1.1   INTRODUCTION

The conduction of every discrete solid-state electronic devices or integrated circuit begins with semiconductor materials of the highest quality. Therefore, in this introductory chapter we will discuss qualitatively about the semiconductor.

Based on the electrical conductivity, that is, the ability to conduct current, all the materials in the world can be classified under three categories,

(1) **Conductors** : Examples of conductors are as Aluminium, Iron, Copper, ... etc.,).

(2) **Insulators** : Examples of insulators are Wood, mica, ... etc.,).

(3) **Semiconductors** : Examples of semiconductors are Germanium, Silicon, ..., etc.,).

Among all these three materials, conductors have highest conductivity whereas insulators have the lowest conductivity. Semiconductor materials have electrical conductivity which lies in between conductors and insulators.

Out of these three classes of materials, semiconductors are the most important in electronics engineering because their electrical properties can be readily engineered. In its pure form, silicon is the most widely used semiconductor which exhibits a conductivity of 5.0×10^{-4} S/m at 300°K. However by introducing a very small amount of impurity (few parts per million) in silicon, it is possible to increase this value by several orders of magnitude. This unique property of semiconductors has fuelled intense research in this field that has rooted in the success of semiconductor devices and integrated circuits.

1.1.1   Review of Atomic Structure

The smallest distinguishable unit of different kinds of matter is called an atom. An atom consists of a nucleus at centre with electrons (negative particles) orbiting around nucleus as shown in Fig. 1.1.1,

Electrons• Neutrons N± Protons P+
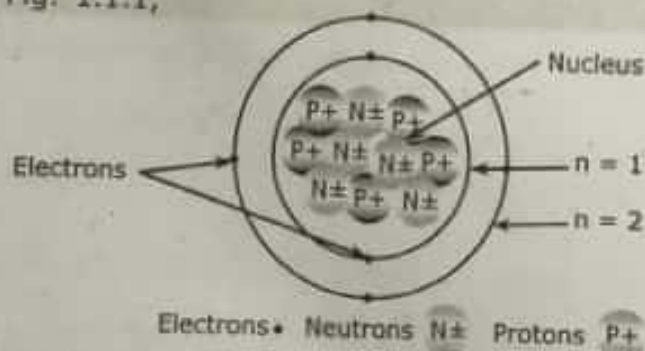
Fig. 1.1.1 Atoms are Composed of Protons, Neutrons and Electrons

As shown in Fig. 1.1.1, the nucleus of an atom is a cluster of two types of particles, namely protons and neutrons. Protons have positive electrical charge (equal in magnitude but opposite in polarity) to the negative charge of an electron. Neutrons has no charge at all. In a normal, stable atom, the number of electrons in the orbits exactly equals to the number of protons in the nucleus. This means that the *total electrical charge of the atom is zero* (i.e., all the atoms are electrically neutral).

1.2 ENERGY LEVELS

We have mentioned in section 1.1.1, that in an atom, the electrons revolve around the nucleus in certain orbits. This is similar to planets orbiting around the sun. The electrons possess kinetic energy which is corresponding to the radius of the orbit. Infact, the electron can possess only certain discrete energies and hence can remain in certain specific orbits. The electrons located in such orbits are known to be in 'stationary states'. The energy level E_n (in Joules) of any stationary state can be calculated by the expression,

$$E_n = - \frac{m\,(e)^4}{8\,h^2\,\varepsilon_0^2} \cdot \frac{1}{n^2}$$ — (1.2.1)

Where n is an integer,

m = Mass of an electron (in kilogram)

e = Charge of an electron (in coulombs)

h = Planck's constant (in Joule-seconds)

ε_0 = Permittivity of free space.

These energy levels are commonly expressed in an unit called electron volts (eV), where,

1 eV = 1.60 × 10^{-19} Joules
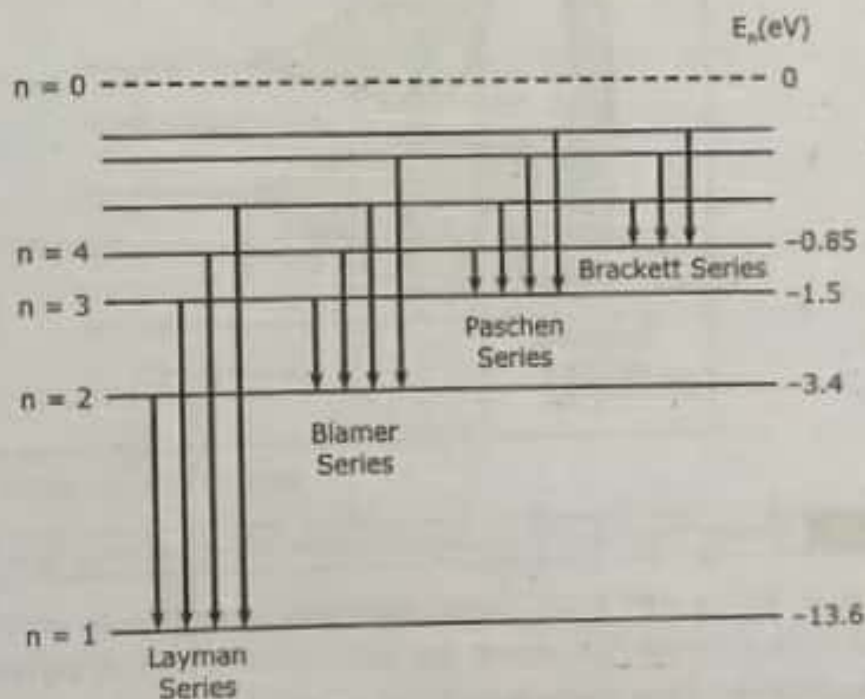
Fig. 1.2.1, shows the energy level diagram for hydrogen,

Fig. 1.2.1 Energy Level Diagram of Hydrogen Atom

The number which is immediate to the left of a line gives the value of integer n, while the number to the right of each line gives the energy to this level in electron volts. The lowest energy level E_1 is called the normal or the ground state of the atom and the higher energy levels E_2, E_3, E_4, ... are called the excited states. As n increases, the energy levels crowd and tend to form a continuum.

If an electron changes its orbit from one 'stationary state' (n = 2 with energy level E_2) to another stationary state (n = 1 with energy level E_1) then it will emit a radiation of energy corresponding to ($E_2 - E_1$). It is more convenient to specify the emitted radiation by its wavelength.
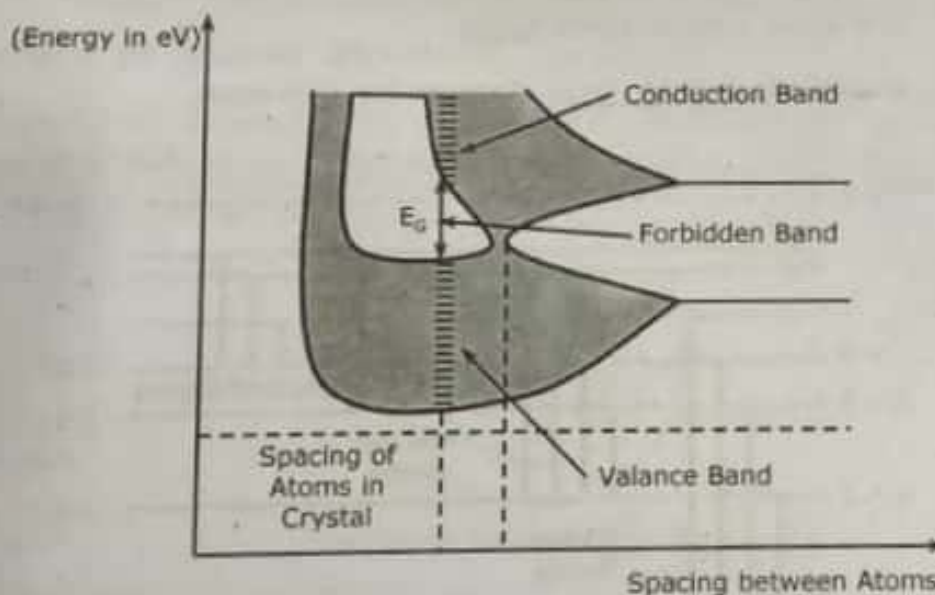
λ in Angstroms is given as,

$$\lambda = \frac{12,400}{E_2 - E_1}$$ ... (1.2.2)

1.2.1 Energy Levels in Crystals

We know that majority of metals and semiconductors have crystalline structure, in which the atoms/molecules of the material are arranged in particular structural pattern, in three dimensions.

Fig. 1.2.2 Energy Band in Crystal as a Function of Interatomic Spacing

The electrons in an isolated atom (here hydrogen) have energy levels as shown in Fig. 1.2.1, however, in a crystal the atoms are not isolated, on the contrary, atoms are rather close to each other. Such closeness of the atoms results in change in the energy levels of the electrons of the outermost shell, due to sharing of electrons.
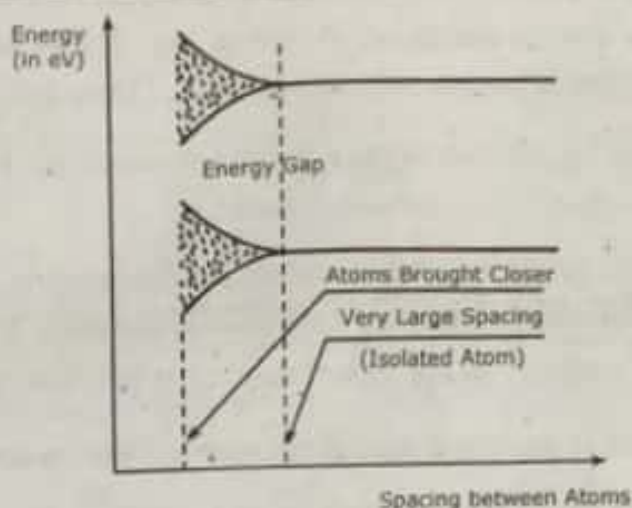
Fig. 1.2.3 | Formation of Energy Band in a Crystal

For understanding the effects of this closeness, let us imagine that we reduce the spacing between atoms. An atom will now exert electric force on its neighbours and because of this the energy levels, which had definite values for isolated atoms, will now widen to become energy bands, as shown in Fig. 1.2.2, the X-axis of the graphs of Figs. 1.2.2 and 1.2.3, represents the spacing between atoms. The electrons which possess enough energy to go to conduction band can move freely within the material for conduction. The electrons possessing little lesser energies remain in the valance band and therefore remain attached to the atom. However, if the electrons in the valance band can manage to acquire sufficient energy, they can move up to conduction band. For that these electron must acquire an energy atleast equal to E_G.

1.2.2 Energy Band Diagrams

The graphical representation of the energy-levels in a solid is called energy band diagram. The distinction among each of the three materials can now be made based on the energy band diagrams of a material.

Following Fig. 1.2.4 illustrates the discrete energy levels,
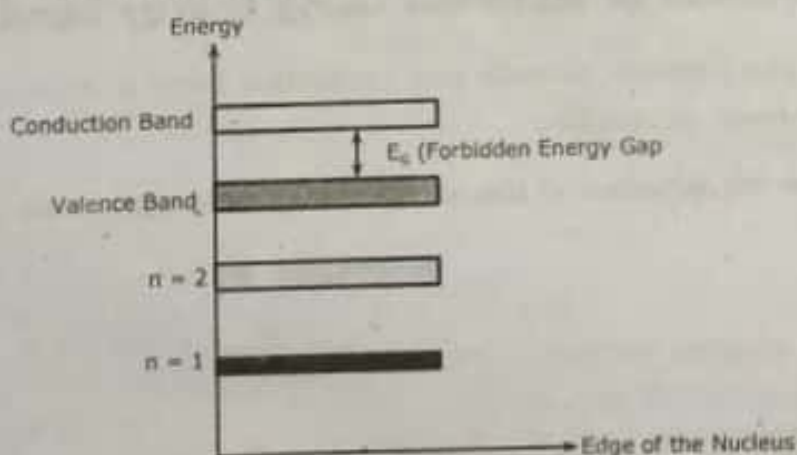
Fig. 1.2.4 | Discrete Energy Levels

We focus on three energy bands as shown in Fig. 1.2.4, which are most important to differentiate the electrical properties of materials. They are,

(1) **Conduction Band :** The highest energy band separated by a forbidden gap from the valence band, is called the conduction band.

   The electrons in conduction band constitute the electric current in the materials. These electrons are often called as free electrons, since they can move relatively free in a material without being associated with any particular atom.

   COMMENT : *The electric current is zero if the material has empty conduction band.*

(2) **Forbidden Band :** Forbidden energy band is separated by regions of energy bands that cannot have any electrons. This energy band is completely empty and the minimum energy required for moving electrons from valence band to conduction band is called as Energy band gap, denoted by E_G, and is measured in electron volts (eV).

   Electrons in the valence shell must acquire energy greater than E_G to become a free electron. An energy less than E_G will not be accepted by materials because there is no permissible level between valence band and conduction band.

   COMMENT : *Forbidden gap has no electrons.*

(3) **Valence Band :** The energy bands which are completely filled by electrons at absolute zero temperature ($0°K$) is called as valence band. No electrons in a completely filled energy band can move, since there is no empty space to move. Therefore, an electron in a valence band does not contribute to electric current. Electrons in the valence band can be moved if they are excited by heat, or external voltage source.

1.2.3 Classification of Materials Using Energy Band Diagram

The energy gap between valence and conduction band is an important measure of how materials behave electrically.

Depending on the structure of the energy band, materials can be classified into three categories,

They are,

(1) Insulators.

(2) Semi-conductors.

(3) Conductors.

(a) Insulator   (b) Semi-conductors   (c) Conductors
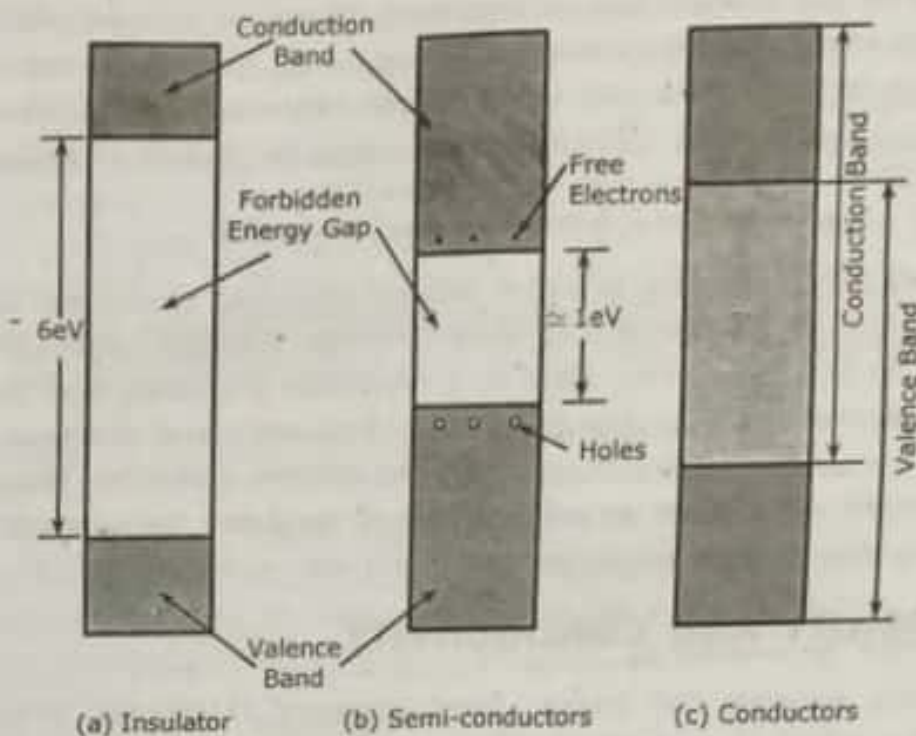
Fig. 1.2.5 Energy-Band Diagram

(1) **Insulators :** The materials in which the conduction band and valence band are separated by a wide energy ($\approx$ 6eV) gap as shown in Fig. 1.2.5(a) are called Insulators. Since the forbidden energy gap is very large, the applied electric field will not provide sufficient energy to the electrons to jump from the valence band to the conduction band. Therefore in an insulator, conduction is very poor. Few good examples for insulators are diamond, wood, etc.,

(2) **Semi Conductors :** The materials in which the conduction band and valence band are separated by the small forbidden energy gap ($\approx$ 1eV) are called semiconductors as shown in Fig. 1.2.5(b). Silicon and germanium are the most commonly used semiconductors. A small energy gap implies that relatively a small amount of energy is required to move the electrons from the valence band to conduction band. A vacant space created by moving electron from valence band to conduction band is called as Hole.

The forbidden energy gap of germanium and silicon semiconductors are,

$$E_G(\text{Germanium}) = 0.67 \text{ eV}$$
$$E_G(\text{Silicon}) = 1.1 \text{ eV}$$

At absolute zero temperature (0^0K), the semiconductor behaves like a perfect insulator since no valence electrons in outermost shell acquire sufficient energy (i.e., more than E_G) to move into conduction band. But as the temperature is increased from 0^0K, some of the valence electrons acquire sufficient thermal energy greater than E_G and move into the conduction band.

1.8

Thus, as the temperature is increased, it results in more free electrons in the conduction band and holes in the valence band, which increases the conductivity of the material. In other words, the resistivity decreases with increase in temperature.

Thus, *semiconductor has negative temperature coefficient of resistance.*

COMMENT : *Semiconductors behave as an insulator at* $0°K$.

(3) **Conductors** : The materials in which valence band and conduction band overlap each other are called conductors as shown in Fig. 1.2.5(c), although the number of electrons in the conduction band in a conductor increases with temperature, their number becomes so vast that they collide frequently and interfere with each other's progress under the influence of an applied electric potential. Therefore, it becomes more difficult to establish an uniform flow of resistance for conductors. In conductors current is due to free electrons only.

1.3 MOBILITY AND CONDUCTIVITY

Previously we saw the energy-band pictures of metals, semiconductors and insulators. In a metal, an outer (or) valence electrons of an atom are as much associated with one ion as with another ion. So that the electron attachment to any individual atom is almost zero. In the previous discussion, at higher energies, there are no forbidden levels because of the valence electrons may not be filled when band occupied by this valence electrons. Depending upon the metal, the electrons are free to move atleast one (or) some-times two (or) three per atom throughout the interior (or) inside of the metal under the action of applied fields.

Fig. 1.3.1, shows the charge distribution within a metal by using sodium,

0 1 2 3 4 5

Å units
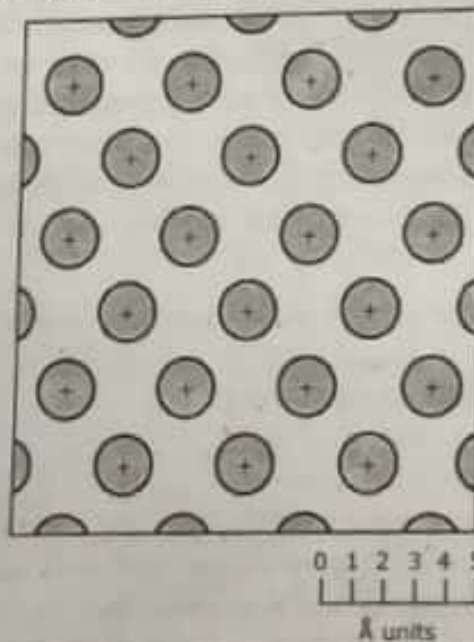
Fig. 1.3.1 Arrangement of the Sodium Atoms in One Plane of the Metal

In this, the plus sign represents heavy positive sodium nuclei of the individual atoms. Here, two regions are present i.e., shaded and unshaded. Shaded region represent the electrons the nucleus. These are inappreciably disturbed as the atoms come together to form the metal. The unshaded volume contains the outer (or) valence electrons in the atom. These electrons cannot be said to belong to any particular form, instead, they have completely lost their individuality and can move freely from atom to atom in the metal. Thus, a metal is visualized as a region containing a periodic three-dimensional array of heavy, tightly bound ions permeated within a swarm of electrons that may move about quite freely. This picture is known as the electron-gas description of a metal.

