

# Semiconductor Physics

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## 2.1 Introduction

Many modern electronic gadgets like iPods, MP3 players, LCDs and plasma TVs, etc. incorporate semiconducting materials in one form or other. A knowledge of the fundamental properties of semiconductors enables the readers to look for new materials as physical dimensions of semiconductor devices undergo miniaturisation and more complicated compound semiconductor materials find a place in electronic circuits. Basically, semiconductors are the class of materials having electrical resistivities that lie between good conductors like metals and insulators like glass, mica, etc. For example, at ordinary room temperature a cubic centimetre of pure copper (good conductor) offers a resistance of about  $1.7 \times 10^{-6}$  ohm to current flow while a cubic centimetre of slate (an insulator) has resistance of about  $1.0 \times 10^8$  ohms. On the other hand, a cubic centimetre of germanium (a semiconductor) offers a resistance of about 60 ohms to current flow. Commonly used semiconducting materials are Si, Ge, GaAs, Inp, InGaP, InGaAl, etc.

## 2.2 Types of Semiconductors

Semiconductors can be classified into various types based on different characteristics. Based on the number of constituting elements and on purity aspects, semiconductors can be classified as:

1. Elemental semiconductors.
2. Compound semiconductors.

### *Elemental semiconductors*

Semiconductors which are composed of single species of atoms are called elemental semiconductors. Elemental semiconductors are found in group IV of the Periodic table.

*Examples:* Si and Ge.

### *Compound semiconductors*

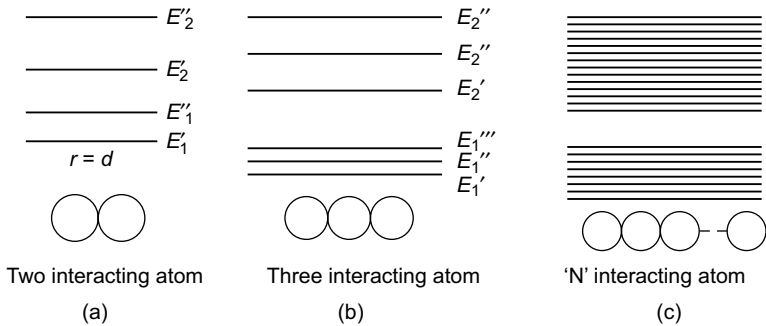
Semiconductors which are composed of two or more different species of atoms are called compounds or compound semiconductors.

These semiconductors can be formed by combining different group elements from the Periodic table.

## 2.3 Energy Bands of Solids

A solid is an ordered structure as shown by X-ray diffraction studies. Atoms in solids occupy the lattice sites and the spacing between the atoms is of the same order as that of the linear dimensions of atoms. Therefore, atoms in solid interact strongly and set up an internal electric field which is *periodic* in nature. The periodic electric field affects the motion of free electrons and an electron in a periodic potential energy shows *energy bands*.

In isolated atoms, the energy levels of electrons are discrete; and wide regions of forbidden energies separate the allowed energy levels. Let us consider a large number ( $N$ ) of identical atoms, which are far enough apart such that their interactions are negligible. Every atom has the *same* energy-level diagram. We may imagine a solid as having formed by allowing initially free atoms to gradually approach one another. When the atoms uniformly approach each other, they interact more and more. By interaction we mean that the positive nucleus of one atom attracts the electrons and repels the nucleus of the adjacent atom and vice versa. Because of the interactions between atoms, the discrete energy levels of atoms in the solid are split up. The transformation of a single energy level into two or more separate energy levels is known as **energy level splitting**. When two atoms come close, one energy level splits into two energy levels (Fig. 2.1a). When three atoms approach each other closely, the original level splits into three levels (Fig. 2.1b); four atoms produce four levels, and so on. In general,  $N$  interacting atoms cause a particular energy level to split into  $N$  levels. The group of energy levels resulting from splitting is so closely spaced that they form a virtual continuum, which is called an **energy band** (see Fig. 2.1c)



**Fig. 2.1** Energy level splitting and band formation.

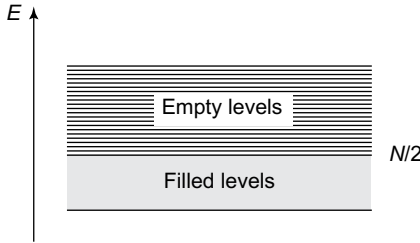
The large number of energy levels resulting from splitting of an energy level will be very closely spaced and form an energy continuum that is called **energy band structure**. The individual valence electrons no longer belong to individual atoms; but they now belong to all nuclei in the solid. As the atoms approach, a continuously increasing interaction occurs between the atoms. Each of the energy levels splits into many distinct levels and form energy bands. It is seen that corresponding to each allowed energy level of an isolated atom, there is an allowed energy band, and that the allowed energy bands are separated by forbidden bands of energy.

While occupying an energy band, electrons start from the lowest energy level in the band and fill the levels one after the other in the ascending order of energy. When  $2N$  electrons occupy the  $N$  levels available in a band, the band is said to be **full completely filled**. In case of non-availability of  $2N$  electrons, the energy band gets **partially filled**. When there are no electrons to occupy the levels the energy band remains **vacant or empty**.

