassium is 2.1 eV. What are the energies for which the probability of occupancy at 300 K are 0.99 and 0.01?

MU - May 13, 3 Marks

Soln. :

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$



$$\text{For } k = 1.38 \times 10^{-23} \text{ J/K}$$

$$\text{and } T = 300 \text{ °K}$$

$$kT = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}}$$

$$= 0.026 \text{ eV}$$

$$\text{Hence for } f(E) = 0.99$$

$$0.99 = \frac{1}{1 + e^{(E - 2.1)/0.026}}$$

$$\therefore 1 + e^{(E - 2.1)/0.026} = \frac{1}{0.99} = 1.01$$

$$\therefore e^{(E - 2.1)/0.026} = 0.01$$

Taking \ln on both sides

$$(E - 2.1)/0.026 = e^{0.01} = 4.605$$

$$\therefore E - 2.1 = 0.1197$$

$$\therefore E = 1.98 \text{ eV}$$

...Ans.

Similarly for $f(E) = 0.01$

$$\text{We get } E = 2.218 \text{ eV}$$

...Ans.

Ex. 3.12.5 : Fermi energy of silver is 5.5 eV. Find the energy for which the probability of occupancy of 300 K is 0.9.

MU - Dec. 2014, 3 Marks

Soln. :

Formula :

$$F(E) = \frac{1}{1 + e^{(E - EF)/KT}}$$

Here,

$$E_F = 5.5 \text{ eV}$$

$$T = 300 \text{ K}$$

$$F(E) = 0.9$$

Consider

$$K = 1.38 \times 10^{-23} \text{ J/K}$$

$$= 86.25 \times 10^{-6} \text{ eV}$$

$$\therefore KT = 86.25 \times 10^{-6} \times 300$$

$$= 0.026$$

Substitute all these in formula]

$$\therefore 0.9 = \frac{1}{1 + e^{(E - 5.5)/0.026}}$$

$$\therefore e^{(E - 5.5)/0.026} = \frac{1}{0.9} - 1 = 0.111$$

Taking in on both sides

$$\frac{(E - 5.5)}{0.026} = \ln(0.111) = -2.197$$

$$\begin{aligned} E &= -2.197 \times 0.026 + 5.5 \\ &= 5.443 \text{ eV} \end{aligned}$$

...Ans.

Ex. 3.12.6 : What is the probability of an electron being thermally promoted to conduction band in diamond at 27 °C if band gap is 5.6 eV?

MU – May 15, May 16, 3 Marks

Soln. :

$$f(E) = \frac{1}{1 + \exp\left[\left(\frac{E_c - E_v}{2}\right)/KT\right]} \text{ for insulator}$$

$$\text{as } t = 27^\circ\text{C}$$

$$\therefore T = 300^\circ\text{K}$$

$$\begin{aligned} \text{take } K &= 1.38 \times 10^{-23} \text{ J/K} \\ &= 86.25 \times 10^{-6} \text{ eV} \end{aligned}$$

$$\therefore KT = 0.026 \text{ eV}$$

$$\text{also } E_g = \frac{E_c - E_v}{2} = 5.6 \text{ eV}$$

$$\therefore f(E) = \frac{1}{1 + \exp\left[\frac{5.6}{2 \times 0.026}\right]} = 1.7 \times 10^{-1}$$

...Ans.

(Since diamond is an insulator, very poor probability)

3.13 Solved Problems on Hall Effect

Ex. 3.13.1 : An n-type of Ge sample has a $N_D = 10^{21}/\text{m}^3$ and width 5 mm. It is arranged in a Hall effect experimental set up. If $B = 0.6 \text{ T}$, $J = 500 \text{ A/m}^2$, find Hall voltage.

Soln. :

$$\text{We know } V_H = \frac{BIw}{neA}$$

$$\text{Here } wd = A$$

$$\text{and taking } \frac{I}{A} = J$$

$$V_H = \frac{Bw}{ne} \cdot J$$

$$\text{take } n = N_D = \frac{BwJ}{N_D e}$$

$$\begin{aligned} \therefore V_H &= \frac{0.6 \times 5 \times 10^{-3} \times 500}{10^{21} \times 1.6 \times 10^{-19}} \\ &= 9.3 \text{ mV} \end{aligned}$$

...Ans.

Ex. 3.13.2 : A copper strip 2cm wide and 1mm thick is placed in a magnetic field $B = 1.5 \text{ wb/m}^2$. If current of 200A is set up in the strip, calculate Hall voltage that appears across the strip. (Given $R_H = 6 \times 10^{-7} \text{ m}^3/\text{C}$)

MU - May 10, 5 Marks



Soln.: Using equation (3.10.5)

$$R_H = \frac{V_{Ht}}{BI}$$

$$V_H = R_H \frac{BI}{t} = 6 \times 10^{-7} \times \frac{200 \times 1.5}{1 \times 10^{-3}}$$

$$V_H = 0.18 \text{ Volt}$$

...Ans.