According to the electron gas theory of a metal, the free (conduction) electrons move quite freely inside the metal. They do not interact much with the atoms or the covalent bonds present in the crystal. The only interaction is with the heavy ions and deviates its path on each collision. Therefore the motion of electrons is random. On an average, the number of electrons crossing an unit area in one direction is equal to the number of electrons crossing the same area in opposite direction. Hence the net current is zero.

1.3.1 Mobility and Drift Velocity

Suppose when a steady electric field (E) is applied across a metal, the negatively charged electrons experiences a constant force and moves towards the positive terminal of applied voltage. In their path, electrons collide continuously with the atoms and rebound in a random fashion. Each collision being inelastic (i.e., the electron loses some kinetic energy). After the collision, the electrons are accelerated and gains certain component of velocity in opposite direction to that of applied electric field and loses its energy at the next collision. As a result, the applied electric field does not stop collisions and random motion, instead causes the electrons to drift towards the positive terminal.

The average velocity with which the charge carriers drift in a definite direction under the influence of an applied electric field is called drift velocity v_d.

Its value depends on two factors, namely,

(1) Nature of charge carriers.

(2) Applied electric field.

The drift velocity is proportional to the electric field and is given by,

$$v_d \propto E \text{ (or) } \boxed{v_d = \mu E} \qquad \qquad ... (1.3.1)$$

Where μ is the proportionality constant called as mobility.

The mobility of charge carriers can be defined from Eq. (1.3.1) as the drift velocity (in m/s) per unit applied electric field (in V/m). That is,

$$\mu = \frac{v_d}{E}$$

The units of μ are,

In MK.S system : $\dfrac{m/sec}{V/m} = \dfrac{m}{sec} \cdot \dfrac{m}{V} = m^2/V\text{-}sec$

In C.G.S system : $\dfrac{cm/sec}{V/cm} = \dfrac{cm}{sec} \cdot \dfrac{cm}{V} = cm^2/V\text{-}sec$

The value of mobility depends upon many factors, such as temperature, purity of the material and the type of impurity added. For germanium and silicon the mobility of electrons in the conduction band is more than that of the holes in the valence band. This arises from the fact that the electrons in the conduction band are more free of the attractive forces of the nuclei than are the holes in the valence band, which move only as a result of the slower drift of the electrons in the covalent bonds.

Effect of Temperature on Mobility : Mobility μ of a charge carrier varies as T^{-m} over a temperature range of 100 to 400°K.

For silicon, m = 2.5 for electron and 2.7 for hole.

For germanium, m = 1.66 for electron and 2.33 for hole.

1.3.2 Conductivity

Consider a conductor of length L and area of cross-section A. A battery of voltage V is applied across its length, as shown in Fig. 1.3.2,
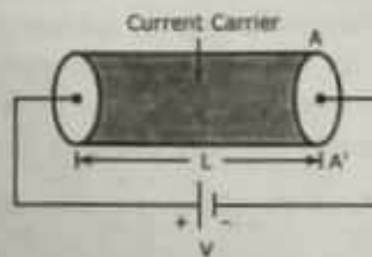

Fig. 1.3.2 Illustration of Conductivity in a Conductor

Let n be the concentration of charge carriers (say, electrons) and e be the charge on each electron. If v_d is the drift velocity acquired, then the time taken by a charge carrier to cross the length L of the conductor is,

$$t = \dfrac{L}{v_d}$$

The total amount of charge in unit volume = ne

The total charge in the conductor, Q = ne × (volume) = neAL

As this charge crosses AA' in 't' seconds, the electric current flowing through the conductor is, by definition the equation is given as,

$$I = \dfrac{Q}{t} = \dfrac{neAL}{L/V_d} = enAv_d = neA\mu E \qquad (\because v_d = \mu E) \qquad \dots (1.3.2)$$

The current density J, that is, the current per unit area of cross-section given as,

$$J = \frac{I}{A} = ne\mu E \quad \text{... (1.3.3)}$$

Replacing the quantity $ne\mu$ by a constant σ,

$$\sigma = ne\mu$$

This constant (for a given conductor at a given temperature) is called the conductivity of the conductor. Eq. (1.3.3), can now be thus written as,

$$\therefore \quad J = \sigma E \quad \text{... (1.3.4)}$$

Thus, the electrical conductivity is the current density per unit electric field is given as,

$$\boxed{\sigma = \frac{J}{E}}$$

Eq. (1.3.4) is simply Ohm's law ($I = GV$, where G is the total conductance). Put in another form, the conductivity σ is just the inverse of resistivity ρ,

$$\boxed{\sigma = \frac{1}{\rho}} \ (S/m)$$

In SI, σ is given in siemens/meter (i.e., S/m). 1 siemen equals 1 mho.

EXAMPLE PROBLEM 1

(a) Prove that the concentration n of free electrons per cubic meter of a metal is given by,

$$n = \frac{dv}{AM} = \frac{(A_0 dv) \times 10^3}{A}$$

Where,

d = Density, kg/m^3

v = Valence, free electrons per atom

A = Atomic weight

M = Weight of a atom of unit atomic weight, kg (Appendix A)

A_0 = Avogadro's number, molecules/mole

(b) Compute the mobility of the free electrons in aluminum for which the density is 2.70 l³, atomic weight is 26.98 and the resistivity is 3.44 × 10⁻⁶ Ωcm. Assume that the aluminum has three valence electrons per atom.

SOLUTION

(a) Since, the mass of any atom m_a(kg) is given by the product of the atomic weight of the atom (A) and the fixed mass M($=1.660 \times 10^{-27}$ kg) of a hypothetical atom with unit atomic weight, the mass of any atom can be expressed as,

$$m_a = AM \frac{kg}{atom}$$

If there are x number of atoms in a metal per m^3(i.e., per unit volume), We can get,

$$m_a x = d$$

(or) $$x = \frac{d}{m_a} = \frac{d}{AM} \text{ atoms/m}^3$$

Since v represents the number of free electrons per atom, the number of free electrons per m^3 (i.e., the concentration of free electrons) can be expressed in the desired form as,

$$n = v \frac{electrons}{atoms} \times x \frac{atoms}{m^3} = \frac{dv}{AM} \frac{electrons}{m^3}$$

It may be mentioned here that the Avogadro's number represents the number of molecules present in one gram-mole (i.e., gram-molecular weight) of any material which is always a constant A_0 ($= 6.023 \times 10^{23}$). For the metals, since each molecule consists of a single atom, the gram-molecular weight equals to the gram-atomic weight and hence the mass of the hypothetical atom with unit atomic weight can be given by,

$$M = \frac{1}{A_0} \frac{g}{atom} = \frac{10^{-3}}{A_0} \frac{kg}{atom} = \frac{1}{A_0 \times 10^3} \frac{kg}{atom}$$

Substituting $M = \frac{1}{A_0 \times 10^3}$ in the expression for the concentration of free electrons, we can get the desired result for n as,

$$n = \frac{dv}{AM} = \frac{(A_0 dv) \times 10^3}{A} \frac{electrons}{m^3}$$

(b) Using the values of A = 26.98, M = $1.660 \times 10^{-27} \frac{kg}{atom}$, $v = 3 \frac{electrons}{atom}$ and

$d = 2.70 \frac{g}{cm^3} = \frac{2.70 \times 10^{-3} kg}{10^{-6} m^3} = 2.70 \times 10^3 \frac{kg}{m^3}$, the concentration of free electrons in aluminum is given by,

$$n = \frac{2.70 \times 10^3 \frac{kg}{m^3} \times 3 \frac{electrons}{atom}}{26.98 \times 1.660 \times 10^{-27} \frac{kg}{atom}}$$

$$= 1.808 \times 10^{29} \frac{electrons}{m^3}$$

From Eq. $\sigma = ne\mu$, the conductivity of the aluminum can be given by,

$$\sigma = 1.808 \times 10^{29} \frac{electrons}{m^3} \times 1.60 \times 10^{-19} \frac{Coulomb}{electron} \times \mu \frac{m^2}{V\,sec}$$

$$= 2.893 \times 10^{10} \times \frac{1}{\Omega m}$$

Since resistivity is the reciprocal of the conductivity, the mobility of electron in the aluminum metal is obtained as,

$$3.44 \times 10^{-8} \Omega m = \frac{1}{\sigma}$$

$$= \frac{1}{2.893 \times 10^{10} \times \mu} \Omega m$$

(or) $$\mu = \frac{1}{3.44 \times 10^{-8} \times 2.893 \times 10^{10}} \frac{m^2}{V\,sec}$$

$$= \frac{10^4}{9.952 \times 10^2} \frac{cm^2}{V\,sec}$$

$$= 10.04 \frac{cm^2}{V\,sec}$$

1.4 CLASSIFICATIONS OF SEMICONDUCTORS

Semiconductors are classified into two types. They are,

(1) Intrinsic semiconductors.

(2) Extrinsic semiconductors.

The detailed explanation of above two types are discussed in below sections.

1.4.1 Intrinsic Semiconductors

A semiconductor material which is available in its purest form (i.e., free of impurity) called as intrinsic semiconductors or pure semiconductors. A semiconductor is not considered as an pure semiconductor unless its impurity content is reduced to less than 1 part of impurity in 10^3 million parts of a semiconductor.

(1) **Electron-Hole Concept :** The electrical conductivity of a pure semiconductor is totally governed by the number of electrons excited from the valence band to the conduction band is called intrinsic conductivity. At absolute zero temperature ($0°K$), the crystal structure of an intrinsic semiconductor is as shown in Fig. 1.4.1(a) and it behaves as an insulator because no free charge carriers are available.

(a) Crystal Structure
Semiconductor at T = 0°K

(b) Crystal Structure of Intrinsic
Semi Conductor at T > 0°K
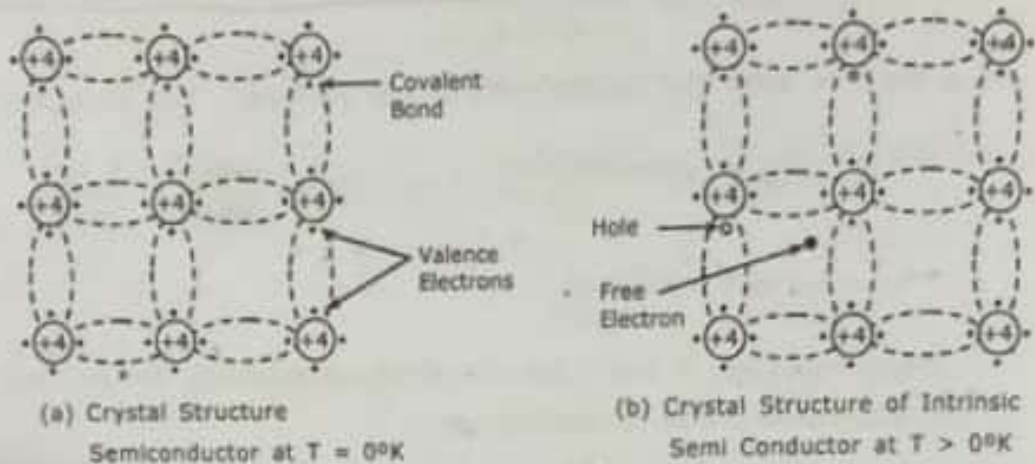
Fig. 1.4.1 Two Dimensional Crystal Structure of an Intrinsic Semiconductor at T = 0°K and T > 0°K

As the temperature increases above $0°K$, some of the valence electrons acquires energy greater than E_g and moves from the valence band to the conduction band of a semiconductor by breaking its covalent bond, thereby leaves behind an unfilled electron state as shown in Fig. 1.4.1(b). This unfilled electron state, or vacancy, is called a hole. Since it denotes the absence of a negatively charged electron, hence it is treated as a positively charged particle in the valence band. Hence, a semiconductor has two kinds of charges that constitute electric currents (Both electron and holes). For convenience, *a hole is considered as an active particle in the valence band, and an electron is considered as an active particle in the conduction band.*

(2) **Energy Band-Diagram of Intrinsic Semiconductor :** A free electron and hole has same magnitude of charge equal to 1.6×10^{-19} C. The energy band diagrams illustrating the concept of electron-hole is as shown in Fig. 1.4.2,
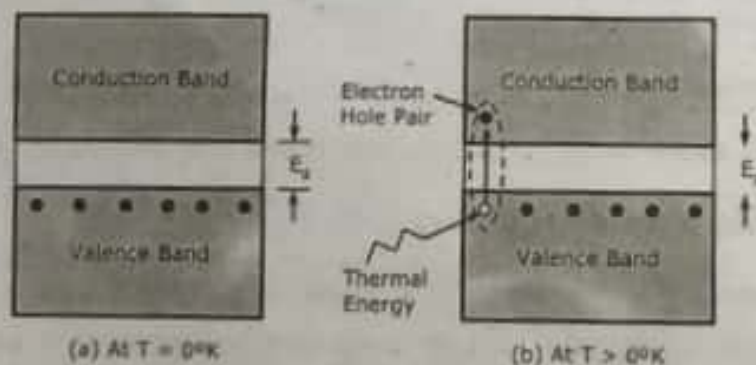
(a) At T = 0°K

(b) At T > 0°K

Fig. 1.4.2 Energy Band Diagram of Intrinsic Semiconductor at T = 0°K and T > 0°K

(3) Why electrons have more mobility than holes? : The movement of holes in the crystal actually involves in the movement of electrons. But this movement is quite different from the movement of conduction electrons. The conduction electrons move quite freely (without much interaction with the atoms and the bonds). But for the hole-movement, the electrons jump from one bond to the other. This is the reason why the holes appear to travel more slowly than the conduction electrons. In other words, the mobility of holes is less than that of free electrons.

1.4.2 Extrinsic Semiconductors

Inorder to develop useful electronic devices, the carrier concentration of intrinsic semiconductors is not sufficient for devices like diodes, transistor, and integrated circuits. So to acquire the sufficient electrical conductivity, we add some impurities to the intrinsic semiconductors.

(1) *The process of adding impurities to a pure (intrinsic) semiconductor material is called as Doping*, and the semiconductor materials thus obtained are called *extrinsic semiconductors*. Extrinsic semiconductors are also called as *impure semiconductors*, because they are being doped by adding some impurities.

(2) **Types of Dopants** : *The impurities added to intrinsic semiconductors are called as Dopants*. Two types of dopants are generally used. They are,

(i) **Pentavalent Atoms** : Atoms having five valence electrons in its outermost shell are called as pentavalent atoms.

Example : Phosphorous, Arsenic or Antimony, Bismuth. For the aid of memory remember these atoms with their starting letter as 'PAAB'.

(ii) **Trivalent Atoms** : Atoms having three valence electrons in its outermost shell are called as trivalent atoms.

Example : Boron, aluminium, Galium, Indium. For the aid of memory, remember them as "BAGI".

(3) **Types of Extrinsic Semiconductors** : Based on impurities added to intrinsic semiconductors, extrinsic (impure) semiconductors are again categorized as two types, namely,

(i) **P-type Extrinsic Semiconductor** : Doping with trivalent atoms lead to the formation of P-type semiconductors.

(ii) **N-type Extrinsic Semiconductor** : Doping with pentavalent atoms lead to the formation of N-type semiconductors.

1.4.2 P-type Semiconductors

When a trivalent impurity atom (such as Boron or Aluminium) is added to a pure semiconductor crystal during the crystal growth, the resulting crystal is called as P-type semiconductor.

Let us consider the case when trivalent impurity Aluminium (which has 3 valence electrons) is added to pure silicon crystal. Crystal structure formed is as shown in Fig. 1.4.3, such that three valence electrons of aluminium atom form covalent bonds with the valence electrons of silicon atom. There is a deficiency of one electron, which is called a hole.
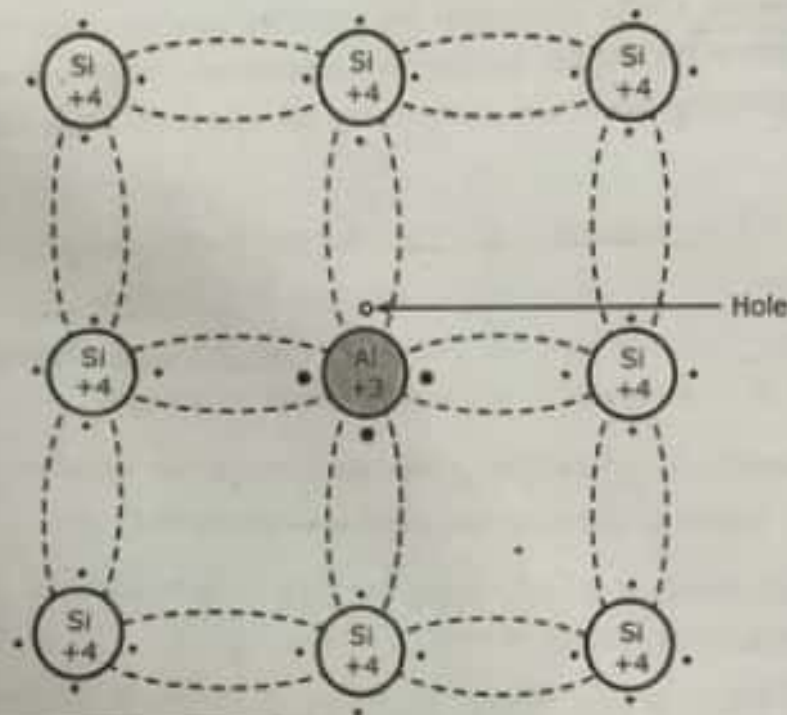

Fig. 1.4.3 Two Dimensional Crystal Structure of P-Type Extrinsic Semiconductor

Impurity atoms that contribute holes in this manner are termed as acceptors because they accept electrons from silicon atoms. Since current carriers are positively charged particles (holes) hence this type of semiconductor is called as P-type semiconductor.

Energy Band Diagram of P-type Semiconductor : When acceptor impurity is added to Silicon atom, the allowable energy levels are introduced at a very small distance above the valence band as shown in Fig. 1.4.4. These levels are called as acceptor energy levels. At room temperature due to thermal energy the electrons from the valence band are easily transferred to the acceptor level until these levels are filled. This produces a large number of holes in the valence band. When a external electric field is applied to p-type semiconductor, these holes will act as carriers of current. Due to this, the p-type semiconductor shows its electrical conductivity much improved than what it was for pure semiconductor.
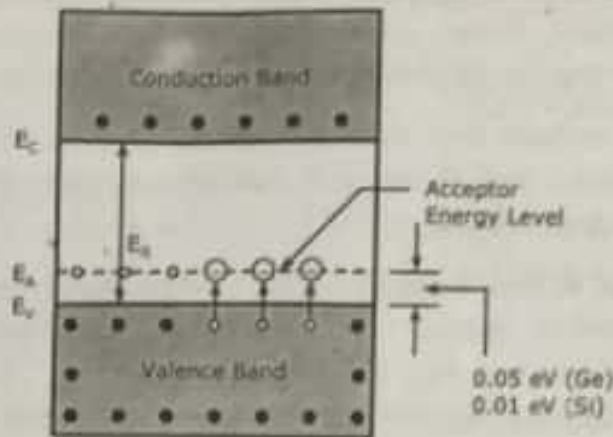
Fig. 1.4.4 Energy Band Diagram of P-type Semiconductor

1.4.2.2 N-type Semiconductors

When a pentavalent impurity such as arsenic is added to a pure semiconductor crystal during the crystal growth, the resulting crystal is called N-type extrinsic semiconductor.