An energy band diagram is a graphic representation of the energy levels associated with top energy band and the next lower energy band in a solid. The energy band diagram shows two bands with a gap in between. The upper band is called the **conduction band** and lower energy band is called the **valence band**. These two bands are separated by a forbidden gap. This energy gap is more popularly called **band gap** and is denoted by the symbol  $E_g$ . The band gap does not contain energy levels. The conduction band corresponds to the energy values of free electrons that have broken from their valence bonds, and have become free to move in the crystal.

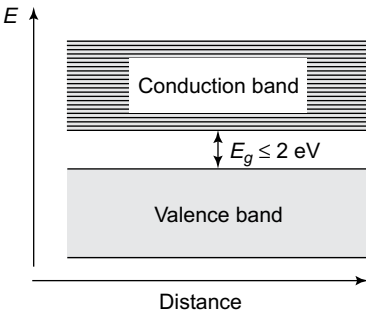
### 2.4 Classification of Solids Based on Energy Bands

According to the band theory, a solid is characterized by the energy gap  $E_g$  separating the outermost energy bands, namely, the valence band and the conduction band.

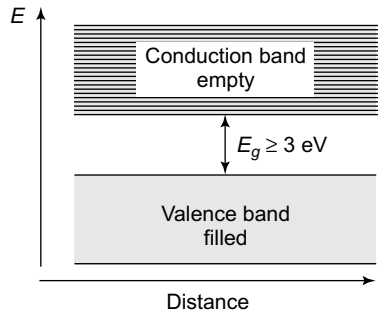


**Fig. 2.2(a)** Energy band formation in a conductor.

**Conductors:** In some solids an upper vacant band overlaps on the valence band (Fig.2.2a). It means that electrons in the valence band have easy access to upper vacant levels. For this reason, very large numbers of electrons are available for conduction even at extremely low temperatures. Therefore, these solids exhibit good electrical conductivity and are called **conductors**.



**Fig. 2.2(b)** Energy band structure of a semiconductor.



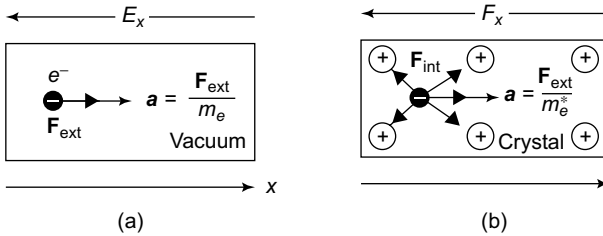
**Fig. 2.2(c)** Energy band structure of an insulator.

**Semiconductors:** In some solids the band gap is narrow and is of the order of 2 eV or less as shown in Fig. 2.2(b). Acquisition of small amounts of energy from the vibrations of atoms can raise electrons from the valence band to the conduction band. The conduction band is then partially filled. If a potential is applied across the material, it causes the electrons in the conduction band to move to upper levels. As a result, current flows in a modest measure in the solid. Such solids are called **semiconductors**.

**Insulators:** Some solids (Fig. 2.2(c)) have band gaps that very wide ( $E_g > 6$  eV). It would require the acquisition of very large amounts of energy to cause an electron to jump from the valence band to the conduction band. Very few electrons can get this large amount of energy to jump from valence band to conduction band at ambient temperature. Hence, there are very few electrons in the conduction band. When a voltage is applied across the solid, negligible current flows and the solid exhibits very low electrical conductivity. These solids are called **insulators**.

## 2.5 Concept of Effective Mass

Let us first ask a question: Why it is necessary to talk about the effective mass of an electron or hole in a solid? The answer lies in the concept of how we manage with absolute mass in what circumstances. Let us consider two situations—(a) the electron is kept in a vacuum chamber and (b) the electron is kept inside a solid as shown in Fig. 2.3. In both cases an external electric field  $\mathbf{F}_{\text{ext}}$  is applied on the electron. Here a comparative study has been made of these cases.



**Fig. 2.3** An external force  $\mathbf{F}_{\text{ext}}$  applied to an electron (a) in a vacuum results in an acceleration  $\mathbf{a}_{\text{vacuum}} = \mathbf{F}_{\text{ext}}/m_0$  and (b) in a solid results in an acceleration  $\mathbf{a}_{\text{solid}} = \mathbf{F}_{\text{ext}}/m_e^*$ .

In Fig. 2.3(a) the electron is an isolated one and there is no influence of any other species from the surroundings. Therefore, the only force that acts on this electron is  $\mathbf{F}_{\text{ext}}$  due to the applied external field.

$$\mathbf{F}_{\text{ext}} = -e\mathbf{E}_{\text{ext}} \quad (\text{i})$$

From Newton's law, the acceleration of the electron is

$$\mathbf{a}_{\text{vacuum}} = \mathbf{F}_{\text{ext}}/m_0 \quad (\text{ii})$$

In Fig. 2.3 (b), the electron is inside the solid and Eq. (i) cannot be strictly valid, because the movement of an electron in a lattice will, in general, be different from that of an electron in free space. In addition to the external force, there are internal forces in the crystal due to positively charged ions and negatively charged electrons.