Ex. 3.13.3 : The mobility of holes is $0.025 \text{ m}^2/\text{V}\cdot\text{sec}$. What would be the resistivity of p-type silicon if the Hall coefficient of the sample is $2.25 \times 10^{-5} \text{ m}^3/\text{C}$.

MU - Dec. 10, Dec. 12, May 17, May 19, 3 Marks

Soln.:

Formula :

$$\text{We know, } \sigma = ne\mu \text{ or, } \mu = \frac{1}{ne} \cdot \sigma = R_H \sigma$$

$$\text{or, } \sigma = \frac{\mu}{R_H} \text{ or, Resistivity } \rho = \frac{R_H}{\mu}$$

Data given :

$$R_H = 2.25 \times 10^{-5} \text{ m}^3/\text{C},$$

$$7\mu = 0.025 \text{ m}^2/\text{V}\cdot\text{s}$$

$$\text{So, } \rho = \frac{2.25 \times 10^{-5}}{0.025}$$

$$= 9 \times 10^{-4} \text{ ohm-m}$$

...Ans.

Ex. 3.13.4 : A sample of a n-type silicon has a donor density of $10^{20}/\text{m}^3$. It is used in the Hall effect experiment. If the sample of width 4.5 mm is kept in a magnetic field of (0.55T) with current density of 500 A/m^2 . Find

- (i) Hall voltage developed in it (ii) Hall coefficient (iii) Hall angle if mobility of electron is $0.17 \text{ m}^2/\text{V sec}$.

MU - Dec. 11, 5 Marks

Soln.:

Hall voltage developed

$$V_H = \frac{BJw}{ne} = R_H B J w$$

$$\text{Hall coefficient } R_H = \frac{1}{ne}$$

Data given :

$$n = 10^{20}/\text{m}^3, e = 1.6 \times 10^{-19} \text{ C}$$

So,

$$R_H = \frac{1}{10^{20} \times 1.6 \times 10^{-19}} = 0.0625 \text{ m}^3/\text{C}$$

(i) Hall voltage

$$V_H = R_H B J w$$

Data given :

$$B = 0.55, J = 500 \text{ A/m}^2, w = 4.5 \times 10^{-3} \text{ m}$$

$$V_H = 0.0625 \times 0.55 \times 500 \times 4.5 \times 10^{-3}$$

$$= 77.3 \times 10^{-3} \text{ V}$$

$$= 77.3 \text{ mV}$$

...Ans.

(ii) Hall coefficient

$$R_H = 0.0625 \text{ m}^3/\text{C}$$

...Ans.

(iii) Hall angle

$$\theta_H = \tan^{-1}(\mu B)$$

$$= \tan^{-1}(0.17 \times 0.55)$$

$$= 5.3^\circ$$

...Ans.

Ex. 3.13.5 : The Hall coefficient of a specimen is $3.66 \times 10^{-4} \text{ m}^3/\text{C}$. Its resistivity is $8.93 \times 10^{-3} \Omega \cdot \text{m}$. Find μ and n .

MU - May 2011, 4 Marks

Soln. :

Formula :

Hall coefficient

$$R_H = \frac{1}{n e}$$

$$n = \frac{1}{R_H \cdot e}$$

Data given :

$$R_H = 3.66 \times 10^{-4} \text{ m}^3/\text{C}$$

So,

$$n = \frac{1}{3.66 \times 10^{-4} \times 1.6 \times 10^{-19}}$$

$$= 1.7 \times 10^{22}/\text{m}^3$$

...Ans.

Also, we know

$$\sigma = n e \mu$$

$$\mu = \frac{\sigma}{n e} = \sigma \times R_H = 1/\rho \times R_H = \frac{R_H}{\rho}$$

$$= \frac{3.66 \times 10^{-4}}{8.93 \times 10^{-3}}$$

$$\mu = 0.040 \text{ m}^2/\text{V} \cdot \text{s}$$

...Ans.

Ex. 3.13.6 : A bar of n-type Ge of size $0.010 \text{ m} \times 0.001 \text{ m} \times 0.001 \text{ m}$ is mounted in a magnetic field of $2 \times 10^{-1} \text{ T}$. The electron density in the bar is $7 \times 10^{21}/\text{m}^3$. If one millivolt is applied across the long ends of the bar, determine the current through the bar and the voltage between Hall electrodes placed across the short dimensions of the bar. Assume $\mu_e = 0.39 \text{ m}^2/\text{Vs}$.