Let us consider the case, when pentavalent arsenic atom (which has 5 valence electrons), is added to a pure silicon crystal. The crystal structure formed is as shown in Fig. 1.4.5.
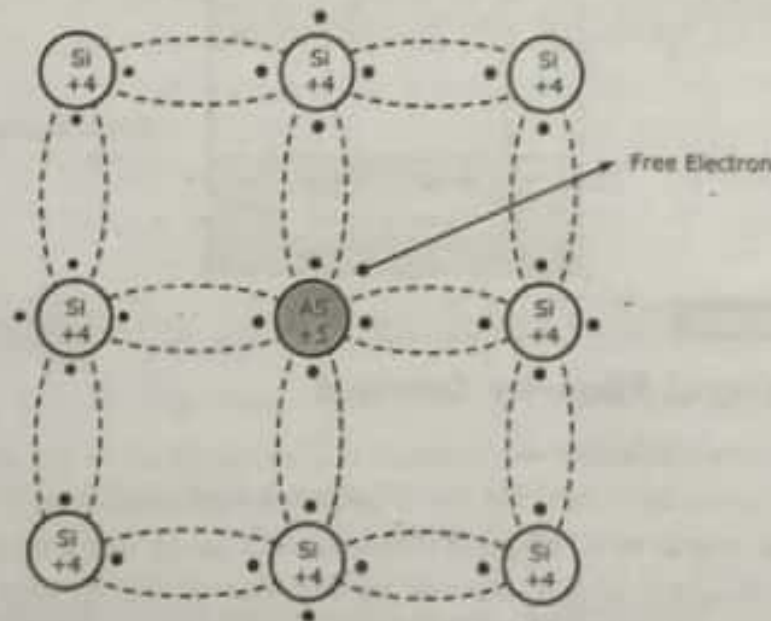
Fig. 1.4.5 Crystal Structure of Si After Doped with Donor Im-

Such that four valence electrons of the arsenic atom for-
valence electron of silicon atom. The fifth electron of
that is, loosely bound to the arsenic atom.
from the valence band. A very small
is enough to detach the 5th el-
electron is free to m-

BASIC ELE-

_____urity

... covalent bonds with the four
arsenic atom is nominally unbounded,
...his unbound electron can be easily detached
...mount of energy ($\approx 0.01eV$ for Ge and $0.05eV$ for Si)
...ctron from the attractive force of arsenic atom. So the formed
...ve in conduction band and thereby constitute electric current.

Since each impurity atom donates one free electron, thus this type of impurities are called as donor impurities. Since, current carriers are negatively charged particles (electrons), hence this type of semiconductor is called as N-type semiconductor.

Here it should be noticed that impurity atoms after giving away one electron, it becomes positively charged ion. However it cannot take part in conduction, since it is tightly fixed into the crystal lattice.

Energy Band Diagram of N-type Semiconductor : When donor impurity is added to pure semiconductor, the allowable energy levels are created at a very small distance below the conduction band as shown in Fig. 1.4.6. These levels are called donor energy levels. At room temperature due to thermal energy, electrons from donor levels are easily transferred to the conduction band. When on external electric field is applied to this semiconductor, these electrons move randomly and constitute electric current. Due to this, the N type semiconductor shows the conductivity remarkably improved than intrinsic semiconductor.
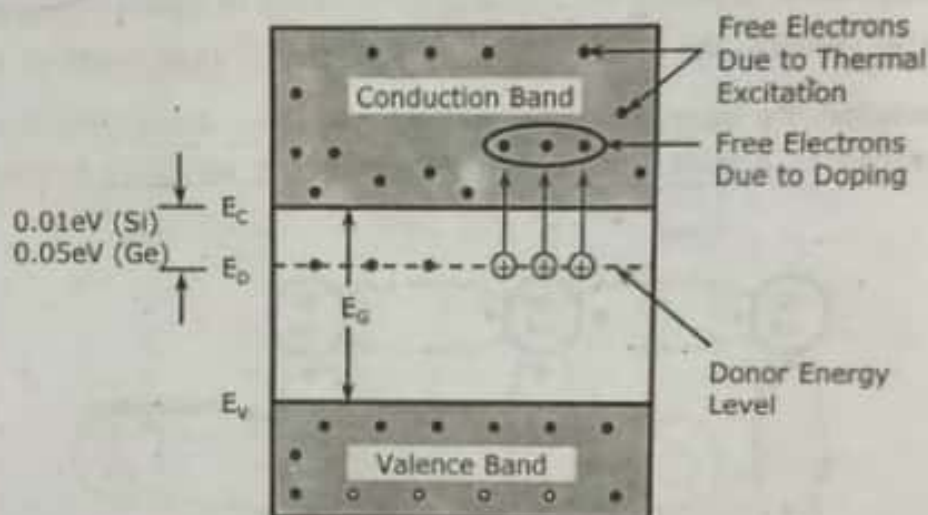

Fig. 1.4.6 Energy Band Diagram of N-type Semi Conductor

1.4.2.3 Majority and Minority Carriers

In an intrinsic semiconductor, the number of free electrons in Ge or Si is due to those few electrons in the valence band that have acquired sufficient energy from light or heat sources. The vacant space left behind in the covalent bond represents the holes. When an N-type impurity is added to this intrinsic semiconductor the number of electrons (both dopants added and thermally generated) is greater than the number of holes (thermally generated). Hence in an N-type semiconductor, electrons are majority carriers and holes are minority carriers as shown in Fig. 1.4.7(a). N-type doping not only produce more number of free electrons but also creates a immobile positive ions for generation of every free electron.

On the other hand P-type materials have holes as majority carriers and free electrons as minority carrier and also constitute immobile negative ions as shown in Fig. 1.4.7(b).
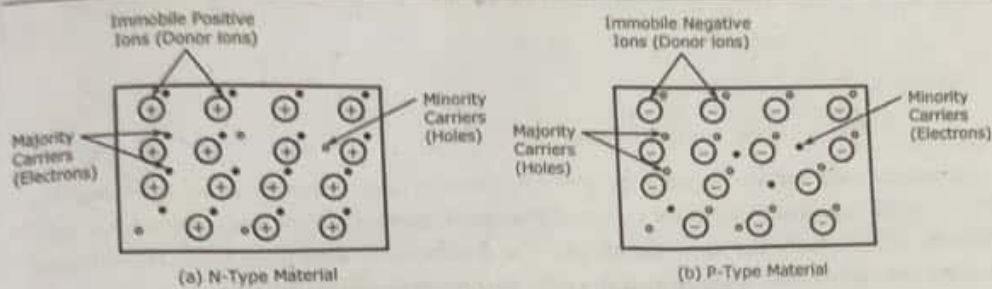
(a) N-Type Material   (b) P-Type Material

Fig. 1.4.7   Majority and Minority Carriers

1.4.2.4 Effect of Temperature on Extrinsic Semiconductors

The number of charge carriers in extrinsic semiconductors (due to thermal agitation and addition of small amount of impurity) is larger than intrinsic semiconductors (here charge carriers produced only due to thermal agitation). Thus the conductivity of extrinsic semiconductors is many times that of an intrinsic semiconductor.

Consider an N-type semiconductor at room temperature. All the donors have already donated electrons. If the temperature is raised above room temperature, more covalent bonds are broken. As a result, the concentration of minority carriers (holes) increases and becomes approximately same as that of number of majority carriers (electrons). Thus extrinsic semiconductor now behaves like an intrinsic semiconductor with high conductivity. The temperature at which the number of minority carriers approximately equals to the majority carriers in an extrinsic semiconductor is called critical temperature. Any semiconductor device either P-type or N-type will failed at such a temperature. The critical temperature is 85° in case of Ge and 200° in case of Si.

1.4.3 Conductivity of a Semiconductor

After creating each electron-hole pair, two charge-carrying particles are formed. One is negative (free electrons) of mobility μ_n and other is positive (holes) of mobility μ_p. These particles will move in opposite direction in an electric field E, but since they are of opposite sign, each of the current is in same direction. Hence, the current density J is given by,

... (1.4.1)

$$J = (n\mu_n + p\mu_p)eE = \sigma E$$

Where,

n = Magnitude of free electron (negative) concentration.

p = Magnitude of hole (positive) concentration.

σ = Conductivity.

... (1.4.2)

Hence, $\sigma = (n\mu_n + p\mu_p)e$

BASIC ELECTRONICS

For the instrinsic semiconductor considered as,

$$n = p = n_i$$

Where,

n_i = The intrinsic concentration.

At room temperature, in pure germanium there is about one hole-electron pair for every 2×10^9 germanium atoms. The density of electron-hole pair increases with increasing temperature and correspondingly, the conductivity also increases. The intrinsic concentration 'n,' varies with temperature in accordance with the relationship is,

$$n_i^2 = A_0 T^3 \exp(-E_{GO} / kT) \qquad \qquad \dots (1.4.3)$$

Important physical quantities for germanium and silicon are given in Table 1.4.1.

Table 1.4.1 Properties of Germanium and Silicon*

Property	Ge	Si
Atomic number	32	14
Atomic weight	72.6	28.1
Density, g/cm³	5.32	2.33
Dielectric constant (relative)	16	12
Atoms/cm³	4.4×10^{22}	5.0×10^{22}
E_{GO} eV, at 0°K	0.785	1.21
E_G, eV, at 300°K		0.72
		1.1
n_i at 300°K, cm⁻³	2.5×10^{13}	1.5×10^{10}
Intrinsic resistivity at 300°K, Ωcm	45	230,000
μ_n, cm²/V sec	3,800+	1,300
μ_p, cm²/V sec	1,800	500
D_n cm²/sec = $\mu_n V_T$	99	34
D_p cm²/sec = $\mu_p V_T$	47	13

EXAMPLE PROBLEM 1

Consider intrinsic germanium at room temperature (300°K). By what percent does the conductivity increase per degree rise in temperature?

SOLUTION

Substituting $n = p = n_i = \sqrt{A_0} T^{3/2} \exp\left(-\dfrac{E_{G0}}{2kT}\right)$ from Eq. (1.4.3) in Eq. (1.4.2), we can write the expression for conductivity of any intrinsic semiconductor as,

$$\sigma = \left\{ e(\mu_n + \mu_p)\sqrt{A_0} \right\} T^{3/2} \exp\left(-\frac{E_{G0}}{2kT}\right)$$

Taking logarithm on both sides and differentiating with respect to T,

We get, $$\frac{\left(\dfrac{d\sigma}{\sigma}\right)}{dT} = \frac{3}{2T} + \frac{E_{G0}}{2kT^2}$$

$\left\{ e(\mu_n + \mu_p)\sqrt{A_0} \right\}$ is a constant.

Putting T = 300°K, E_{G0} = 0.785 eV (i.e., forbidden or band-gap energy of germanium at 0°K) and k = 8.62 × 10⁻⁵ eV/°K in the above relation,

We can get, $$\frac{\left(\dfrac{d\sigma}{\sigma}\right)}{dT} = \frac{3}{2 \times 300°K} + \frac{0.785eV}{2 \times 8.62 \times 10^{-5}(eV/°K)300°K)^2}$$

$$= 0.0556/°K$$

Which shows that the conductivity of the intrinsic germanium increases by 5.56% per degree Kelvin rise in temperature.

1.4.4 Carrier Concentration in an Intrinsic Semiconductor

From Eq. (1.4.2), the conductivity of a semi-conductor can be calculated and it is necessary to know the concentration of free electrons n and the concentration of holes p. The equation for electron E is given as follows,

$$dn = N(E)f(E)dE \qquad \qquad ... (1.4.4)$$

Where,

dn = The number of conduction electrons for cubic meter whose energies lies between E and dE + dE.

The density of states N(E) is that the bottom of the conduction band is at zero potential. In a semiconductor, the lowest energy in the conduction band E_c is generalized follows,
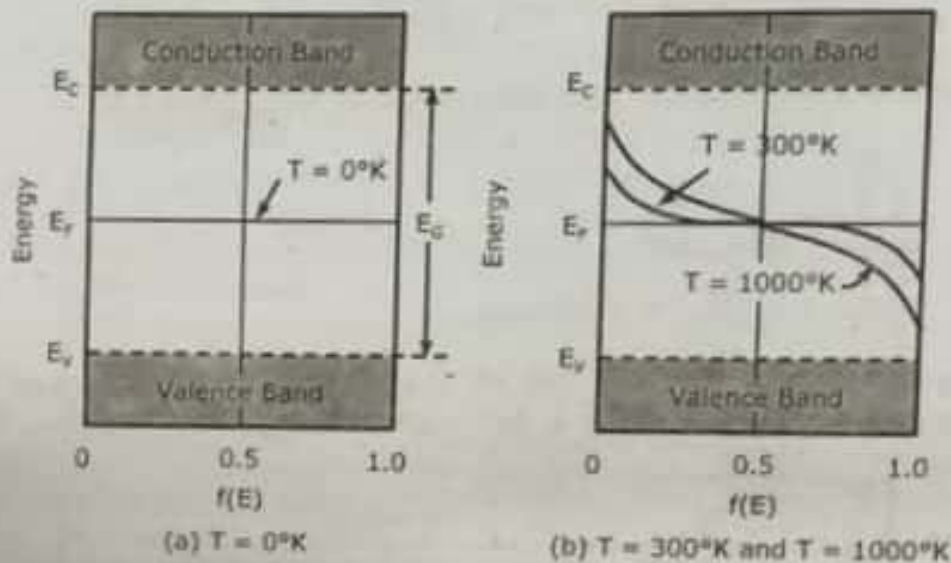
$$N(E) = r^{(E-E_c)^{1/2}} \qquad \qquad \cdots (1.4.5)$$

Now, the fermi function f(E) is given as,

$$f(E) = \frac{1}{E + e^{(E+E_F)/kT}} \qquad \qquad \cdots (1.4.6)$$

At room temperature kT = 0.03 eV, so that f(E) = 0 if $E - E_F \gg 0.003$ and f(E) = 1 if $E - E_F \ll 0.03$.

Fig. 1.4.8, shows fermi dirac distribution and energy-band diagram for an intrinsic semiconductor,

(a) T = 0°K   (b) T = 300°K and T = 1000°K

Fig. 1.4.8 Fermi-Dirac Distribution and Energy-band Diagram for an Intrinsic Semiconductor

In the Fig. 1.4.8, shows that the fermi level lies in the region of the energy gap midway between the valence and conduction bands.

From the Fig. 1.4.8, the concentration of electrons in the conduction band is,

$$n = \int_{EC}^{\infty} N(E)f(E)dE \qquad \qquad \cdots (1.4.7)$$

For E > EC, E - EF >> kT and Eq. (1.4.6), can be reduced to,

$$f(E) = e^{-(E-E_F)/kT}$$

And hence,

$$n = \int_{EC}^{\infty} r(E - E_c)^{1/2} e^{-(E-E_F)/kT} dE \qquad \qquad \cdots (1.4.8)$$

Now, assume $E - E_c = (KT)x$ in Eq. (1.4.8),

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We get, $n = (kT)^{3/2} \dfrac{4}{\sqrt{\pi}} \left(\dfrac{2\pi m_n}{h^2}\right)^{3/2} \times (1.60 \times 10^{-19})^{3/2} e^{[-(E_C - E_F)/kT]} \displaystyle\int_0^\infty x^{1/2} e^{-x} dx$

$= \dfrac{4}{\sqrt{\pi}} \left[\dfrac{2\pi m_n kT}{h^2}\right]^{3/2} \times (1.60 \times 10^{-19})^{3/2} e^{[-(E_C - E_F)/kT]} \times \displaystyle\int_0^\infty x^{1/2} e^{-x} dx$

Now, we replacing, $r = \dfrac{4}{\sqrt{\pi}} \left[\dfrac{2\pi m_n}{h^2}\right]^{3/2} \times (1.60 \times 10^{-19})^{3/2}$ and $\displaystyle\int_0^\infty x^{1/2} e^{-x} dx = \dfrac{\sqrt{\pi}}{2}$ in the above equation,

Hence, the concentration of electrons in the conduction band can be expressed as,

$$n = N_C \, e^{[-(E_C - E_F)/kT]} \qquad\qquad \cdots (1.4.9)$$

Where,

$$N_C = 2\left(\dfrac{2\pi m_n kT}{h^2}\right)^{3/2} (1.60 \times 10^{-19})^{3/2} = 2\left(\dfrac{2\pi m_n kT}{h^2}\right)^{1/2} \qquad \cdots (1.4.10)$$

The above equations are called effective density states function in the conduction band.

Number of Holes in the Valence Band : From the Eq. (1.4.5), the valence band is E_V, the density of states is given by,

$$N(E) = r(E_V - E)^{1/2} \qquad\qquad \cdots (1.4.11)$$

In this, hole signifies an empty energy level, the fermi function for a hole is $1 - f(E)$, where $f(E)$ is the probability that the level is occupied by an electron. For example, if the probability that a particular energy level is occupied by an electron is 0.2, but in the hole the probability of energy level is empty. From Eq. (1.4.6),

We obtain, $1 - f(E) = \dfrac{e^{[(E - E_F)/kT]}}{1 + e^{[(E - E_F)/kT]}} \approx e^{[-(E_F - E)/kT]} \qquad\qquad \cdots (1.4.12)$

But from the Fig. 1.4.8, $E_F - E \gg kT$ for $E \le E_V$.

Hence, the number of holes for cubic meter in the valence band is,

$$P = \int_{-\infty}^{E_V} r(E_V - E)^{1/2} e^{[-(E_F - E)/kT]} dE \qquad\qquad \cdots (1.4.13)$$

Sub. $E_V - E = (kT)x$, the above integral evaluates to,

$$P = (kT)^{3/2} \dfrac{4}{\sqrt{\pi}} \left(\dfrac{2\pi m_p}{h^2}\right)^{3/2} \cdot (1.60 \times 10^{-19})^{3/2} e^{[-(E_F - E_V)/kT]} \int_0^\infty x^{1/2} e^{-x} dx$$

But, we know that $r = \dfrac{4}{\sqrt{\pi}}\left(\dfrac{2\pi m_p}{h^2}\right)^{3/2}(1.60 \times 10^{-19})^{3/2}$ and the values of r and $\dfrac{\sqrt{x}}{2}$ can be replaced in above equation,

We get, $P = N_v e^{[-(E_F - E_V)/kT]}$ ... (1.4.14)

Where, N_v is called the effective density of states function in the valence band. Similarly, N_c, N_v can also be defined as hypothetical electron state density placed at the top of the valence band energy E_v, which absolute temperature T. The value of N_v for germanium and silicon at room temperature are $6.0 \times 10{-19}$ cm-3 and 1.04×10^{19} cm-3 respectively.

EXAMPLE PROBLEM 1

For a particular semiconductor, the density of state function is given by,

$$N(E) = C = Constant$$

Derive an expression for the conclusion of electrons in the conduction band. Assume that the Fermi statistics is valid for this semiconductor.