These forces influence the motion of electrons in the lattice. Therefore, the total force on the electron is

$$\mathbf{F}_{\text{total}} = \mathbf{F}_{\text{ext}} + \mathbf{F}_{\text{int}} \quad (\text{iii})$$

and the acceleration of the electron is

$$\mathbf{a}_{\text{solid}} = (\mathbf{F}_{\text{ext}} + \mathbf{F}_{\text{int}})/m_0 \quad (\text{iv})$$

where  $\mathbf{F}_{\text{int}}$  are the internal forces. The parameter  $\mathbf{a}$  is the acceleration and  $m_0$  is the rest mass of the particle. The acceleration  $\mathbf{a}_{\text{solid}}$  will be different than  $\mathbf{a}_{\text{vacuum}}$  due to the different environment the electron faces in the solid. To the outside agent applying the force  $\mathbf{F}_{\text{ext}}$ , the electron will appear to be exhibiting a different inertial mass, since its acceleration will be different. It would be more useful to the external agent if the effect of the internal forces  $\mathbf{F}_{\text{int}}$  could be accounted for in a simple way and if the acceleration could be calculated from the external force  $\mathbf{F}_{\text{ext}}$  alone, through something like Eq. (ii). This is indeed possible. Since it is difficult to take into account all of the internal forces, we will write Eq. (iv) as

$$\mathbf{a}_{\text{solid}} = \mathbf{F}_{\text{ext}}/m^* \quad (\text{v})$$

where  $m^*$  is the effective mass. It is a quantum mechanical quantity and behaves in the same way as the inertial mass in classical mechanics. It is to be noted that once the effective mass is considered, the particle can be treated as free and we are not bothered about the medium in which it is moving.

## 2.6 Carrier Drift and Mobility

At finite temperatures, due to thermal agitation and lattice vibrations, some of the valence band electrons are always present in the conduction band, i.e., at ordinary temperatures. An intrinsic semiconductor always contains some free electrons in the conduction band and an equal number of holes in the valence band. In the absence of any applied electric field, these electrons and holes move in the random directions and constitute no current. When an electric field is applied, these electrons and holes get accelerated towards the opposite ends of the field and their velocity begins to increase. The net movement in charge is known as ‘**drift**’. This increase in velocity, however, does not continue indefinitely because of the collision of these carriers with the various types of obstacles, such as atomic nuclei, phonons, etc. present in the semiconductors. Depending on the mean free path, the carriers acquire an average increment in the velocity. This extra velocity acquired by the carriers in the presence of an applied electric field is called the **drift velocity** and is denoted by  $v_d$ . It is proportional to the strength  $E$  of the applied electric field, i.e.

$$v_d \propto E$$

$$v_d = \mu E$$

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

$\mu$  is called the mobility of the charge carrier and is defined as the drift velocity acquired by a carrier per unit electric field strength. Drift velocities of electron and hole are denoted by the  $v_{de}$  &  $v_{dh}$  and mobilities of electron and holes are denoted by the  $\mu_e$  and  $\mu_h$  respectively.

## 2.7 Conductivity and Resistivity

In case of the metals, the current is due to motion of free electrons. Under the application of electric field  $E$ , if the average drift velocity acquired by the electrons is  $v_d$ , the current density  $J$  which is the charge passing through unit cross-section per unit time is given by

$$J = (e) (n_e) (V_d)$$

where  $n_e$  is number of electrons per unit volume.

But 
$$V_d = \mu_e E$$

$$J = n \cdot e \cdot \mu_e \cdot E$$

But  $J = \sigma E$ , where  $\sigma$  is conductivity

i.e. 
$$\boxed{\sigma = n \cdot e \cdot \mu_e}$$
 for metals.

Applying the same concept to a semiconductor, we can find the conductivity of a semiconductor. For an intrinsic semiconductor, the current flow is due to electrons as well as equal number of holes. Although the applied electric field  $E$  causes the electrons and holes to flow in opposite directions, the direction of the conventional current flow due to motion of each carrier as in the same direction as the field. The total current in a semiconductor is thus

$$J = J_e + J_h$$

$$J = (ne\mu_e + p \cdot e \cdot \mu_h) E \quad (1)$$

where  $n$  : concentration of electrons

$p$  : concentration of holes

Hence, the electrical conductivity is

$$\sigma = n \cdot e \cdot \mu_e + p \cdot e \cdot \mu_h \quad (2)$$

For intrinsic semiconductor,

$$n = p$$

$$\therefore \boxed{\sigma_i = n \cdot e \cdot (\mu_e + \mu_h)} \quad (3)$$

For extrinsic semiconductor, at room temperature only one carrier predominates. For  $n$ -type semiconductor  $n \gg p$ .

$\therefore$  Current density is  $J_n$  and

$$J_n = n \cdot e \cdot \mu_e \cdot E$$

$$\sigma_n = n \cdot e \cdot \mu_e$$

$$\boxed{\sigma_n = N_d \cdot e \cdot \mu_e} \quad (4)$$

where  $N_d$  is concentration of donor atoms

For  $p$ -type semiconductor,  $p \gg n$ ,

$\therefore$  Current density is

$$\sigma_p = p \cdot e \cdot \mu_h$$

$$\text{or } \sigma_p = N_a \cdot e \cdot \mu_h \quad (5)$$

where  $N_a$  is the concentration of acceptor atoms.