MU - May 13, 5 Marks

Soln. :

$$\text{As } \rho = \frac{1}{\mu_n e} = \frac{1}{0.39 \times 7 \times 10^{21} \times 1.6 \times 10^{-19}}$$

$$= 2.29 \times 10^{-3} \text{ ohm/m}$$

$$\text{Now } R = \frac{\rho l}{A} = \frac{2.29 \times 10^{-3} \times 0.01}{(0.001 \times 0.001)} = 22.9 \Omega$$

(Here long side is used as length as instructed and other two sides are forming width and height which in turn gives cross-sectional area)

Using Ohm's law



$$I = \frac{V}{R} = \frac{1 \times 10^{-3}}{22.9} = 43.66 \mu\text{A}$$

Using formula for Hall voltage

$$V_H = R_H BJw$$

$$\text{As, } R_H = \rho \times \mu$$

$$\text{And, } J = \frac{I}{A} = \frac{I}{w \times t}$$

$$V_H = \rho \times \mu \times B \times \frac{I}{wt} \times t = \frac{\rho \mu B I}{w}$$

$$= \frac{2.29 \times 10^{-3} \times 0.39 \times 0.2 \times 43.66 \times 10^{-6}}{0.001}$$

$$= 7.798 \mu\text{V}$$

...Ans.

Ex. 3.13.7 : In a semiconductor with Hall coefficient 145 cc/C having width 2 cm and thickness 0.2 cm with a magnetic field induction of 2T along the smaller dimension, a current of 150 mA is calculate the current density and Hall voltage.

MU - Dec. 14, 5 Marks

Soln. :

Given :

Hall coefficient $R_H = 145 \text{ cc/C}$, Width $w = 2 \text{ cm}$

thickness $t = 0.2 \text{ cm}$, magnetic field $B = 2TI = 150 \text{ mA}$

Current density

$$\begin{aligned} J &= \frac{I}{A} = \frac{I}{W \times d} \\ &= \frac{150 \times 10^{-3}}{2 \times 10^{-2} \times 0.2 \times 10^{-2}} \\ &= 3750 \text{ A/m}^2 \end{aligned}$$

Now

Hall co-efficient

$$R_H = \frac{V_H/d}{JB}$$

$$V_H = R_H JB$$

$$\begin{aligned} \text{Now, } w &= 145 \times 10^{-6} \times 3750 \times 2 \times 0.2 \times 10^{-2} \\ &= 21.75 \text{ mV} \end{aligned}$$

...Ans.

Ex. 3.13.8 : In an n-type semiconductor the Fermi level lies 0.4 eV below the conduction band. If the concentration of donor atom is doubled, find the new position of the Fermi level w.r.t. the conduction band.

MU - May 13, 5 Marks

Note : This problem needs assumption of temperature to arrive at the answer

Soln. : Given :

$$E_C - E_F = 0.4 \text{ eV}$$

Now concentration of donor atom is doubled, hence number of electrons will be doubled.

∴ At any temperature $T > 0^\circ \text{K}$

$$n_e = N e^{-(E_C - E_F)/kT} \quad \dots(1)$$

where n_e = Number of electrons in conduction band

When donor concentration is doubled, $n'_e = 2 n_e$, and Fermi level must have been shifted to a new location say E'_F ,

$$2 n_e = N e^{-(E_C - E'_F)/kT} \quad \dots(2)$$

Divide equation (2) by (1)

$$\begin{aligned} \frac{2n_e}{n_e} &= \frac{N e^{-(E_C - E'_F)/kT}}{N e^{-(E_C - E_F)/kT}} \\ \alpha &= e^{[(E'_F - E_C) + (E_C - E_F)]/4kT} \end{aligned}$$

For Boltzmann constant $K = 1.38 \times 10^{-23} \text{ J/K}$ and with an assumption $T = 300^\circ \text{K}$

$$\begin{aligned} KT &= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \\ &= 0.026 \text{ eV} \end{aligned}$$

∴ Equation (3) becomes,

$$2 = e^{[(E'_F - E_C) + (E_F - E_C)]/0.026}$$

Taking \ln on both sides

$$\ln 2 = \frac{[(E'_F - E_C) + (E_F - E_C)]}{0.026}$$

$$0.026 \times \ln 2 = (E'_F - E_C) + (E_F - E_C)$$

But $E_F - E_C = 0.4 \text{ eV}$ given

$$0.01802 = (E'_F - E_C) + 0.4$$

$$E_C - E'_F = 0.4 - 0.01802 = 0.38198 \quad \dots\text{Ans.}$$

∴ Fermi level will be shifted towards conduction band.

Ex. 3.13.9 : In a Hall effect experiment a potential difference of $4.5 \mu\text{V}$ is developed across a foil of zinc of thickness 0.02 mm . When a current of 1.5 A is in a direction perpendicular to applied magnetic field of 2T , calculate

- a) Hall coefficient of zinc b) Concentration of electrons

MU - Dec. 16, 7

Marks

Soln. : Using formula

$$1. \quad R_H = \frac{V_H t}{BI} = \frac{4.5 \times 10^{-6} \times 0.02 \times 10^{-3}}{2 \times 10^5} = 3 \times 10^{-11}$$

$$2. \quad \text{As } R_H = \frac{1}{n_e}$$

$$\begin{aligned} \therefore n &= \frac{1}{R_H \cdot e} = \frac{1}{3 \times 10^{-11} \times 1.6 \times 10^{-19}} \\ &= 2.083 \times 10^{29} / \text{m}^3 \end{aligned}$$

... Ans.