SOLUTION

From Eq.s (1.4.6) (1.4.7), the concentration of electrons in the conduction band of the given semiconductor is given by,

$$n = \int_{E_C}^{\infty} C\frac{1}{1 + \exp[(E - E_F)/kT]}\,dE$$

Substituting $\dfrac{E - E_F}{kT} = x$ in the above relation,

We get, $n = (kT)C \displaystyle\int_{(E_C - E_F)/kT}^{\infty} \dfrac{1}{1 + \exp(x)}\,dx$

$$= (-kT)C \int_{(E_C - E_F)/kT}^{\infty} \frac{d(1 + \exp(-x))}{1 + \exp(-x)}$$

$$= (kT)C \ln(1 + \exp[-(E_C - E_F)/kT])$$

Thus, the concentration of electron in the given semiconductor is,

$$n = (kT)C \ln(1 + \exp[-E_C - E_F)/kT])$$

For $(E_C - E_F) \gg kT$, $\exp[-E_C - E_F)/kT] \ll 1$. Since $\ln(1 + x) = x$ for $x \ll 1$, the electron concentration may approximately given by,

$$n = (kT)C\exp[-E_C - E_F)/kT] \text{ for } (E_C - E_F) \gg kT$$

Note that the above expression can also derived by using the Boltzman approximation of the Fermi function in Eq. (1.4.7) with $N(E) = C$ and,

$$f(E) = \frac{1}{1 + \exp[(E - E_F)/kT]} = \exp[-(E = E_F)/kT] \text{ for } E - E_F \gg kT$$

MPLE PROBLEM 2

(a) For a particular semiconductor, the effective mass of electron is $mn = 1.4\ m$. If EC − EF = 0.25 eV, determine the effective density of states in the conduction band and concentration of electrons in the semiconductor at T = 300°K.

(b) Repeat part (a) for T = 400°K

UTION

(a) Using Eq. 1.4.10, the effective density of states in the conduction band at T = 300°K is given by,

$$N_C = 2\left(\frac{2\pi \times (1.4 \times 9.1 \times 10^{-31}kg) \times (8.62 \times 10^{-5}eV\,/\,°K) \times (300°K) \times (1.60 \times 10^{-19}C)}{(6.626 \times 10^{-34}J - sec)^2}\right)^{\frac{3}{2}}$$

$$= 4.15 \times 10^{25}\ m^{-3}$$

The concentration of electrons in the semiconductor can be obtained by Eq. (1.4.9) as,

$$n = (4.15 \times 10^{25})\exp\left(-\frac{0.25eV}{0.259eV}\right)$$

$$= 2.67 \times 10^{21}m^{-3}$$

(b) At T = 400°K, N_C is given by,

$$N_C = 2\left(\frac{2\pi(1.4 \times 9.1 \times 10^{-31}kg) \times (8.62 \times 10^{-5}eV/°K) \times (400°k) \times (1.6 \times 10^{-19}C)}{(6.626 \times 10^{-34}J - sec)^2}\right)^{\frac{3}{2}}$$

$$= 6.38 \times 10^{25}m^{-3}$$

The concentration of electrons at T = 400°K is obtained as,

$$n = (6.38 \times 10^{25})\exp\left(-\frac{0.25eV}{0.29eV}\right)$$

$$= 4.1 \times 10^{21}m^{-3}$$

It can be observed that the concentration of electrons and effective density of states in a semiconductor are increased with the increase in the temperature.

1.4.5 Fermi-Dirac Distribution

In calculating semiconductors electrical properties and analyzing device behaviour is often necessary to know the charge concentrations per cm³ in the material. Though the majority carrier concentration is usually obvious in the heavily doped material, (as one majority carrier is obtained for each impurity atom) but the concentration of minority carriers is not obvious and also the temperature dependence of the charge concentrations. So inorder to obtain equations for the charge concentrations we must study the distribution of charge carriers over the available energy states.

The equation defined for the probability of occupancy of electrons or holes in the allowed energy states is called the Fermi-Dirac probability function and specifies the fraction of all states at energy E (in eV) occupied under the condition of thermal equilibrium. $f(E)$ is given by relation,

$$f(E) = \frac{1}{1 + \exp[(E - E_F)/K_B T]}$$

Where,

K_B = Boltzman constant, eV°/K.

T = Temperature.

E_F = Fermi level or characteristic energy, for the crystal, eV.

$f(E)$ = Probability of occupancy of state with energy 'E'.

The Fermi level represents the energy state with 50% probability of being filled if no forbidden band exists. The reason for the last statement is that, for an energy E equal to the Fermi level energy E_F, the occupation probability is,
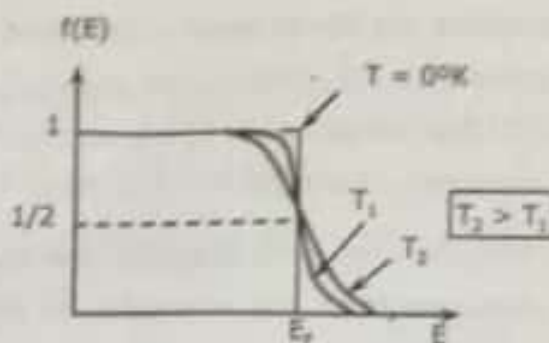
$$f(E) = \frac{1}{1 + e^{\frac{0}{kT}}} \qquad (\because E = E_F)$$

$$\Rightarrow \quad f(E) = \frac{1}{1+1} = \frac{1}{2}$$

Thus, "*an energy state at the fermi level has a probability $\frac{1}{2}$ of being occupied by an electron*".

A closer examination of $f(E)$ indicates that at absolute zero temperature (0°K) the distribution takes the simple rectangular form shown in Fig. 1.4.9,

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Fig. 1.4.9 illustrates the fermi-dirac distribution function,

Fig. 1.4.9 The Fermi-Dirac Distribution Function

With $T = 0°K$, in the denominator of exponent, f(E) is $\frac{1}{1+0} = 1$, when the exponent is negative (i.e., $E_f > E$) and f(E) is $\frac{1}{1+\infty} = 0$. When the exponent is positive (i.e., $E > E_f$).

For better understanding, consider the following two cases that exist at absolute zero temperature,

CASE 1 : When $E >> E_f$

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

This shows that the probability of finding an occupied quantum state of energy greater than E_f is empty at absolute zero temperature.

CASE 2 : When $E << E_f$

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

This shows that all quantum levels with energies less than E_f is occupied at absolute zero temperature.

Following points are worthy noting,

(1) Fermi energy is the maximum energy that any electron may possess at absolute zero temperature.

(2) The rectangular distribution of Fermi-dirac shown in Fig. 1.4.9, implies that at 0°K every available energy state up to E_f is filled with electrons and all states above E_f are empty, since there are no electrons at OK which have energies in excess of E_f.

At temperature higher than absolute zero temperature (0°K), there is some probability exists for states above the Fermi level to be filled. For instance, at T = T₁ in Fig. 1.4.9, there is some probability F(E) that states above E_f are filled, correspondingly there is a probability (1 - F(E)) that states below E_f are empty. The probability of occupancy increases as temperature increases (Example for T_2). Here $T_2 > T_1$.

The relation between f(E) and the band diagram can be visualized by the F(E) Vs E diagram with 'E' scale corresponds to the energies of the band diagram as shown in Fig. 1.4.10,
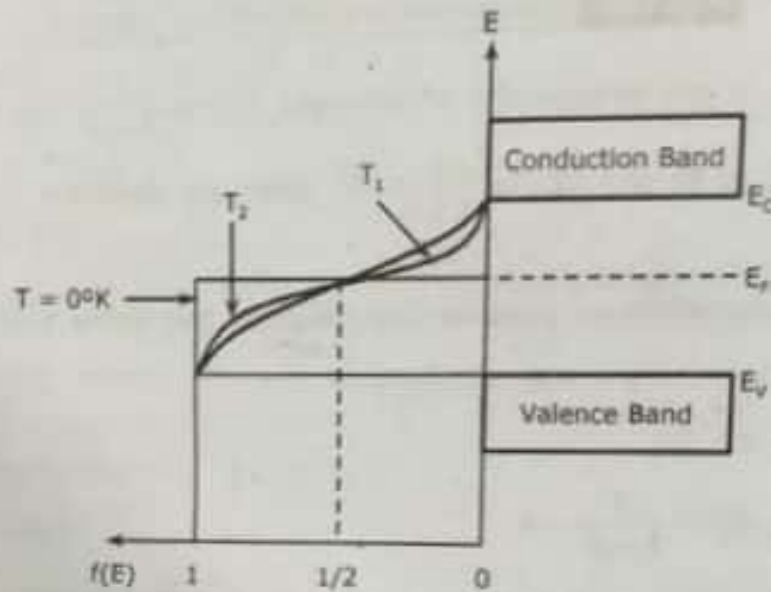

Fig. 1.4.10 f(E) Versus Energy Band Diagram

1.4.6 Fermi Level in Intrinsic Semiconductors

From the Eq. (1.4.9), and Eq. (1.4.14), the concentration of electrons in conduction band and holes in valence band are given by,

$$n = N_c e^{-(E_c - E_f)/kT}$$
$$\quad \text{... (1.4.15)}$$

$$p = N_v e^{-(E_f - E_v)/kT}$$
$$\quad \text{... (1.4.16)}$$

Where, N_c and N_v represents the effective density of states at conduction band and valence band respectively are given by,

$$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$$
$$\quad \text{... (1.4.17)}$$

And
$$N_v = 2\left(\frac{2\pi m_p kT}{h^2}\right)^{3/2}$$
$$\quad \text{... (1.4.18)}$$

Where,

m_n, m_p = Effective mass of electrons, holes respectively.

$\bar{k}$ = Boltzmann constant in Joules/kelvin (1.38×10^{-23}J/°K)

h = Plancks constant (6.625×10^{-34})

Since in case of intrinsic semiconductor, the number of electrons equals to the number of holes. Thus,

$$n = p$$

$\Rightarrow$ $$N_c e^{-(E_c-E_f)/kT} = N_v e^{-(E_f-E_v)/kT}$$

Taking the logarithm on both sides, we obtain,

$$\ln\left(\frac{N_c}{N_v}\right) = \frac{E_c + E_v - 2E_f}{kT}$$

$\Rightarrow$ $$E_f = \frac{E_c + E_v}{2} - \frac{kT}{2}\ln\left(\frac{N_c}{N_v}\right)$$

... (1.4.19)

If the effective masses of a hole and a free electron are the same, then $N_c = N_v$ (Refer Eq. 1.4.17) and Eq. (1.4.18) this Eq. (1.4.19), becomes,

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

Hence the Fermi-level lies in the center of the forbidden energy band as shown in Fig. 1.4.8.

1.4.7 Charge Densities in Semiconductors

1.4.7.1 Mass Action Law

Mass action law states that the product of concentration of free electrons (n) and concentration of holes (p) is constant under equilibrium condition which is independent of amount of acceptor and donor impurities.

In an intrinsic semiconductor, the number of holes and electrons are always equal in concentration. We have seen that when an N-type impurities are added to intrinsic semiconductor, then the concentration of holes is reduced below the intrinsic value. When a P-type impurities are added to intrinsic semiconductor, then the concentration of free electrons reduces below the intrinsic value. Theoretical analysis at thermal equilibrium noticed that the product of concentration of free electrons and holes is always constant and is independent of doping concentrations of impurity atoms. This is known as Mass-Action law. Mathematically given as,

$$np = n_i^2$$

$$\cdots (1.4.20)$$

Where,

$n_i \rightarrow$ Intrinsic carrier concentration.

$n, p \rightarrow$ Electron, hole concentrations respectively.

1.4.2 Charge Concentrations After Doping

We have seen incase of intrinsic semiconductor the carrier concentrations is given by,

$$n.p = n_i^2$$

Let, this equation be further interrelated by the law of electrical neutrality. Let N_D be the concentration of donor atoms. Since the donor atoms are ionized (loses electron) at room temperature, hence there will be N_D positive charges per cubic meter contributed by donor ions. Now total positive charge density is $(N_D + P)$. Similarly, let N_A be the concentration of acceptor atoms. At room temperature, acceptor atoms are ionized, hence there will be N_A negative charges per cubic meter. The total negative charge density is thus $(N_A + n)$. Since the semiconductor is electrically neutral that is, the magnitude of positive charge density must be equal to the magnitude of negative charge density. Thus,

$$N_D + p = N_A + n$$

$$\cdots (1.4.21)$$

Eq. (1.4.21) is called as *law of electrically neutrality.*

N-Type Semiconductors : According to electrically neutrality, we have,

$$p + N_D = n + N_A$$

Since for a N-type semiconductor, electrons are majority carriers and holes are minority carriers, let us give following notations to them,

Concentration of free electrons $\rightarrow n_n$

Concentration of holes $\rightarrow p_n$

Concentration of donor atoms $\rightarrow N_D$

In N-type semiconductor, N_A (Acceptor doping) = 0. Hence,

$$p_n + N_D = n_n$$

Since concentration of electrons in N-type semiconductor is much greater than holes, i.e., $n_n >> p_n$, we have,

$$N_D = n_n$$

According to Mass-Action law for N-type: $p_n n_n = n_i^2$

$$\boxed{N_D = \frac{n_i^2}{p_n}} \Rightarrow \boxed{p_n = \frac{n_i^2}{N_D}}$$

p - Type Semiconductors : According to electrically neutrality, we have,

$$p + N_D = n + N_A$$

Since for a P-type semiconductor, electrons are majority carriers and holes are minority carriers, let us give following notations to them.

Concentration of free electrons $\rightarrow n_p$

Concentration of holes $\rightarrow p_p$

Concentration of acceptor atoms $\rightarrow N_A$

In P-type semiconductor, N_D (Donor doping) = 0. Hence,

$$p_p = n_p + N_A$$

Since concentration of holes in P-type semiconductor is much greater than electrons, i.e., $p_p \gg n_p$, hence we have,

$$N_A \simeq p_p$$

According to Mass-Action law for P-type: $p_p n_p = n_i^2$

$$\boxed{N_A = \frac{n_i^2}{n_p}} \Rightarrow \boxed{n_p = \frac{n_i^2}{N_A}}$$

1.4.8 Intrinsic Concentration of Semiconductors

From the Eq. (1.4.9) and Eq. (1.4.14), the product of electron hole concentrations can be given as,

$$nP = NCN_V e^{[-(E_C - E_V)/KT]} = N_C N_V e^{(-(E_G/kT))} \qquad \ldots (1.4.22)$$

Note that the above product term is independent of Fermi level and depend on the temperature and the energy gap $E_G = E_C - E_V$. The above Eq. (1.4.20) is valid for both instrinsic as well as extrinsic materials.

Let us assume, $P = P_i$ (or) $n = n_i$ and (According to mass action law),

We get, $\quad nP = n_i^2 \qquad \ldots (1.4.23)$

Regardless of the individual magnitudes of n and p, the product is always a constant at a fixed temperature substituting numerical values for the physical constants in Eq. (1.4.10), we obtain,

$$NC = 4.82 \times 10^{21} \left(\frac{m_n}{m}\right)^{3/2} T^{3/2} \qquad \cdots (1.4.24)$$

Where, N_c has the dimensions of concentration and NV is given by right side of the Eq. (1.4.24) with mn replaced by m_p. From the Eq. (1.4.22) to Eq. (1.4.24),

$$nP = n_i^2 = (2.33 \times 10^{43}) \left[\frac{m_n m_p}{m2}\right]^{3/2} T^3 e^{(-(E_G/kT))} \qquad \cdots (1.4.25)$$

But, the energy gap decreases linearly with temperature,

So that, $\qquad E_G = E_{GO} - \beta T \qquad \cdots (1.4.26)$

Where,

$\qquad E_{GO}$ = The magnitude of the energy gap at 0° K.

The above relation substitute into Eq. (1.4.25),

We get, $\qquad n_i^2 = A_0 T^3 e^{(-E_{GO}/kT)} \qquad \cdots (1.4.27)$

Where,

$$A_0 = (2.33 \times 10^{43}) \left(\frac{m_n mp}{m2}\right)^{3/2} e^{(-\beta/k)} \text{ and it is a constant and } \beta \text{ has the dimension}$$

of electron volt per degree kelvin.

EXAMPLE PROBLEM 1

For a particular semiconductor material, $N_c = 1.5 \times 10^{18} cm^{-3}$, $N_v = 1.3 \times 10^{19} cm^{-3}$ and $E_G = 1.43$ eV at T = 300°K.

(a) Determine the position of the intrinsic Fermi level with respect to the center of the bandgap. What is the position of the Fermi level with respect to the top of the valence band E_v?

(b) Find the intrinsic carrier concentration of the semiconductor at T = 300 °K.

(c) Determine effective masses m_n and m_p of electron and hole respectively.

SOLUTION

(a) The position of the Fermi level with respect to centre of the bandgap E_{midgap} is obtained from Eq. (1.4.19) as,

$$E_F - E_{midgap} = -\frac{0.0259}{2} \ln\left(\frac{1.5 \times 10^{18}}{1.3 \times 10^{19}}\right)$$

$$= 0.028 \text{ eV}$$

Thus, the Fermi level is located at 0.028 eV above the center of the bandgap. The position of the Fermi level with respect to E_V is determined as follows,

From Eq. (1.4.19) we can write,

$$E_F = \frac{E_C - E_V + 2E_V}{2} - \frac{kT}{2} \ln\left(\frac{N_C}{N_V}\right)$$

$$= \frac{E_C - E_V}{2} + E_V - \frac{kT}{2} \ln\left(\frac{N_C}{N_V}\right)$$

Substituting $E_G = E_C - E_V$ in the above equation, we can get,

$$E_F - E_V = \frac{E_G}{2} - \frac{kT}{2} \ln\left(\frac{N_C}{N_V}\right)$$

$$= 0.715 + 0.028$$

$$= 0.743 \text{ eV}$$

Hence the Fermi level is located at 0.743 eV above the valence band edge EV. Note that the position of the Fermi level with respect to the conduction band edge E_C can be obtained as,

$$E_F = \frac{2E_C - E_G}{2} - \frac{kT}{2} \ln\left(\frac{N_C}{N_V}\right)$$

(or) $\quad E_F - E_C = -\frac{E_G}{2} - \frac{kT}{2} \ln\left(\frac{N_C}{N_V}\right) = -0.687 \text{ eV}$

which implies that the Fermi level is located at 0.687 eV below E_C.

(b) Combining Eqs. (1.4.22) and (1.4.23), we can get,

$$n_i^2 = N_C N_V \exp(-E_G/KT)$$

$$= (1.5 \times 10^{18} \text{cm}^{-3})(1.3 \times 10^{19} \text{cm}^{-3}) \exp\left(-\frac{1.43 \text{eV}}{0.0259 \text{eV}}\right)$$

$$= 2.05 \times 10^{13} \text{ cm}^{-6}$$

Thus the intrinsic carrier concentration is given by,

$$n_i = p_i = 4.53 \times 10^6 \text{ cm}^{-3}$$

(c) Using $N_C = 1.5 \times 10^{18} cm^{-3} = 1.5 \times 10^{24} m^{-3}$ in the effective mass of electron is obtained as,
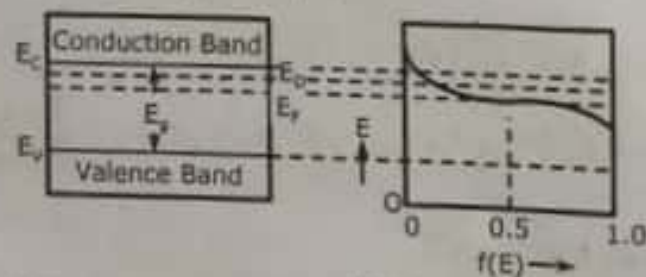
$$m_n = \left\{ \left(\frac{N_c}{4.82 \times 10^{21}} \right)^{\frac{2}{3}} \frac{1}{T} \right\} m$$

$$= \left\{ \left(\frac{1.5 \times 10^{24}}{4.82 \times 10^{21}} \right)^{\frac{2}{3}} \frac{1}{300} \right\} m$$

$$= 0.135 \, m$$

$$= 0.135 \times 9.1 \times 10^{-31}$$

$$= 1.23 \times 10^{-31} \, kg$$

Similarly, the effective mass of hole can be given as,

$$m_p = \left\{ \left(\frac{N_V}{4.82 \times 10^{21}} \right)^{\frac{2}{3}} \frac{1}{T} \right\} m$$

$$= \left\{ \left(\frac{1.3 \times 10^{25}}{4.82 \times 10^{21}} \right)^{\frac{2}{3}} \frac{1}{300} \right\} m$$

$$= 0.646 \, m$$

$$= 5.88 \times 10^{-31} \, kg$$

1.4.9 Fermi Level in a Extrinsic Semiconductors

The energy band diagrams for n-type and p-type semiconductors are given in Fig. 1.4.11(a) and Fig. 1.4.12(a), respectively.