Resistivity: The reciprocal of conductivity is called resistivity:

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

Semiconductors have  $\rho$  of the order of  $10^{-1}$  to  $10^1 \sim \Omega\text{m}$

## 2.8 Intrinsic and Extrinsic Semiconductors

Based on purity, semiconductors are of two types.

1. Intrinsic semiconductors
2. Extrinsic semiconductors

### *Intrinsic Semiconductors*

The intrinsic semiconductors are pure semiconductor materials. The elemental and compound semiconductors can be of intrinsic type.

The energy gap between valence band and conduction band is relatively very small. Hence, at room temperature, some electrons may possess enough thermal energy to cross over the band gap and enter the conduction band. Thus, the excited electrons leave behind a vacancy which may be filled by another electron in the valence band. The vacancy produced in the valence band due to the electron excitation is called a **hole**.

In an intrinsic semiconductor for every conduction electron promoted to the conduction band, there is a hole in the valence band. Holes and electrons created in this way are known as intrinsic charge carriers. Thus, in an intrinsic semiconductor.

$$n_e = n_h$$

i.e., the density of electrons = the density of holes.

In an intrinsic semiconductor, when an electron moves to fill a hole, another hole is created at the original electron source. Consequently, the holes appear to act as positively charged electron and carry an electrical charge.

When a voltage is applied to the material, the electrons in the conduction band accelerate towards the positive terminal and the holes in the valence band move towards the negative terminal. Hence, current conduction takes place due to the movement of both the charge carriers, electrons and holes.

Thus, the expression for conductivity is given by

$$\sigma_i = n_e e \mu_e + n_h e \mu_h$$

$$\text{or } \sigma_i = n_i e (\mu_e + \mu_h)$$

where  $n_e = n_h = n_i$  is called the intrinsic carrier concentration and  $\mu_e, \mu_h$  are the mobilities of electrons and holes respectively.

### Extrinsic semiconductors

Extrinsic semiconductor is an impure semiconductor formed from an intrinsic semiconductor by adding a small quantity of impurity atoms also called dopants.

The process of adding impurities to the semiconductor crystal is known as **doping**. The conductivity of an extrinsic semiconductor depends primarily on the number of dopant atoms. The purpose of doping is to produce an enormous amount of charge carriers in the semiconductors.

Based on the element of doping, the extrinsic semiconductors are of two types,

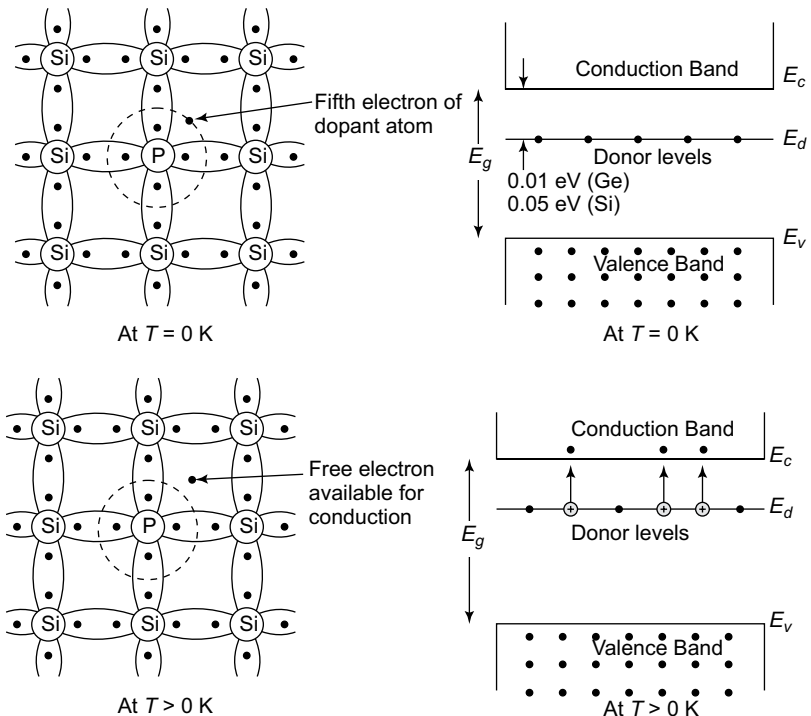
- (i) *n*-type semiconductor
- (ii) *p*-type semiconductor

#### *n*-type Semiconductor

A *n*-type semiconductor gets formed on doping atoms that have five valence electrons to an intrinsic semiconductor like Si or Ge.

Consider the intrinsic semiconductor Si which has 4 valence electrons. Each of the four valence electron is covalently bonded with one of the four adjacent Si atoms.

To this Si atom, if an atom with five valence electrons such as phosphorus (P), arsenic (As) or antimony (Sb) is incorporated into the crystal then, four of the electrons from the dopant atom will participate in the covalent bond formation thereby leaving an extra electron (fifth electron) in the unbonded state as shown in Fig. 2.4.