(a) Energy Band Diagram   (b) Position of Fermi Level in an n-type Material

Fig. 1.4.11 n-type Semiconductors

(a) Energy Band Diagram   (b) Position of Fermi Level
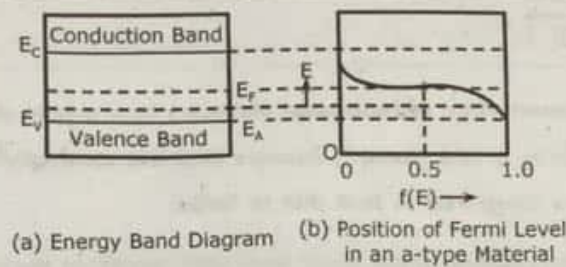   in an a-type Material

Fig.1.4.12 p-type Semiconductors

Here E_D and E_A denotes the donor and the acceptor level, respectively. Assuming complete ionization of the donor atoms at a finite temperature, we find that the free electrons coming from the donor atoms fill the states near the bottom of the conduction band. Hence it is more difficult for the electrons in the valance band to cross the band gap by the thermal agitation. Therefore, the number of holes in the valance band decreases. As the Fermi level E_F is the energy for which the probability of occupancy is half, E_F must move close to the conduction band for an n-type semiconductor [Fig. 1.4.11(b)].

Similar arguments show that E_F must move from the centre of the band gap closer to the valence band for a p-type semiconductor [Fig. 1.4.12(b)]. If the doping is very high, the Fermi level moves into the conduction band for an n-type semiconductor, and into the valance band for a p-type material.

As the temperature of the semiconductor rises, we have seen that both n and p-type semiconductors become essentially intrinsic. Thus, when the temperature of n-type or p-type semiconductors increases, the Fermi level E_F moves towards the centre of the band gap.

(1) **P-Type Semiconductors :** An exact position of the Fermi level in an P-type material can be obtained if we substitute $p = N_A$. Substituting $p = N_A$ in Eq. (1.4.16),

We get, $N_A = N_v e^{[-(E_F - E_v)/kT]}$

Solving for E_F, we get,

$$E_F = E_V + kT \ln\left(\frac{N_V}{N_A}\right)$$

(2) **N-Type Semiconductor :** Similarly an exact position of Fermi-level in an N-type material is obtained by substituting $n = N_D$ in Eq. (1.4.15),

Thus, $N_D = N_c e^{[-(E_c - E_v)/kT]}$

Solving for E_F, we get,

$$E_F = E_c - kT \ln\left(\frac{N_c}{N_D}\right)$$

EXAMPLE PROBLEM 1

(a) Find the concentration of holes and electrons in a p-type germanium at 300°K if the conductivity is 100 $(\Omega cm)^{-1}$. Assume that the conductivity due to electrons is negligible as compared to that due to holes.

(b) Determine the position of the Fermi level with respect to the edge of the conduction band of the germanium of part (a).

Assume $N_v = 6.0 \times 10^{19}$ cm^{-3} and $E_G = 0.72$ eV at 300°K

SOLUTION

(a) L ε_p and n_p be the concentrations of holes and electrons of the given germanium. Since the semiconductor is of p-type, the conductivity due to electron is negligible as compared with holes and hence the conductivity can be approximately given by,

$$\sigma \approx \sigma_p = p_p \mu_p e$$

Using the value of $\mu_p = 1800$ cm^2/V sec from Table 1.4.1 in the above equation, the concentration of hole is obtained as,

$$p_p = \frac{\sigma}{\mu_p e}$$

$$= \frac{100(\Omega cm)^{-1}}{1800(cm^2/V\ sec) \times (1.60 \times 10^{-19} C)}$$

$$= 3.41 \times 10^{17}\ cm^{-3}$$

Now the concentration of electrons can be determined by using the value of p_p in NA $= \dfrac{n_i^2}{p_p}$ as,

$$n_p = \frac{n_i^2}{p_p}$$

$$= \frac{(2.5 \times 10^{13} cm^{-3})^2}{3.41 \times 10^{17} cm^{-3}}$$

$$= 1.83 \times 10^{9}\ cm^{-3}$$

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(b) Since for a p-type semiconductor $p_p \approx N_A$, using equation $E_F = E_v + kT/n \frac{N_v}{N_A}$ we can write,

$$E_F - E_v = kT/n\left(\frac{N_v}{p_p}\right)$$

$$= (0.0259)/n\left(\frac{6.0 \times 10^{19}}{3.41 \times 10^{17}}\right)$$

$$= 0.134 \text{ eV}$$

Which shows that the Fermi level is located at 0.134 eV above the edge of the valence band. The position of E_F with respect to the edge of the conduction band can be given by,

$$E_F - E_C = (E_F - E_v) - (E_C - E_v)$$

$$= (E_F - E_v) - E_G$$

$$= 0.134 - 0.72$$

$$= -0.586 \text{ eV}$$

Thus, the Fermi level is at 0.586 eV below the edge of the conduction band.

EXAMPLE PROBLEM 2

In an n-type silicon the donor concentration is 1 atom per 2×10^8 silicon atoms. Assume that the effective mass of the electron equals to the true mass and the density of atoms in the silicion in 5×10^{22} atoms cm³. At what temperature will the Fermi level coincide with the edge of the conduction band?

SOLUTION

The concentration of donor atoms per cm³ is given by,

$$N_D = \frac{1}{2 \times 10^8} \times (5 \times 10^{22})$$

$$= 2.5 \times 10^{14} \text{ atoms/cm}^3$$

Since the Fermi level coincides with the edge of the conduction band, using equation $E_F = E_C = 0 = kT/n \frac{N_C}{N_D}$ we can get,

$$E_F - E_C = 0 = kT/n\left(\frac{N_C}{N_D}\right)$$

(or) $\qquad N_C = N_D = 2.5 \times 10^{20} \text{m}^{-3}$

Using $m_n = m$ in Eq. (1.4.24) and substituting the result in the above equation, the desired temperature can be obtained as,

$$T = \left(\frac{2.5 \times 10^{20}}{4.82 \times 10^{21}} \right)^{\frac{2}{3}}$$

$$= 0.14^\circ K$$

## 1.4.10 Comparison of Intrinsic and Extrinsic Semiconductors

Table 1.4.2 Comparison of Intrinsic and Extrinsic Semiconductors

S.No.	Intrinsic Semiconductor	Extrinsic Semiconductors
(1)	It is pure semiconductor. It could be either Ge or Si.	These are obtained by adding impurities to pure semiconductor. These are two types viz. n-type and p-type.
(2)	At zero temperature, it becomes insulator. With increase of temperature, conductivity increases.	Such is not the case with extrinsic semiconductors. Conduction is possible at room temperature also.
(3)	Conductivity is in between metal and insulators. It is less compared to extrinsic semiconductors.	Conductivity is much higher than intrinsic semiconductor (through much lower than metals).
(4)	Number of electrons and holes are equal (at any temperature)	Number of electrons and holes are not equal. In n-type, electrons >> holes. In p-type, holes >> electrons.
(5)	Fermi level is exactly midway between conduction band and valence band.	Fermi level is close to conduction band in n-type and is close to valence band in p-type.

1.5 DIFFUSION AND DRIFT CURRENT

1.5.1 Drift Current

If a battery is connected across a semiconductor bar as shown in Fig. 1.5.1, then electrons being negative charged particles moves towards the positive terminal of the battery and holes being positive charged particles moves towards the negative terminal of the battery. Hence, the movement (drift) of holes and electrons contribute to electric current. This is called as drift current.
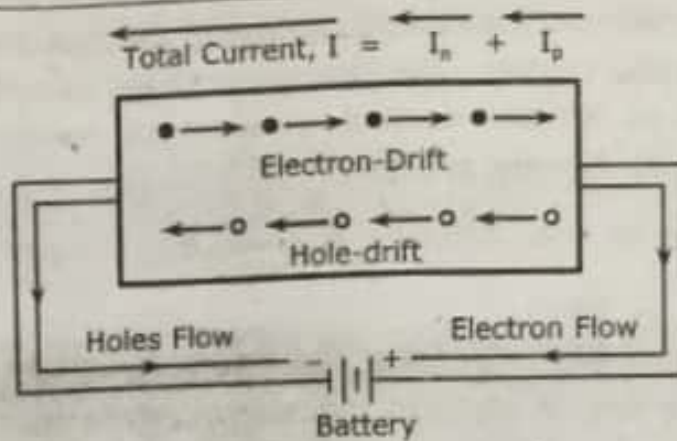
Fig. 1.5.1 Drift Current in an Intrinsic Semiconductor

The electron drift in the conduction band produces a component J_n given by,

$$J_n(\text{drift}) = ne\mu_n E$$

The hole drift in the valence band produces a component J_p given by,

$$J_p(\text{drift}) = pe\mu_p E$$

Thus, the total drift current density is given by,

$$J(\text{drift}) = J_n(\text{drift}) + J_p(\text{drift})$$

This equation is applicable for both intrinsic as well as extrinsic semiconductors.

1.5.2 Diffusion Current

There is also another possibility for an electric current to flow in a semiconductor even in the absence of applied electric field provided a concentration gradient exists in the material.

Let us consider a semiconductor bar in which the concentration of charge carriers (electrons or holes) in one region is greater than the other region of the semiconductor as shown in Fig. 1.5.2,
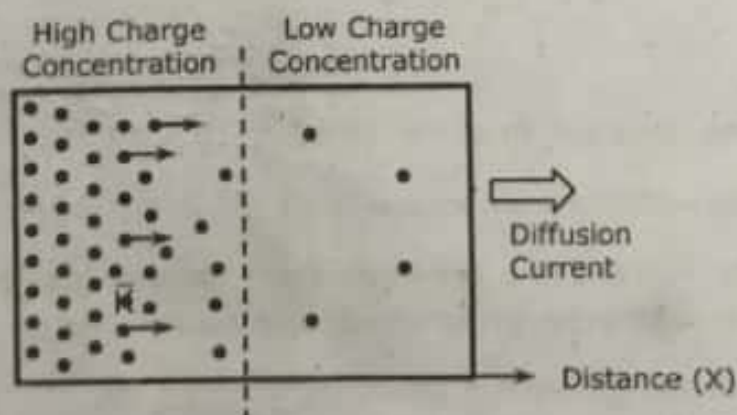
Fig. 1.5.2 Diffusion Current Due to Charge Gradient

Because of charge gradient, the charge carriers in the high concentration region mov towards the low concentration region. This process is called as diffusion and thus produce electric current is called as diffusion current. The current density due to this diffusion proportional to the carrier density gradient.

Current density due to hole diffusion is given by,

$$J_p = -eD_p \frac{dp}{dx}$$

... (1.5.1

And current density due to electron diffusion is given by,

$$J_n = +eD_n \frac{dn}{dx}$$

... (1.5.2)

Where,

D_p = Hole diffusion constant (m^2/s),

D_n = Electron diffusion constant (m^2/s)

$\frac{dp}{dx}$ = Density gradient of holes

$\frac{dn}{dx}$ = Density gradient of electrons

Einstein Relationship : The relationship which exists between the mobility and diffusion coefficient of a particular type of charge carrier in the same semiconductor is known as Einstein relationship for semiconductor. It is defined as,

$$\boxed{\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T}$$

... (1.5.3)

Eq. (1.5.3), gives the Einstein relationship, Where, V_T represents the "Volt-equivalent of temperature" and is given by,

$$V_T = kT = \frac{\bar{k}T}{e} = \frac{T}{11,600}$$

Where,

k = Boltzmann constant in eV/°K (8.62 × 10^{-5} eV/°K)

$\bar{k}$ = Boltzmann constant in Joules/°K (1.38 × 10^{-23} J/°K)

Total Current : The total current in a semiconductor material may be possible to have the currents contributed by both charge gradient and electric field.

Thus, the total current in such a situation is given by,

$$J_n(Total) = J_n(drift) + J_n(diffusion)$$

$$J_n = ne\mu_n E + eD_n \frac{dn}{dx}$$

And $J_p(Total) = J_p(drift) + J_p(diffusion)$

$$J_p = ne\mu_p E + eD_p \frac{dp}{dx}$$

1.6 HALL EFFECT

When a current carrying conductor is placed in a magnetic field (B) a transverse effect is noticed. This effect is called the Hall effect. In 1879, Hall found that, "When a magnetic field is applied at right angles to the direction of the electric current, an electric field is set up which is perpendicular to both the directions of electric current (I) and the applied magnetic field (B)."

In other words, *"when any specimen (metal or semiconductor) carrying a current I is placed in the transverse magnetic field B, then an electric field E is induced in the direction perpendicular to both B and I and the phenomenon known as Hall effect".*

Fig. 1.6.1 shows a specimen carrying current I in the positive x direction.
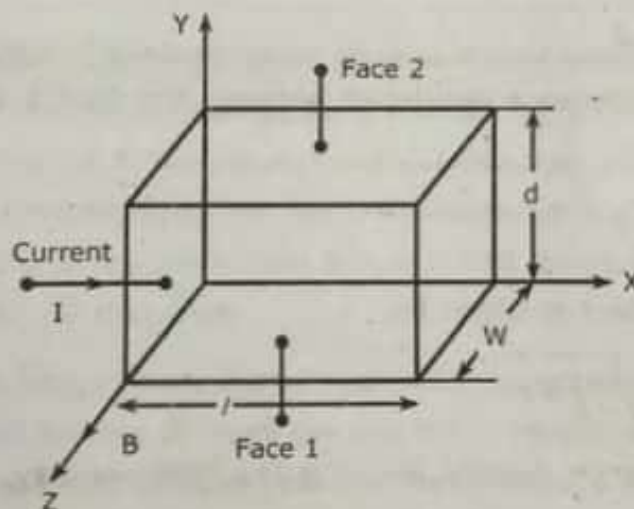
Fig. 1.6.1 Current Carrying Semiconductor Bar Subject to Transverse Magnetic Field

Let magnetic field B_z be applied in the positive-z direction. Then according to Hall effect, a force (due of electric field) gets exerted on the charge carriers (whether electrons or holes) in the negative-y direction. This current I may be due to holes moving in the positive-x direction or due to free electrons moving in the negative-x direction through the semiconductor specimen. Hence, irrespective of the nature of charge carriers, whether holes or electrons, these charge carriers get, pressed towards face 1 of the specimen shown in Fig. 1.6.1.

1.42

Let us consider the case where the material of the bar is P-type. Hence the direction of current is from left to right. Since the electromagnetic force is acting in negative y-direction, hence more holes will be accumulated on face 1. Thus face 1 becomes more positively charged with respect to face 2. Hence a potential difference develops between face-1 and face-2 and is called "*Hall voltage*".

Consider another case when the material of bar is n-type. A current flow from left to right is possible when free electrons are moving from right to left. Due to electromagnetic force, these electrons will accumulate towards the bottom side (i.e., face 1) making it negatively charged with respect face 2.

If we are given a bar of semiconductor (but it is not known whether it is p-type or n-type), by measuring the polarity of the Hall voltage appearing between face 1 and face 2, we can determine whether it is n-type or p-type.

1.6.1 Experimental Determination of Mobility

The equilibrium condition of the specimen shown in Fig. 1.6.1, requires that the electric field intensity due to Hall effect exerts a force on the carrier equal in magnitude to that exerted by the magnetic field. That is,

$$e \cdot E = evB$$

$$\Rightarrow \qquad E = vB \qquad \qquad \text{... (1.6.1)}$$

Let the potential difference developed between the face 1 and face 2 be V_H. Hence electric field is,

$$E = \frac{V_H}{d} \qquad \qquad \text{... (1.6.2)}$$

Also current density J is given by,

$$J = \frac{I}{W \times d} = \rho v \qquad \qquad \text{... (1.6.3)}$$

Where ρ is the charge density and v is the drift velocity,

Using Eq. (1.6.1) and Eq. (1.6.2), we get,

$$V_H = E \cdot d = vBd$$

$$\Rightarrow \qquad V_H = B \times \frac{J}{\rho} \times d = \frac{B}{\rho} \times \frac{I}{W \times d} \times d \qquad [\because v = J/\rho \text{ from Eq. (1.6.3)}]$$

$$\Rightarrow \qquad V_H = \frac{BI}{\rho W} \qquad \qquad \text{... (1.6.4)}$$

Thus the value of ρ can be determined by measuring the quantities V_H, B, I and W for specimen,

Hall Co-efficient : The Hall-co-efficient R_H is defined as,

$$R_H = \frac{1}{\rho}$$ ... (1.6.5)

From Eq. (1.6.4), we get,

$$R_H = \frac{V_H \cdot W}{BI}$$ ... (1.6.6)

The conductivity, in any extrinsic semiconductor, is due to primarily charges of only one sign and given as,

$$\sigma = \rho\mu$$ ... (1.6.7)

If both R_H and σ are measured, the mobility may be defined from the following relation,

$$\mu = \sigma R_H \qquad \left(\because R_H = \frac{1}{\rho} \right)$$ ... (1.6.8)

In the above discussion it is assumed that all coverage carriers move with mean drift speed v. In fact, the charge carriers have a random motion.

EXAMPLE PROBLEM 1

Consider a rectangular cross-rectangular cross-sectional semiconductor bar with length $l = 12$ mm, width $w = 5$ mm and thickness $d = 4$ mm which is placed in the coordinate system as shown in Fig. 1.6.2. The positive and negative terminals of a battery of voltage $V_d = 5$ V are connected between the two cross-sectional surfaces of the bar at $x = 0$ and $x = l$ respectively. A magnetic field $B = 6 \times 10^3$ Gauss is applied perpendicular to the bar along the +Z-direction.

(a) If the bar is of n-type semiconductor with electron concentration $n_n = 2.5 \times 10^{15}$ cm^{-3} and the current flowing through the bar is $I = 10$ mA, determine the magnitude and polarity of the Hall voltage between the terminal 1 and 2 (see Fig.). Also find the value of the Hall coefficient.

(b) Repeat part (a) for a p-type semiconductor bar with hole concentration $p_p = 2.5 \times 10^{15}$ cm^{-3}.

(c) If Hall voltage is V_H, derive an expression for the mobility of majority carrier in terms of V_H, applied voltage V_d and dimensions of the semiconductor bar.

(d) If the Hall voltage V_H of the terminal 2 is –6 mV measured with respect to the terminal 1 and the Hall co-efficient, carrier concentration and mobility of the majority carrier of the semiconductor.

1.44
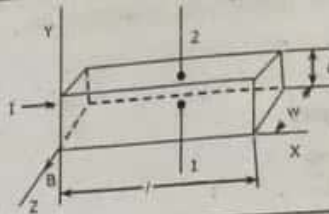
Fig. 1.6.2 Pertaining to the Hall Effect. The Carriers (Whether Electrons or Holes) are Subjected to a Source in the Negative Y Direction

SOLUTION

(a) Since the semiconductor is of n-type with $n_n = 2.5 \times 10^{15}$ cm^{-3}, the charge density ρ is given by,

$$\rho = -en_n = -(1.60 \times 10^{-19}C) \times 2.5 \times 10^{15} \text{ cm}^{-3}$$

$$= -4.0 \times 10^{-4} \text{ C/mc}^3$$

The negative sign is used to denote that the type of majority carrier involved in the conduction of current in the semiconductor is electron.

Substituting the values of $I = 10 \times 10^{-3}$ A, $B = 6 \times 10^3$ Gauss $= (6 \times 10^3)$ $\times (10^{-8}$ Wb/cm$^2) = 6 \times 10^{-5}$ Wb/cm^2, $\rho = 4.0 \times 10^{-4}$ C/cm^2 and $w = 5 \times 10^{-1}$ cm in Eq. (1.6.4), the magnitude of the Hall voltage is given by,

$$V_H = \frac{BI}{\rho w}$$

$$= \frac{(6 \times 10 - 5 \text{Wb/cm}^2) \times (10 \times 10^{-3} A)}{(4.0 \times 10^{-4} \text{cm}^3) \times (5 \times 10^{-1} \text{cm})}$$

$$= 3.0 \times 10^{-3} \text{ V}$$

$$= 3.0 \text{ mV}$$

Since the direction of applied electric field is in the +X direction, the velocity of the electron v must be in the −X direction. Thus, the direction of deflection of the electrons can be determined as follows,

Let the magnetic field and velocity of electrons in the bar be expressed as,

$$B = B\hat{z} \text{ and } v_e = -v\hat{x}$$

Where $\hat{x}$ and $\hat{z}$ are the unit vectors along the +X and +Z directions,. Thus, the force acting on an electron is given by,

$$F_e = e(B \times v_e)$$

$$= eBv(-\hat{z} \times \hat{x})$$

$$= eBv(-\hat{y})$$

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Where $\hat{y}$ is the unit vector in the +Y direction. Since the force is acting on the electron in the -Y direction, the polarity of the Hall voltage at terminal 1 is negative with respective to the terminal 2.

Using Eq. (1.6.5), the Hall coefficient can be obtained as,

$$R_H = \frac{1}{\rho}$$

$$= \frac{1}{4.0 \times 10^{-4} C/cm^{-3}}$$

$$= 2.5 \times 10^3 cm^3/C$$

The negative sign in the value of Hall coefficient indicates that the sample used for Hall measurement is an n-type semiconductor.

(b) In this case the charge density is,

$$\rho = ep_p = (1.60 \times 10^{-19}C) \times 2.5 \times 10^{15} cm^{-3}$$

$$= 4.0 \times 10^{-4} C/cm^3$$

Following the similar method as in part (a), the Hall voltage and Hall coefficient are given by,

$$V_H = 3\ mV$$

And $\quad R_H = \frac{1}{\rho}$

$$= 2.5 \times 10^3 cm^3/C$$

Since the hole moves in the direction of the applied electric field (i.e., opposite to that of electron), the force acting on the hole can be given as,

$$F_h = e(v \times B)$$

$$= eBv(-\hat{z} \times \hat{x})$$

$$= eBv(-\hat{y})$$

Where $v = v\hat{x}$ is the velocity of hole. Thus, it is observed that holes are also deflected in the -Y direction as electron and hence the terminal 1 will be positive with respect to the terminal 2.

(c) Since the applied electric field $\epsilon_x = \frac{V_d}{l}$ is in the +X direction, the current in the bar can be expressed as,

$$I = (\sigma \epsilon_x)wd = \frac{\rho\mu V_d W_d}{l}$$

Thus, the mobility of majority carrier in the given semiconductor is given,

$$\mu = \frac{I\ell}{\rho w d V_d}$$

Substituting $I = \frac{\rho w V_H}{B}$ from Eq. (1.6.4) in the above equation, the mob can given by,

(or) $\mu = \left(\frac{\ell}{\rho w d V_d}\right)\left(\frac{\rho w V_H}{B}\right)$

$$\mu = \frac{\ell}{d}\left(\frac{V_H}{B V_d}\right)$$

Note that if the polarity of VH is negative at terminal 1, the above equati will represent that mobility of the electron in the semiconductor. On the oth hand, if the terminal 2 is negative with respect to terminal 1, then the equati represents the mobility of holes.

(d) Since the terminal 2 negative with respect to the terminal 1, we may say fro part (c) that the majority carrier in the semiconductor is hole. Using Eqs. (1.6. and (1.6.5), we may obtain the Hall coefficient as,

$$R_H = \frac{1}{\rho}$$

$$= \frac{V_H w}{IB}$$

$$= \frac{(6 \times 10^{-3}V) \times (0.5\ cm)}{(10 \times 10^{-3}A) \times (6 \times 10^{-5}Wb/cm^2)}$$

$$= 5 \times 10^3 cm^3/c$$

Hence the concentration of holes in the semiconductor is given by,

$$P_p = \frac{1}{eR_H}$$

$$= \frac{1}{(1.60 \times 10^{-19}C) \times (5 \times 10^3 cm^3/C)}$$

$$= 1.25 \times 10^{15} cm^{-3}$$

From part (c), the mobility of the holes can be obtained as,

$$\mu_p = \frac{1}{d}\left(\frac{V_H}{B V_d}\right)$$

$$= \frac{(1.2\ cm) \times (6 \times 10^{-3}V)}{(0.4\ cm) \times (6 \times 10^{-5}Wb/cm^2) \times (5\ V)}$$

$$= 60\ cm^2/V\ sec$$

1.7 QUALITATIVE THEORY OF THE P-N JUNCTION

Fig. 1.7.1 shows formation of p-n junction.
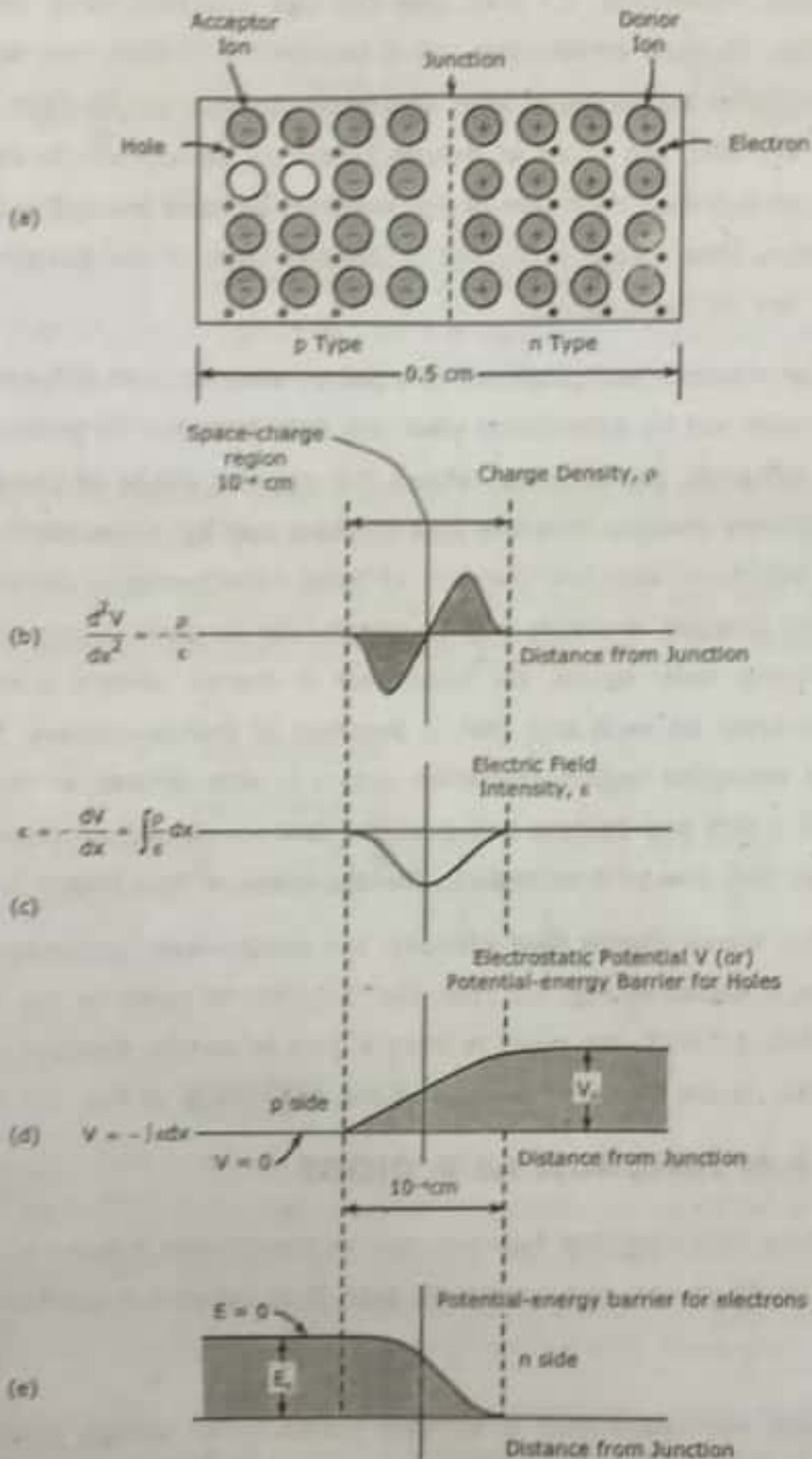
The p-n junction is formed when donor impurities were introduced at one side and acceptors into another side of a single crystal of a semiconductor. Here, we use germanium type semiconductor. In the Fig. 1.7.1(a), plus (+) sign indicates donor ion because after this impurity atom donates an electron, so it becomes a positive ion and negative (-) sign indicates acceptor ion because after this atom accepts an electron, so it becomes a negative ion. Initially, the holes of p-type carrier is placed left to the junction and electrons of n-type is placed right side of the junction. Because there is a density gradient across the junction. That means holes will be diffused right of the junction and electrons will be diffused left of the junction.

The result of displacement of these charges an electric field will appear across the junction. Equilibrium will be established when the field becomes large enough to restrain the process of diffusion. Fig. 1.7.1(b) shows the general shape of charge distribution. Diffusion of negatively charged immobile ions on the p-side by giving some acceptor atoms (on p-side) on additional electron. Diffusion of holes from p-region crossing the junction creates positively charged immobile ions on the N-side by giving some donor atoms (on n-side) an additional hole. Hence, the movement of charge carriers across the junction leaves behind a layer on each side that is depleted of charge carriers. So, the formed region is called depletion region. Depletion region is also defined as region containing immobile negative ions and positive ions near the junction. Depletion region is also called as space-charge (or) charge free region. The thickness of this region is 1 μm.

Fig. 1.7.1(c), shows electric field intensity. The electro-static potential variation in the depletion region is shown in Fig. 1.7.1(d), Fig. 1.7.1(e), is same as Fig. 1.7.1(c), but it is inverted. In Fig. 1.7.1(c), the curve is integral part of density function in Fig. 1.7.1(b). And Fig. 1.7.1(d), is the negative integral of the function & of Fig. 1.7.1(c).

1.8   THE P-N JUNCTION AS A DIODE

The boundary (or) interface between two semiconductor types i.e., p-type and n-type, inside a single crystal semiconductor, then it is called p-n junction.

(or)

When p-type semi-conductor is suitably joined to an N-type semiconductor, the contract surface is formed, then it is called p-n junction. The formation of junction is called diode.
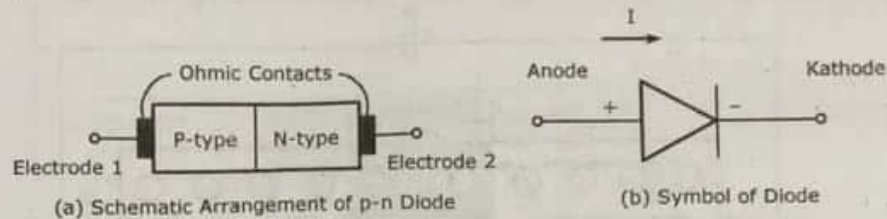
Fig. 1.8.1, shows p-n junction diode.

(a) Schematic Arrangement of p-n Diode   (b) Symbol of Diode

Fig. 1.8.1   p-n Junction Diode

In the above Figure, p-region act as a anode and n-region act as a cathode. The direction of arrow symbol indicates that the flowing of current in which direction. That means the current flow in only one direction.

Operation : When an external voltage applied to it, there are two biasing techniques are performed i.e., forward bias and reverse bias.

Forward Bias Condition : The electronic circuit is in forward bias that means positive is joined with p-region and negative is joined with n-region. Fig. 1.8.2, shows forward biasing of diode.
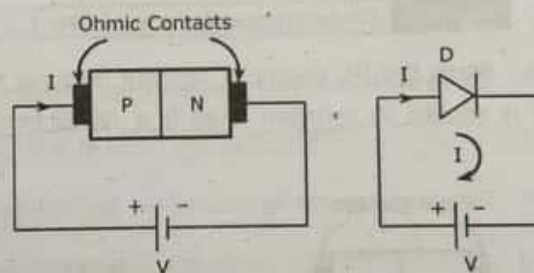

Fig. 1.8.2   Forward Biasing of Diode

When the pn junction is forward biased, the holes in the p-region and electrons in the n-region are repelled from their respective applied voltage terminals. The holes ｅ repelled from p-region to n-region and electrons are repelled from n-region to p-re ...l. Due to this, the depletion region width slowly reduced and the electrons and holes are travelled across the junction, so the potential barrier also decreases.

The applied voltage slightly increases, the depletion region is very narrow and majority charge carrier can easily cross the junction. This large number of majority carriers constitute a current called forward current. Hence, p-region in the holes and n-region in the electrons are called majority charge carriers.

1.50

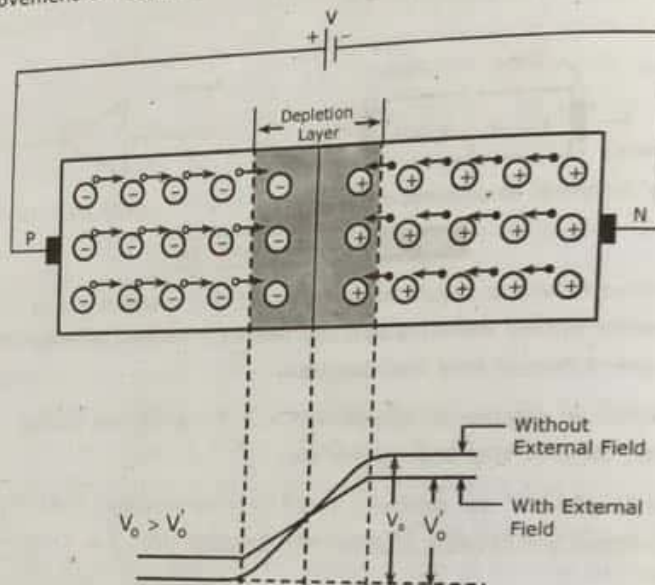The movement of electrons and holes shown in Fig. 1.8.3,

Fig. 1.8.3 | PN-Junction with Forward Bias

Reverse Bias Condition : When the DC source of positive terminal is applied to n-region and negative terminal is applied to p-region, then it is called reverse bias is shown in Fig. 1.8.4,
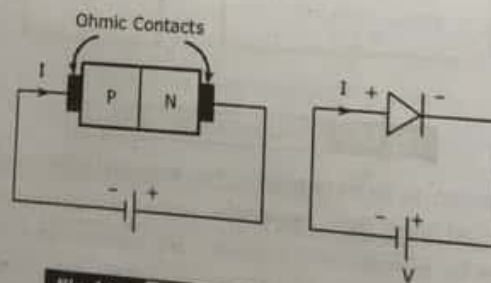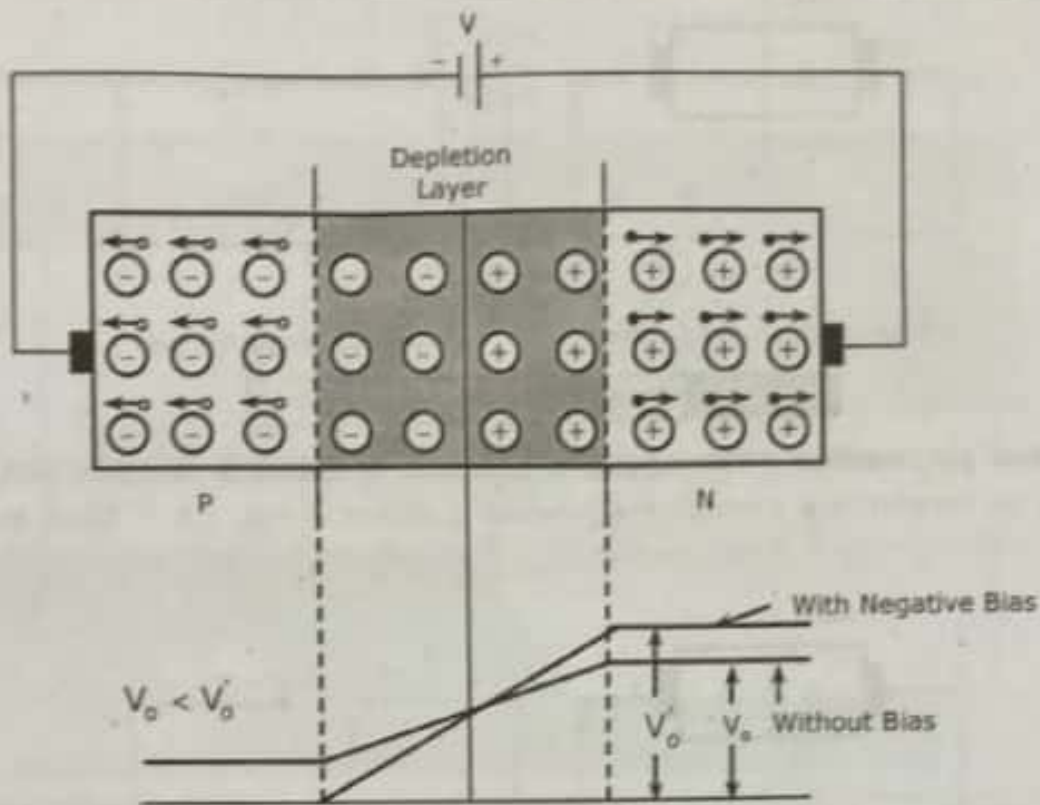

Fig. 1.8.4 | p-n Diode of Reverse Biasing

When the p-n junction is reverse bias, the holes in p-region attracted towards negative terminal of DC source (or) battery and the electrons in the n-region attracted towards positive terminal of DC source of battery. Due to this the depletion region and potential barrier increases as shown in Fig. 1.8.5,

Fig. 1.8.5 Increase in Depletion Layer Due to Reverse Biasing of PN Junction

The increase in potential barrier prevents the flow of majority carriers. However, there are some thermally generated electrons (minority carriers) on the p-side and holes (minority carriers) on the N-side. The potential barrier helps these minority carriers to cross the junction and a small magnitude of reverse current I_0 flow across the junction. This current is called as reverse saturation current.

1.8.1 The Short-Circuited and Open Circuited p-n Junction

Previously, we discuss the operation of p-n junction diode. It satisfies two conditions i.e., forward and reverse bias. Now, this topic is similar to operation of pn-junction diode.