**Fig. 2.4** Charge carrier excitation in a *n*-type semiconductor.

This extra electron is only weakly bound to the atom and enters into an energy level in donor state just below the conduction band as shown in the figure.



Since this extra electron is not tightly bound to the atom, all such electrons at room temperature can get excited to the conduction band even for a small increase in the external energy leaving the parent atom positively ionised.

$E_d$  is the minimum energy required for the electron to enter the conduction band.

**Note:** • Donor energy level: It is the localised electronic state or level introduced by the donor atoms because of the presence of an extra electron.

- $E_d$ : Donor energy is defined as the energy difference between the bottom of the conduction band and the donor energy level.

Since excitation of these weakly bound electrons does not result in the formation of a hole, the number of electrons in such a material far exceeds the number of thermally generated holes. Hence, in this type of semiconductors electrons are the majority carriers and the holes are the minority carriers.

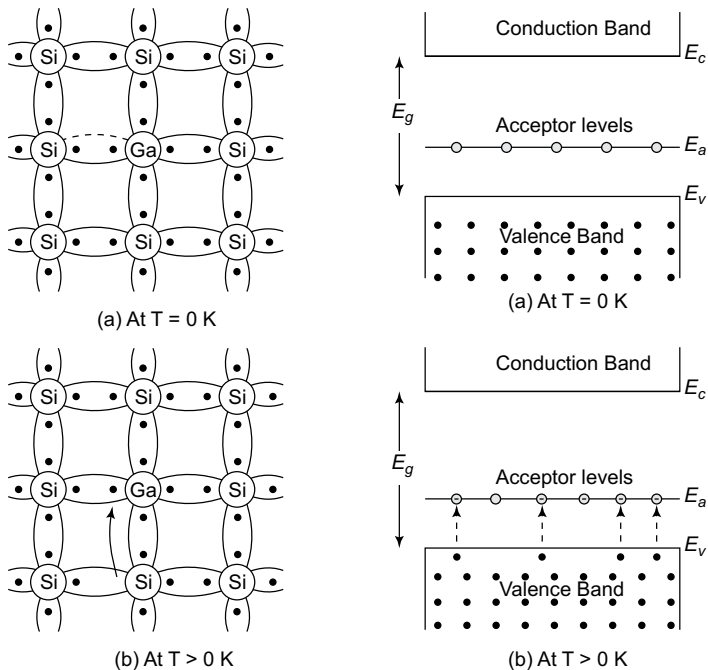
In case, if the thermal energy is sufficiently high, in addition to the ionisation of donor impurity atoms breaking of covalent bond may also occur thereby giving rise to generation of electron hole pairs.

### *p*-type Semiconductor

A *p*-type semiconductor gets formed on doping atoms that have three valence electrons to an intrinsic semiconductor like Si or Ge.

The trivalent elements like gallium (Ga), indium (In) or boron (B) can be added as a dopant to an intrinsic semiconductor.

Let us assume a trivalent element Ga is added to an intrinsic semiconductor Si. All the three valence electrons of Ga will form three covalent bonds with three neighbouring Si atoms as shown in Fig. 2.5.



**Fig. 2.5** Charge carrier excitation in a *p*-type semiconductor.

Thus, the dopant is in need of an extra electron to complete its fourth covalent bond formation with Si.

This extra electron may be supplied by Si, thereby creating an electron hole (i.e., a vacant site) in the valence band that can be filled by electrons from the other locations in the band in turn creating an another vacant site. Thus, the holes act as acceptors of electrons. These hole sites have an energy slightly higher than the normal energy and create an energy level called acceptor energy level which lie just above the valence band.

An electron must gain energy of the order  $E_a$  in order to create a hole in the valence band. Thus, these acceptor atoms get negatively ionised after accepting the electrons from the valence band even at room temperature. Hence, holes are created in the valence band and are ready for conduction.

When a sufficiently large number of acceptor atoms are added, the holes greatly outnumber the thermally excited electrons. Hence, the holes are the majority carriers while electrons are the minority carriers in  $p$ -type semiconductor.

In case, if the temperature is sufficiently high, in addition to the above process, additional electron hole pairs also get generated due to breaking of covalent bonds.

## 2.9 Fermi-Dirac Distribution Function

According to classical statistics any number of particles may have identical energies. Though the classical approach gives an understanding of conductivity in metals but fails to give proper explanation for the contribution by electrons to the specific heat and magnetic susceptibility.

But according to Fermi-Dirac statistics, the electrons are indistinguishable particles which are governed by Pauli's exclusion principle. According to this principle, not more than two electrons may occupy any orbital state, so that at absolute zero of temperature two electrons will go into the ground state, two into each state of next higher energy, and so on, until all the electrons are allocated to states of lowest possible energy. Since the number of electrons is very high, even at absolute zero of temperature, some electrons have kinetic energies of several electron volts. The maximum spacing between consecutive energy level is less than  $10^{-6}$  eV so that the distribution of energy may be regarded as almost continuous or sometimes 'quasi-continuous'.