P-n Junction has a Short Circuited : The positive external voltage is applied to the pn junction. Due to this, the junction will be short circuited and the current flows through the junction is shown in Fig. 1.8.6,

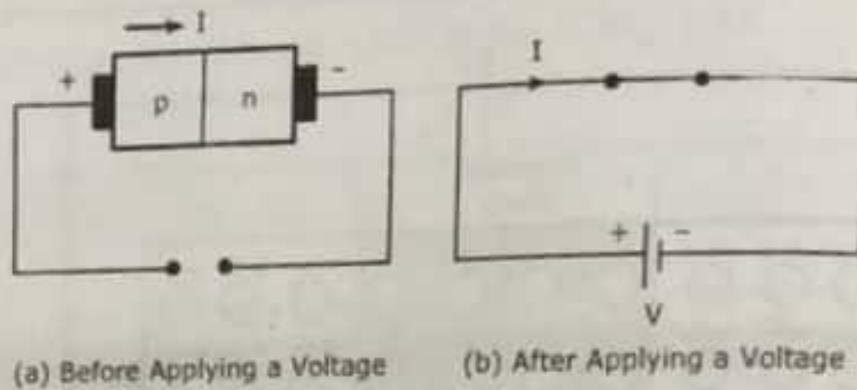(a) Before Applying a Voltage   (b) After Applying a Voltage

Fig. 1.8.6   Short Circuited p-n Junction

Open Circuited pn Junction : The negative external voltage pn junction will be open circuited and no current flow through the junction is shown in Fig. 1.8.7. Then, the current $I = 0$.

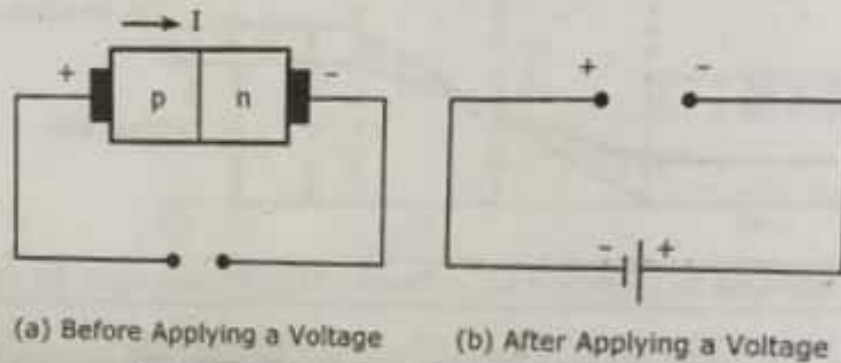(a) Before Applying a Voltage   (b) After Applying a Voltage

Fig. 1.8.7   Open Circuited pn Junction

The same explanation is also used in diode act as a switch.

1.8.2 Band Structure of Open-Circuited p-n Junction

Consider pn junction has p-type and n-type materials in close path contacts at the junction on an atomic scale. At the equilibrium, the Fermi level E_F should be constant throughout the specimen. If this is not so, an average energy of electron on one side of the junction is higher the other side and there would be a transfer of electrons and energy until the Fermi levels on the two sides get equalised. Previously, we verified that the Fermi level E_F is near to the conduction band edge E_{cn} in the n-type material and near to the valence band edge E_{vp} in the p-side. Then the conduction band edge E_{cp} in the p-material cannot be same level as E_{cn} but the valence band edge E_{vn} in the n-side same as E_{vp}. Hence, the energy band diagram for a p-n junction appears as shown in Fig. 1.8.8, where a shift in energy levels E_0 is indicated.

i.e.,

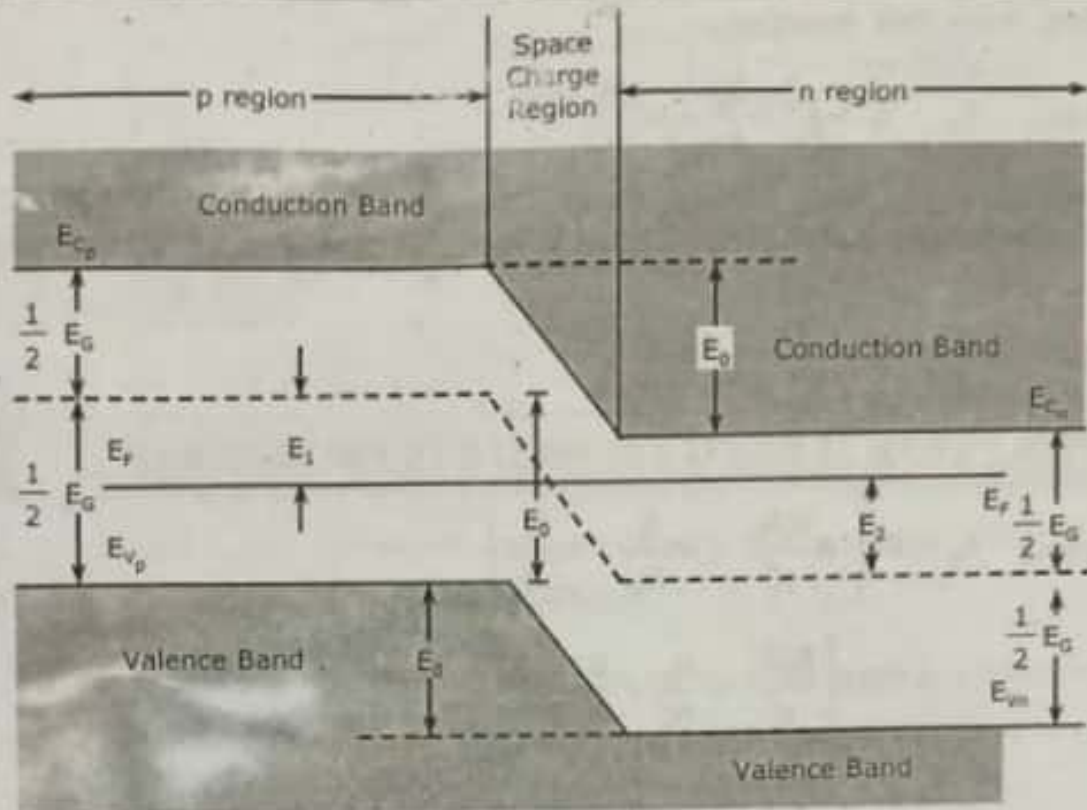$$E_0 = E_{cp} - E_{cn} = E_{vp} - E_{vn} = E_1 + E_2$$

Where,   ... (1.8.1)

E_0 = Potential energy of the electrons at the junction.

Fig. 1.8.8 Band Diagram of a p-n Junction Under Open-circuit Conditions

The Contact difference of Potential : It exists across a open-circuited PN junction. We obtain an expression for E_0. From the Fig. 1.8.8, we find that,

$$E_F - E_{vp} = \frac{1}{2}E_G - E_1 \qquad \qquad \text{... (1.8.2)}$$

And
$$E_{cn} - E_F = \frac{1}{2}E_G - E_2 \qquad \qquad \text{... (1.8.3)}$$

Combining Eq. (1.8.2) and Eq. (1.8.3),

We get, $E_0 = E_1 + E_2 = E_G - (E_{cn} - E_F) - (E_F - E_{vp})$ ... (1.8.4)

We know that,

$$np = N_c N_v e^{-E_G/kT}$$

And $np = n_i^2$ (Mass action law)

From the above equations,

We obtain, $E_G = kT/n \dfrac{N_c N_v}{n_i^2}$ ... (1.8.5)

We know that for N-type material $E_F = E_c - kT/n\dfrac{N_c}{N_D}$.

Therefore, from this equation,

We obtain, $E_{cn} - E_F = kT \ln \dfrac{N_c}{n_n} = kT \dfrac{N_c}{N_D}$

... (1.8.6)

Similarly for p-type material $E_F = E_v + kT \ln \dfrac{N_c}{N_A}$. Therefore, from this equation,

We get, $E_F - E_{vp} = kT \ln \dfrac{N_v}{P_p} = kT \dfrac{N_v}{N_A}$

... (1.8.7)

Substituting from Eq. (1.8.5), (1.8.6) and (1.8.7), into Eq. (1.8.4),

We obtain, $E_0 = kT \left[\ln \dfrac{N_c N_v}{n_i^2} - \ln \dfrac{N_c}{N_D} - \ln \dfrac{N_v}{N_A} \right]$

$$= kT \ln \left[\dfrac{N_c N_v}{n_i^2} \times \dfrac{N_D}{N_c} \times \dfrac{N_A}{N_v} \right]$$

$$E_0 = kT \ln \dfrac{N_D N_A}{n_i^2}$$

... (1.8.8)

In the above equation, E's are expressed in electron volts and k has the dimensions electron volts per degree Kelvin. The contact difference of potential V_0 is expressed in volts and is numerically equal to E_0. We note that E0 (hence V0) depends only upon the equilibrium concentration but not on the charge density in the transition region.

An alternative equation for E_0 may be obtained by substituting the equations of nn

$= N_D, P_n = \dfrac{n_i^2}{N_D}, P_p = n_i^2, P_p = N_A$ and $n_p = \dfrac{n_i^2}{N_A}$ into Eq. (1.8.8). Then we get,

$$E_0 = kT \ln \dfrac{P_{po}}{P_{no}} = kT \ln \dfrac{n_{no}}{n_{po}}$$

... (1.8.9)

In the above Eq. (1.8.9), subscript 0 indicates thermal equilibrium concentration.

1.8.3 Current Components in a p-n Diode

Previously indicated that, when a forward bias is applied to a diode, the holes are pushed into the n side and electrons pushed into p-side. The number of these pushed minority carriers falls of exponentially with distance from the junction. Since the diffusion current of minority charge carriers is proportional to the concentration gradient and this current must also vary exponentially with distance. Fig. 1.8.9 shows the electron and hole-current components vs distance in a p-n junction diode. It having two minority currents Inp and Ipn.
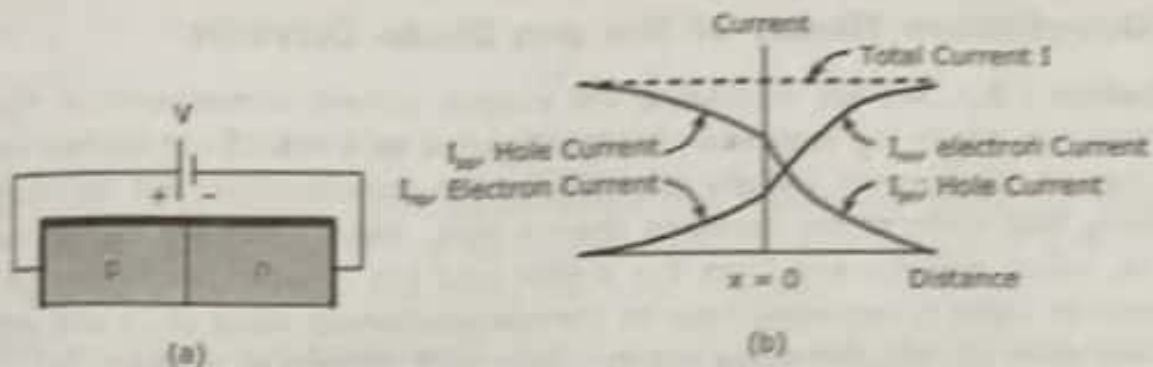
The Hole and Electron-current Components vs. Distance in a p-n Junction Diode. The Space-charge Region at the Junction is Assumed to be negligibly Small

In Fig. 1.8.9, the $I_{np}(x)$ represents electron current in the p-type material and $I_{pn}(x)$ represents hole current in the n-type material.

At x = 0, electrons crossing the junction from right to left from a current in the same direction as hole crossing the junction from left to right. Hence, total current I at x = 0 is,

$$I = I_{pn}(0) + I_{np}(0) \qquad \qquad \text{... (1.8.10)}$$

Here, I is independent of x, since the current is the same throughout a series circuit. Accordingly in the p-side, there must be second component of current I_{pp} is added to I_{np} gives the total current I.

$$I = I_{pp}(x) + I_{np}(x)$$

Therefore, the hole current $I_{pp}(x)$ in the p-side is given by,

$$I_{pp}(x) = I - I_{np}(x) \qquad \qquad \text{... (1.8.11)}$$

Similarly, on n-side, the electron current added to hole current $I_{pn}(x)$ in n-side, then the total current I is given by,

$$I = I_{nn}(x) + I_{pn}(x)$$

Therefore, the electron current $I_{nn}(x)$ in the n-side is given by,

$$I_{nn}(x) = I - I_{pn}(x) \qquad \qquad \text{... (1.8.12)}$$

From the Eqs. (1.8.11) and (1.8.12), the current Ipp decreases towards the junction and enters into n-region, the current I_{pn} also decreases exponentially. Similarly, the current Inn decreases towards the junction and enters into p-region, the current Inp also decrease exponentially.

$$\therefore P = q \omega \omega \left[2 \pm \frac{\sqrt{z^2 - 4c_i^2}}{z c_i} \right]$$

$$\frac{2 \pm \sqrt{z^2 - 4c_i^2}}{2 \pm \sqrt{z^2 - 4c_i^2}}$$

1.56

1.8.4 Quantitative Theory of The p-n Diode Currents

In Section 1.8.3, we are discussing the various current components in the p-n junction. Now, we derive the expression for total current as a function of applied voltage by using current components. Initially, the thickness of depletion-layer will be neglected and assuming that width of the depletion layer is zero. When a forward bias is applied to a diode, holes are injected from the p-side into the n-side. In the n-side, the concentration of holes is increased from its thermal-equilibrium value (p_{no}) and injected hole concentration [$p_n(x)$] decreases exponentially with respect to distance (x).

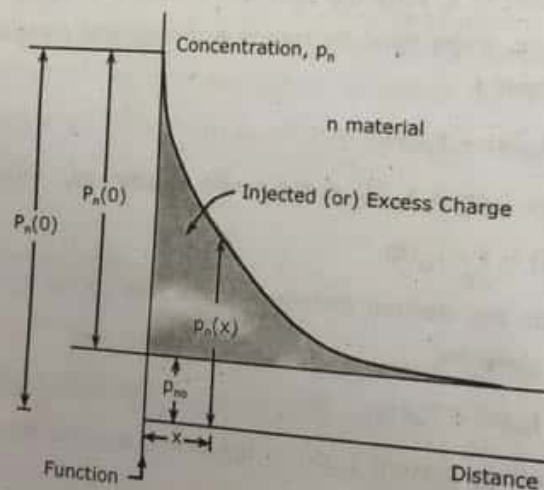$$p_n(x) - p_n - p_{no} = p_n(0)e^{-x/LP}$$

Where,

L_p = The diffusion length for holes in the N-material.

$$p_n(x) = p_{no} + p_n(0)e^{-x/4} \qquad \cdots (1.8.13)$$

Now, we injected hole concentration at x = 0 is,

$$p_n(0) = p_n(0) - p_{no} \qquad \cdots (1.8.14)$$

These several components of hole concentration in the n-side of a forward biased diode are shown in Fig. 1.8.10, in which the density $p_n(x)$ decreases exponentially with distance (x).

Fig. 1.8.10 Defining the Several Components of Hole Concentration in the n Side of a Forward-biased Diode. The Diagram is not Drawn to Scale Since $p_n(0) >> p_{no}$

Let us consider, p_p and p_n are the holes concentration at the edges of the space charge in the p and n sides, respectively. Let $V_B(V_B = V_0 - V)$ be the effective barrier potential across the depletion layer.

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Then, $P_p = P_n e^{V_B/V_T}$ ... (1.8.15)

Where,

V_T = The volt-equivalent of temperature.

The above equation can be called as boltz's man relation of kinetic gas theory and is valid as long as the hole of this equation current is small compared with drift (or) diffusion current. This condition is called low level injection.

Under the open circuit condition i.e., V = 0, $P_p = P_{po}$, $P_n = P_{no}$ and $V_B = V_0$. Eq. (1.8.7) can be written as,

$$P_{po} = P_{no} e^{V_0/V_T}$$ ... (1.8.16)

Under the condition of forward biasing, V be the applied voltage, then the effective barrier voltage is,

$$V_B = V_0 - V$$

The hole concentration entire p-side is constant and equal to the thermal equilibrium value ($P_p = P_{po}$). The hole concentration varies exponentially with distance into the n-side i.e.,

At x = 0, $P_n = P_n(0)$

Mass-action law, $np = n_i^2$ can be changed into,

$$P_{po} = P_n(0)e^{(V_0 - V)/V_T}$$ ... (1.8.17)

Comparing Eq. (1.8.16) and (1.8.17),

We get, $P_n(0) = P_{no}e^{V/V_T}$ ... (1.8.18)

This boundary condition is called low of the junction. The Eq. (1.8.18) can be substitute into Eq. (1.8.14),

We obtain, $P_n(0) = P_{no}(e^{V/V_T} - 1)$ ... (1.8.19)

The diffusion hole current in the n-side is,

$$I_{pn}(x) = -A_e D_p \frac{d_{pn}(x)}{dx} a$$

$$= -A_e D_p \frac{d}{dx}[P_{no} + P_n(0)e^{-x/LP}]$$

$$I_{pn}(x) = \frac{A_e D_p P_n(0)}{L_p} e^{-x/LP}$$ ... (1.8.20)

Let us consider Eq. (1.8.20), it is evident for the injected hole current decreases exponentially with distance.

1.58

Forward Currents : The hole current $I_{pn}(x)$ crossing the junction into the n-side with $x =$ 0 is, (applying x = 0 in Eq. (1.8.20)).

$$I_{pn}(0) = \frac{A_e D_p p_n(0)}{L_p}$$ ... (1.8.21)

We know that, $p_n(0) = p_{n0}(e^{V/V_T} - 1)$ from the Eq. (1.8.19), is substitute into Eq. (1.8.21),

$$I_{pn}(0) = \frac{A_e D_p p_{n0}}{L_p}(e^{V/V_T} - 1)$$

The electron current crossing the junction into the p-side with x = 0 is,

$$I_{np}(0) = \frac{A_e D_n N_p(0)}{L_n}$$

$$= \frac{A_e D_n n p_0}{L_n}(e^{V/V_T} - 1)$$

∴ The total diode current is,

$$I = Ipn(0) + Inp(0)$$

$$I = I_{pn}(0) + I_{np}(0) = I_0(e^{V/V_T} - 1)$$ ... (1.8.22)

Where,

I_0 = Reverse saturation current.

Now, if we consider carrier generation and recombination in the space-charge region, the general equation of the diode current is approximately given by,

$$I = I_0(e^{V/nV_T} - 1)$$ ... (1.8.23)

Where,

V = applied voltage to the diode.

n = A constant and 1 for a germanium and 2 for a silicon.

Reverse Saturation Currents : From the concept of charge densities in a semiconductor, consider $P_n = \frac{n_i^2}{N_D}$ and $n_p = \frac{n_i^2}{N_A}$. Applying these values into the above reverse saturation current I_0,

We get, $$I_0 = \frac{A_e D_p n_i^2}{L_p N_D} + \frac{A_e D_n n_i^2}{L_n N_A}$$

$$= A_e \cdot n_i^2 \left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right] \qquad \qquad ... (1.8.24)$$

From the Eq. (1.4.27), $n_i^2 = A_0 T^3 e^{\frac{-E_{G0}}{K.T}}$,

i.e., $$n_i^2 = A_0 T^3 e^{\frac{-V_{G0}}{V_T}}$$

Where, V_{GO} is a voltage which is numerically equal to the forbidden gap. Energy EG0 is electron volts.

For a germanium diode, the diffusion constants D_p and D_n vary approximately inversely proportional to T. Hence, the temperature dependence of I_0 is,

$$I_0 = k_1 T^2 e^{\frac{-V_{G0}}{V^T}} \qquad \qquad ... (1.8.25)$$

Where,

   k_1 = A constant independent of temperature.

For a silicon diode, I_0 is proportional to n, instead of n_i^2.

Hence, $$I_0 = k_2 T^{3/2} e^{\frac{-V_{G0}}{2V_T}} \qquad \qquad ... (1.8.26)$$

Where,

   k_2 = A constant independent of temperature.

1.8.5 Diode Current Equation

Equation which gives the forward and reverse characteristics of a semiconductor P-N junction diode is called as diode current equation.

It can be shown that for a semiconductor diode, the current I and voltage V are related by the equation,

$$\boxed{I = I_0 (e^{V/nVT} - 1)} \qquad \qquad ... (1.8.27)$$

Where,

   I = Diode forward (or reverse) current.