We can represent the probability of occupying a given state by a continuous distribution function. The occupancy of the energy levels by electrons in conductors is described by the Fermi-Dirac distribution function. The probability  $f(E)$  of an electron occupying a given energy level is given by

$$f(E) = \frac{1}{1 + e^{\frac{E-E_F}{KT}}} \quad (i)$$

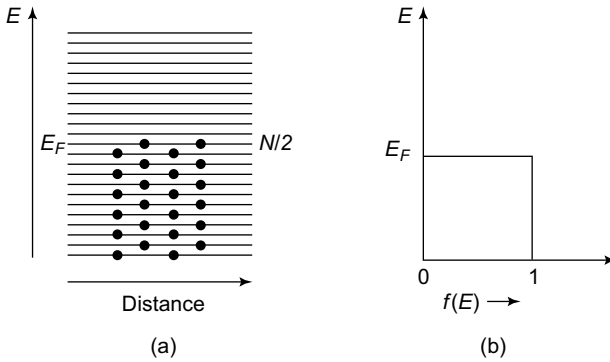
$f(E)$  is called **Fermi-Distribution function**.  $E$  is the energy of the level whose occupancy is being considered,  $E_F$  is the Fermi level or Fermi energy and is a constant for the particular system. At absolute zero  $f(E) = 0$  for  $E > E_F$  and  $f(E) = 1$  for  $E < E_F$ . Thus at absolute zero, the Fermi level divides the occupied

states from the unoccupied states, i.e., it is the highest energy state for the electrons to occupy at absolute zero field.

## 2.10 Fermi Level in Conductors

The occupancy of the energy levels by electrons in conductors is described by the Fermi-Dirac distribution function.

At absolute zero, electrons occupy energy levels in pairs starting from the bottom of the band up to an upper level designated as  $E_F$ . **Fermi level** can be, therefore, defined as the uppermost filled energy level in a conductor at 0K. Correspondingly, **Fermi energy** is defined as maximum energy that a free electron can have in a conductor at 0K. The energy band and the Fermi function at 0K are shown in Fig. 2.6.



**Fig. 2.6** Conduction band in a conductor at 0K (a) Actual distribution of electrons in the band (b) The Fermi-Dirac function.

### Case 1:

Let us now apply Eq. (i) to the solid taking the value of  $T$  as 0K.

- (i) For energy levels  $E$  lying below  $E_F$ ,  $E < E_F$ ,  $(E - E_F)$  is a negative quantity.

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

$f(E) = 1$  indicates that all the energy levels lying below the level  $E_F$  are occupied.

- (ii) For energy levels located above  $E_F$ ,  $E > E_F$ ,  $(E - E_F)$  is a positive quantity.

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

The result  $f(E) = 0$  implies that all the levels above  $E_F$  are vacant at  $T = 0$ K.

- (iii) For  $E = E_F$ , the quantity  $(E - E_F) = 0$ .

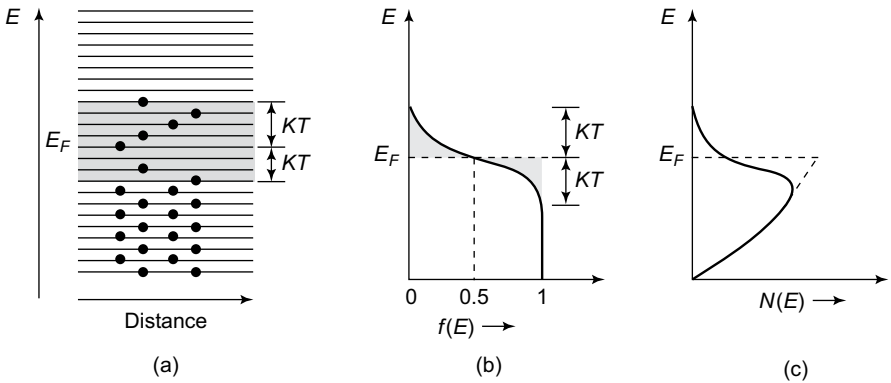
$$\therefore f(E) = \frac{1}{1 + e^{0/0}} = \text{indeterminate}$$

The above result implies that the occupancy of Fermi level at 0K ranges from zero to one.

**Case 2:**

On heating the conductor, electrons are excited to higher energy levels. In general,  $E_F \gg KT$ . Therefore, for most of the electrons lying deep in the conduction band, the thermal energy is not sufficient to cause a transition to an upper vacant level. At normal temperatures, only those electrons occupying the energy levels near the Fermi level can be thermally excited. These levels make up a narrow band of width  $KT$  directly adjacent to the Fermi level. Therefore, upon heating the solid, electrons having energy a little below  $E_F$  jump into levels with energy somewhat above  $E_F$  and a new energy distribution of electrons is obtained.

Thus, as a result of thermal excitation, the probability of finding electrons in the levels immediately below  $E_F$  will decrease. On the same hand, the probability of finding electrons in the levels immediately above  $E_F$  increases. This fact is reflected in the graph (Fig. 2.7b) as a blurring of the step plot.



**Fig. 2.7** The conduction band in a conductor at  $T = 0K$ . (a) Electrons in the levels adjacent to  $E_F$  are excited. (b) Fermi-Dirac function at  $T^\circ K$ . (c) The complete electron distribution function at  $T^\circ K$ .