   I_0 = Reverse saturation current.

   V = Applied voltage. (Positive for forward bias and negative for reverse bias)

η = A constant (emission coefficient) depends on the type of semiconductor material used [η = 1 for Ge and η = 2 for Si]

V_T = Volts equivalent of temperature

Volt-equivalent of temperature indicates the dependence of diode current on temperature, and is given by,

$$\boxed{V_T = \frac{\bar{k}T}{q} = KT = \frac{T}{11,600}}$$
... (1.8.28)

Where,

$\bar{k}$ = Boltzmann constant (in J/°K) = 1.38×10^{-23} J/°K

K = Boltzmann constant (in eV/°K) = 8.62×10^{-5} eV/°K

T = Absolute temperature (in Kelvin °K)

q = Charge of an electron = 1.602×10^{-19} C

COMMENT : *The value of V_T is approximately 26 mV at room temperature (300°K). Often we take V_T = 25 mV for making calculations easier.*

For Forward Bias Junction : For forward-bias, V is positive. The exponential term grows very quickly and becomes very large compared to unity $\left(e^{V/\eta V_T} \gg 1\right)$. The diode current in this case is given by,

$$\boxed{I = I_0 e^{V/\eta V_T}}$$
... (1.8.29)

For Reverse Bias Junction : For reverse-bias, V is negative. As we increase V the exponential term soon becomes negligible compared to unity ($e^{V/\eta V_T} \ll 1$). The diode equation then becomes,

$$\boxed{I = -I_0}$$
... (1.8.30)

This states that the diode current I is constant in reverse bias region.

Current Density Equation : If both sides of diode current equation is divided by a cross sectional area (A) of the junction, then we have,

$$\frac{I}{A} = \frac{I_0}{A} \left[e^{V/\eta V_T} - 1\right]$$

$$J = J_0(e^{V/\eta V_T} - 1)\left(\frac{Ampere}{Meter^2}\right)$$
... (1.8.31)

COMMENT : *Diode current equations for Si and Ge diodes at temperature (T = 20°C) are approximately given by,*

$$I = I_0[e^{40V} - 1] \text{ (For Ge diodes)}$$
$$I = I_0[e^{20V} - 1] \text{ (For Si diodes)}$$

1.9 CHARACTERISTICS OF P-N JUNCTION DIODE

If diode is used as a circuit element in an electric circuit, there may be a requirement to know how it behaves. This type of information may be obtained by a curve known as Volt-Ampere (V-I) characteristics of a diode.

The V-I characteristics of a diode represents a curve drawn between the external voltage applied across its terminals and the current that flows through the diode due to this applied voltage. The V-I characteristics may be divided into two parts namely,

(1) Forward characteristics.

(2) Reverse characteristics.

1.9.1 V-I Characteristics of Forward Bias

Fig. 1.9.1, shows a typical V-I characteristic for a forward-biased P-N junction silicon and germanium diodes.
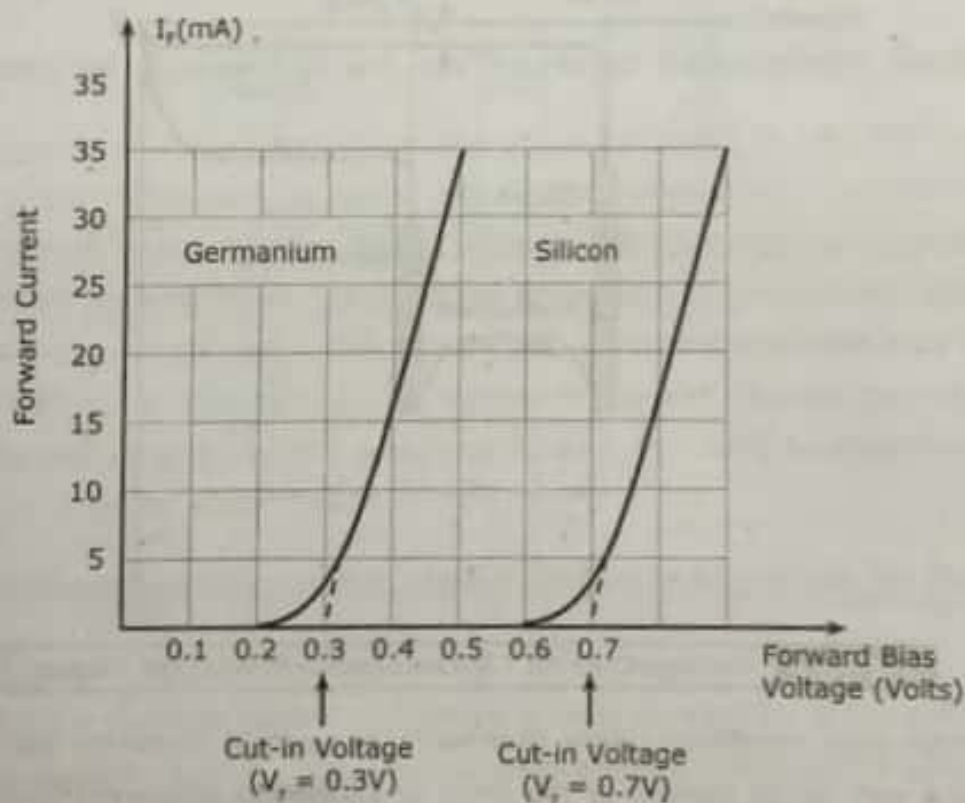
Fig. 1.9.1 Voltage-current Characteristics in Forward Biasing

1.62

As shown in Fig. 1.9.1, in a forward bias condition, a very little current flows until the forward bias voltage exceeds the junction potential barrier. This voltage is known as threshold voltage (V_γ) cut-in voltage or knee-voltage. The value of threshold voltage for Ge and Si diodes are as such :

$$V_\gamma = 0.7V \quad \text{(For Si Diodes)}$$
$$V_\gamma = 0.3V \quad \text{(For Ge Diodes)}$$

For $V < V_\gamma$, the current flow is negligible (less than 1% of maximum rated value). But as the applied voltage increases beyond threshold value, the forward current increases almost linearly with increase in forward voltage. If the forward voltage is increased beyond a certain safe value, it produces an extremely large current that may destroy the junction due to overheating. Ge devices can withstand junction temperature around 100°C, whereas Si devices can function upto 175°C.

1.9.2 V-I Characteristics of Reverse Bias

Fig.1.9.2 shows a typical V-I characteristics for a reverse-biased P-N junction silicon and germanium diodes.
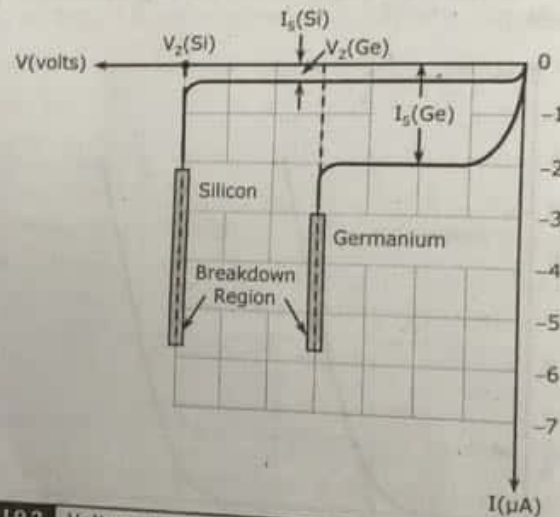

Fig. 1.9.2 Voltage-Current Characteristics in Reverse Biasing

In reversed bias condition, only thermally generated minority carriers cross the junction. Thus a very small current of the order of μA (micro amperes) flows in the circuit. This current is known as *reverse saturation current* (I_S).

It can be seen that as the reverse voltage is increased from zero, the reverse current quickly rises to its maximum (or saturation) value. If the reverse voltage is increased furtherly then the kinetic energy of minority carriers becomes so high such that they knock out other electron from the semiconductor atoms. At this stage breakdown of junction occurs and there is a sudden rise of reverse saturation current, hence the junction is destroyed permanently. For a Si diode the reverse saturation current I_s is of the order of 10 to 20 nA, whereas for Ge diode I_s is of the order of 1 to 10 µA.

(1) **Why reverse saturation current of Si diode is lower than Ge diode?**

The forbidden energy gap for Si (E_g = 1.12 eV) at room temperature is more than that for Ge (E_g = 0.72 eV). At a given temperature, very few number of minority acquire energy greater than forbidden energy gap, so less number of covalent bonds will be broken in Si. Since the reverse saturation current is due to the drift of the minority carriers, hence its value is comparatively less in a Si diode than in a Ge diode.

Si diodes are considered to be better choice for most of the commercial applications.

1.9.3 Temperature Dependence on V-I Characteristics

1.9.3.1 Effect of Temperature on Reverse Saturation Current

As temperature increases, more and more covalent bonds will be broken, thus generating more electron-hole pairs. Hence the conductivity increases. The reverse saturation current is due to the flow of minority carriers and the concentration of the minority carriers is very much temperature dependent. From experimental data, it has been noticed that reverse saturation current (I_s) increases approximately at the rate 7% per °C for both silicon and germanium diodes. Hence the reverse saturation current will be 1.07 times more for every 1°C temperature rise. For 10°C temperature rise, I_s would be $(1.07)^{10} \simeq 2$ times more. Thus,
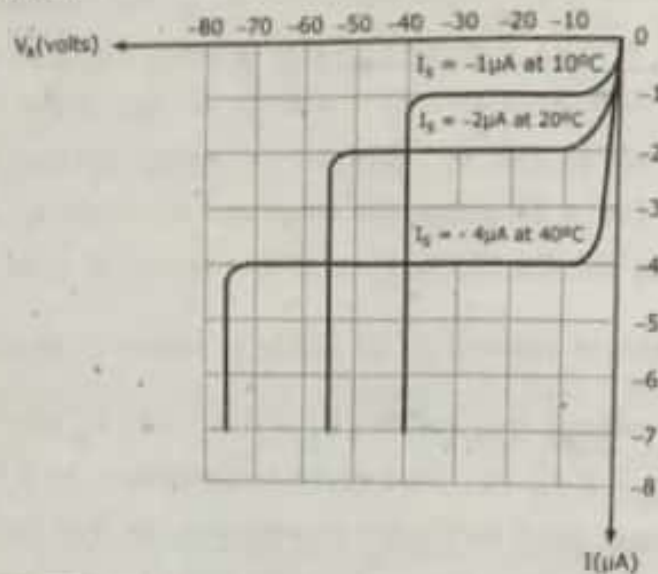
"The reverse saturation current almost doubles in magnitude for every 10°C rise in temperature".

Let I_s be the reverse saturation current known at a given temperature (T_1), for the another temperature level T_2, the reverse saturation current $I_s(T_2)$ is given as,

$$I_s(T_2) = I_s(T_1) \times (2^{T_2 - T_1/10})$$

... (1.9.1)

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From Fig. 1.9.3, it can be seen that for every 10°C rise in temperature, reverse saturation current doubles.


Fig. 1.9.3 Reverse Saturation Current Approximately Doubles Per 10°C Rise in Temperature

1.9.3.2 Effect of Temperature on Barrier Potential

The junction temperature also affects the barrier potential. A higher temperature creates more free electrons and holes. These extra electrons and holes reduce the width of the depletion layer. As a result the barrier potential and hence the threshold voltage V_r is lowered. For a PN-junction, "*the barrier potential decreases by 2.5 mV for each celsius degree rise in temperature*". In other words,

$$\frac{dV}{dT} = -2.5 \text{ mV/ C}$$

... (1.9.2)
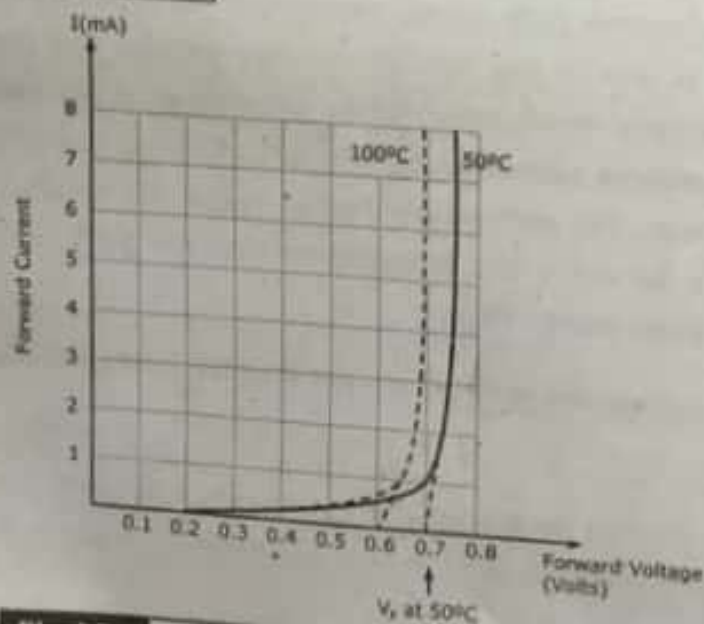
Fig. 1.9.4 Temperature Effect on Barrier Voltage

EXAMPLE PROBLEM 1

The threshold voltage of a silicon diode is 0.7 V at 25°C. What will be the value of threshold voltage if the junction temperature rises to 100°C?

SOLUTION

Given Data : Threshold voltage (V_{T1}) = 0.7 V

Initial temperature (T_1) = 25°C

Final temperature (T_2) = 100°C

The barrier potential decreases by 2.5 mV per celsius degree rise in temperature. Therefore if the temperature rises to 100°C from 25°C, the decrease in barrier potential is given by,

$$= (100 - 25) \times 2.5 \text{ mV} = 187.5 \text{ mV} = 0.1875 \text{ V}$$

Thus, the threshold voltage at 100°C is

$$V_T = 0.7V - 0.1875 \text{ V} = 0.5125 \text{ V}$$

EXAMPLE PROBLEM 2

The reverse saturation current for a semiconductor diode is measured as 25 nA at 25°C and as 75 nA at a temperature T_2. Calculate T_2.

SOLUTION

Given Data : Temperature (T_1) = 25°C

Reverse saturation current at 25°C (I_{S1}) = 25 nA

Reverse saturation current at T_2 (I_{S2}) = 75 nA

From Eq. (1.9.1), we have,

$$I_S(T_2) = I_S(T_1) \times 2^{(T_2 - T_1)/10}$$

$\Rightarrow$ $75 \text{ nA} = 25 \text{nA} \times 2^{(T_2 - 25°)/10}$

$\Rightarrow$ $3 = 2^{(T_2 - 25°)/10}$

Applying log on both sides, we have,

$$\log 3 = \frac{T_2 - 25}{10} \log 2$$

$\Rightarrow$ $\dfrac{T_2 - 25}{10} = \dfrac{\log 3}{\log 2} = \dfrac{0.301}{0.477}$

$\Rightarrow$ $T_2 - 25 = 1.58$

$\Rightarrow$ $T_2 = 25 + 15.84 = 40.84°C$

1.66

1.10 PARAMETERS AND APPLICATIONS

The list below provides details of the various diode characteristics, and diode parameters found in the datasheets and specifications for diodes.

(1) **Semiconductor material :** The semiconductor material used in the PN junction diode is of paramount importance because the material used affects many of the major diode characteristics and properties. Silicon is the most widely used material as it offers high levels of performance for most applications and it offers low manufacturing costs. The other material that is used is germanium. Other materials are generally reserved for more specialist diodes. The semiconductor material choice is of particular importance as it governs the turn on voltage for the diode - around 0.6 volts for silicon and 0.3 volts for germanium, etc..

(2) **Forward voltage drop (V_t) :** Any electronics device passing current will develop a resulting voltage across it and this diode characteristic is of great importance, especially for power rectification where power losses will be higher for a high forward voltage drop. Also RF diodes often need a small forward voltage drop as signals may be small but still need to overcome it.

The voltage across a PN junction diode arise for two reasons. The first of the nature of the semiconductor PN junction and results from the turn-on voltage mentioned above. This voltage enables the depletion layer to be overcome and for current to flow. The second arises from the normal resistive losses in the device. As a result a figure for the forward voltage drop are a specified current level will be given. This figure is particularly important for rectifier diodes where significant levels of current may be passed.

(3) **Peak Inverse Voltage (PIV) :** This diode characteristics is the maximum voltage that a diode can withstand in the reverse direction. This voltage must not be exceeded otherwise the device may fail. This voltage is not simply the RMS voltage of the incoming waveform. Each circuit needs to be considered on its own merits, but for a simple single diode half wave rectifier with some form of smoothing capacitor afterwards, it should be remembered that the capacitor will hold a voltage equal to the peak of the incoming voltage waveform. The diode will then also see the peak of the incoming waveform in the reverse direction and therefore under these circumstances it will see a peak inverse voltage equal to the peak to peak value of the waveform.

(4) **Maximum forward current :** When designing a circuit that passes, any levels of current it is necessary to ensure that the maximum current levels for the diode are not exceeded. As the current levels rise, so additional heat is dissipated and this needs to be removed.

(5) **Leakage current :** If a perfect diode were available, then no current would flow when it was reverse biased. It is found that for a real PN junction diode, a very small amount of current flow in the reverse direction as a result of the minority carriers in the semiconductor. The level of leakage current is dependent upon three main factors. The reverse voltage is obviously significant. It is also temperature dependent, rising appreciably with temperature. It is also found that it is very dependent upon the type of semiconductor material used - silicon is very much better than germanium.

The leakage current characteristic or specification for a PN junction diode is specified at a certain reverse voltage and particular temperature. The specification is normally defined in terms of in microamps, ìA or picoamps, pA.

(6) **Junction capacitance :** All PN junction diodes exhibit a junction capacitance. The depletion region is the dielectric spacing between the two plates which are effectively formed at the edge of the depletion region and the area with majority carriers. The actual value of capacitance being dependent upon the reverse voltage which causes the depletion region to change (increasing reverse voltage increases the size of the depletion region and hence decreases the capacitance). This fact is used in varactor or varicap diodes to good effect, but for many other applications, especially RF applications this needs to be minimized. As the capacitance is of importance it is specified. The parameter is normally detailed as a given capacitance (in pF) at a given voltage or voltages. Also special low capacitance diodes are available for many RF applications.

(7) **Reverse Breakdown Voltage :** If the reverse bias applied to a P-N junction is increased, a point is reached when the junction break down and reverse current shoots upto a value limited only by the external resistance connected in series with the junction. This critical value of the voltage is known as the reverse breakdown voltage.

(8) **Maximum Forward Current ($I_{F,max}$) :** This is the maximum current that may be passed continuously through the diode.

1.10.2 Diode Applications

The various applications of diode are,

(1) **Rectifiers :** This is the main application of diode. The rectifiers are used to convert A.C to D.C. The diode is useful for this purpose as it conducts only for positive half cycle of alternating input voltage.

(2) **Wave Shaping Circuits :** Some circuits are used to cut the unwanted portion of the input waveform, as per the requirement. Such circuits are called wave shaping circuits. The diode plays an important role in these circuits. The clipper and clipper circuits are important wave shaping circuits using diode.

(3) Diodes when used along with operational amplifiers can design many important circuits such as log amplifier, antilog amplifier, peak detectors etc.

(4) Diodes are used for amplitude limiting in oscillators.

(5) Diodes plays a significant role in voltage multiplier circuits.

(6) Provides temperature compensation in various transistor biasing circuits.

(7) The diode is used as a switch in many electronic circuits.

(8) The various types of diodes such as pin diode, tunnel diode, schottkey diode, switching diode, power diode, varactor diode are used in various types of electronic circuits such as modulating devices, photodetectors, high frequency applications, detectors in communication equipments, analog to digital converters, digital computers etc.

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