At  $T > 0K$ , for  $E = E_F$ , the argument of the exponential equation for  $f(E)$  equals to zero.

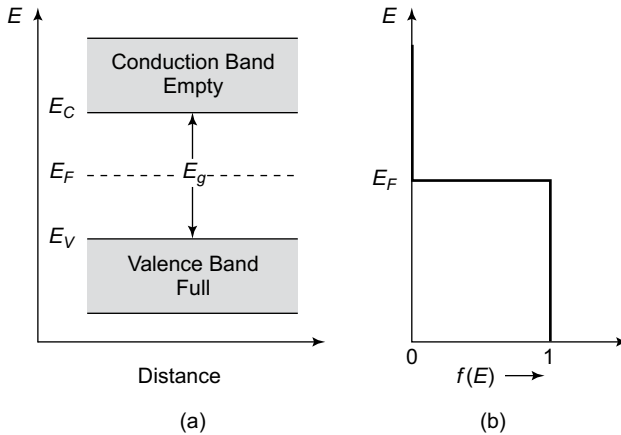
$$f(E) = \frac{1}{1 + e^0} = \frac{1}{1 + 1} = \frac{1}{2}$$

It implies that the probability of occupancy of Fermi level at any temperature other than  $0K$  is  $0.5$ . This fact gives an operational definition of Fermi level. **Fermi level defined as the energy level at which the probability of electron occupancy is one half.** Similarly, an operational definition can be given for Fermi energy. **Fermi energy,  $E_F$  is the average energy possessed by the electrons which participate in conduction process in conductors at temperatures above  $0K$ .**

## 2.11 Fermi Level in Insulator

Insulators are characterized by two energy bands—conduction band and valence band—separated by a large energy gap. As all valence electrons are engaged in covalent bonds, the valence band is full. The absence of any mobile charge carriers keeps the conduction band empty. Since the energy gap is large, electrons cannot jump into the conduction band under normal excitation. Consequently, insulators do not permit flow of current.

The concept of Fermi level can be extended to insulators also. As the energy levels in valence band are filled,  $f(E)$  is equal to unity throughout the valence band. As there are no electrons in the conduction band,  $f(E)$  is zero throughout the conduction band. Since the Fermi function is symmetrical about  $E_F$ , the Fermi level may be expected to be located in the middle of the energy gap. Even though there are no energy levels and no electrons in the band gap, the meaning of Fermi level remains the same. It is an **energy position**. Figure 2.8 shows the energy band diagram for an insulator along with the probability function.



**Fig. 2.8** The energy band structure of an insulator along with the Fermi-Dirac distribution function.

## 2.12 Fermi Level in an Intrinsic Semiconductor

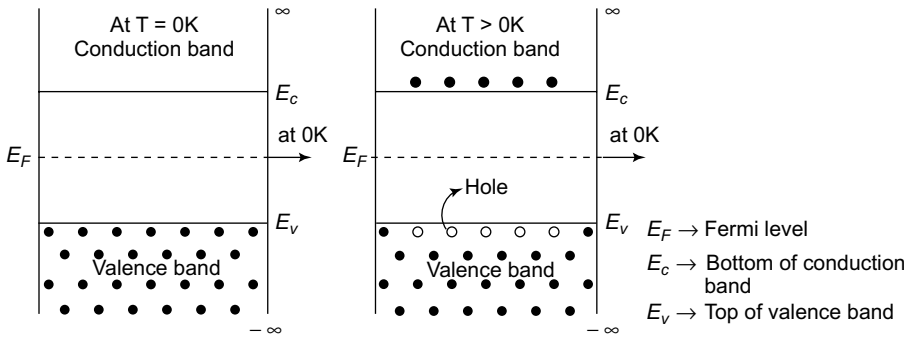
In an intrinsic semiconductor, every electron moving to conduction band leaves behind hole in valence band. The number of charge carriers per unit volume of the material is called carrier concentration.

The density of electrons in conduction band is shown by  $n$  & it is given by

$$n = 2 \left[ \frac{2\pi m_e^* KT}{h^2} \right]^{3/2} e^{-\frac{(E_F - E_C)}{KT}} \quad (i)$$

The density of holes in valence band is shown by  $p$  & is given by

$$p = 2 \left[ \frac{2\pi m_h^* KT}{h^2} \right]^{3/2} e^{-\frac{(E_V - E_F)}{KT}} \quad (ii)$$



**Fig. 2.9** Fermi level in an intrinsic semiconductor at  $T = 0\text{K}$  and  $T > 0\text{K}$ .

As the temperature of the semiconductor is increased, electrons from the valence band get thermally excited to the conduction band. These electrons in the conduction band behave like a free particle with an effective mass  $m_e^*$ .

With increase in temperature, the Fermi level may get displaced toward the bottom edge of conduction band or top edge of valence band. But in most of the materials this shift is insignificant. So in practice the Fermi level in an intrinsic semiconductor is assumed to be independent of temperature and may be regarded as staying the middle of the band gap.

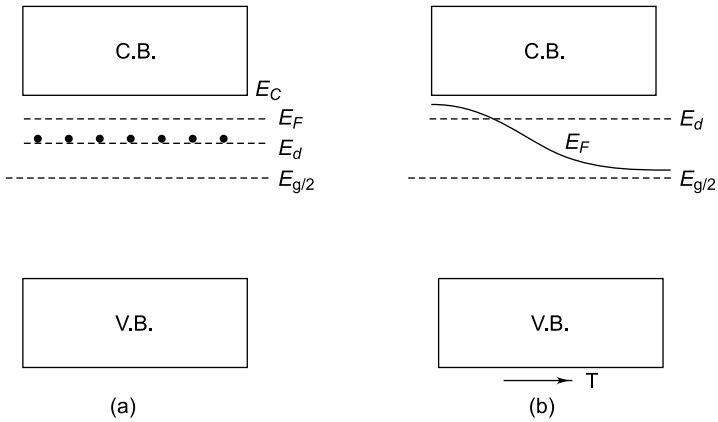
### 2.13 Fermi Level in Extrinsic Semiconductors (Effect of Impurity Concentration & Temperature on Fermi Level)

If a small amount of a pentavalent or trivalent impurity is introduced into a pure germanium (or silicon) crystal, the conductivity of the crystal increases appreciably, and the crystal becomes an extrinsic semiconductor, i.e., either *n*-type semiconductor or *p*-type semiconductor.

#### *n*-type semiconductor

In energy level diagram (Fig. 2.10), the impurity atoms introduce discrete energy levels for such electron just below the conduction band. These are called donor impurity levels. They are only 0.01 eV below the conduction band in case of Ge (0.05 eV in case of Si). Therefore, at room temperature, the fifth electrons of almost all donor atoms are thermally excited from the donor levels into the conduction band where they move as charge carriers when an external field is applied.

Since donor level is very close to conduction band, the effect of valence band may be neglected. Hence, we say that the concentration of electrons in the conduction band must be equal to the number of vacancies per unit volume in the donor level.



**Fig. 2.10** Fermi level in *n*-type semiconductor (a) at 0°K (b) as function of temperature.

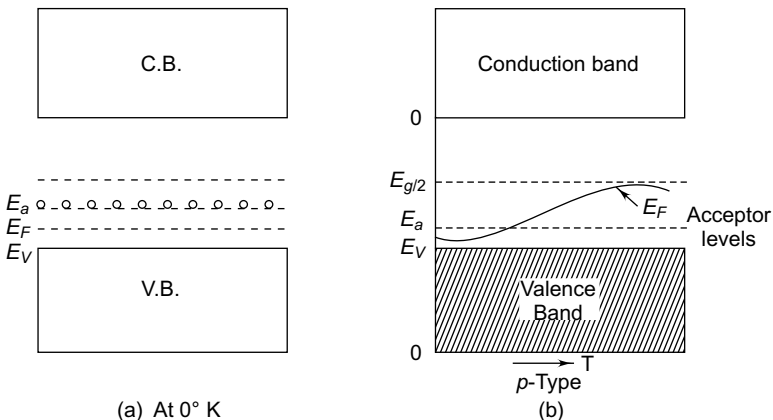
This shows that the Fermi level lies exactly half way between the donor levels and the bottom of conduction band, i.e.,  $E_F = \frac{E_d + E_C}{2}$  as shown in Fig. 2.10(a).

But as temperature increases Fermi level falls below the donor level as shown in Fig. 2.10(b) and at higher temperatures the fermi level approaches the forbidden gap which makes an intrinsic semiconductor.

***p*-type semiconductor**

Since in *p*-type semiconductor the acceptor level is very near to valence band the effect of conduction band is neglected. The Fermi energy lies exactly highway between the acceptor levels and the top of valence band, i.e.,  $E_F = \frac{E_a + E_V}{2}$  as

shown in Fig. 2.11(a). But as temperature increases, the Fermi level rises as shown in Fig. 2.11(b). At higher temperatures, the Fermi level approaches the centre of the band gap and crosses acceptor level which makes the substance an intrinsic semiconductor.

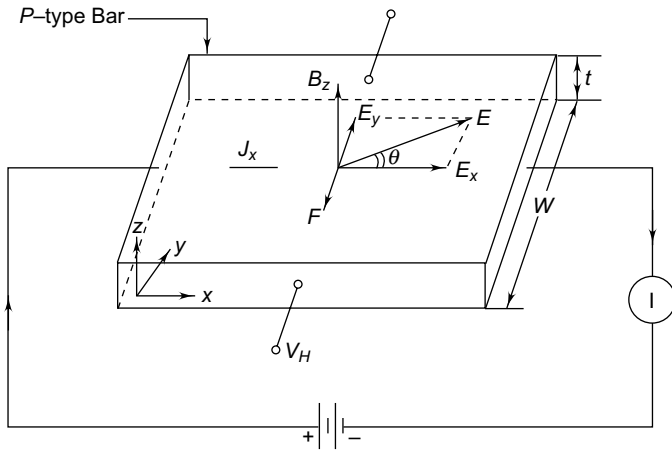


**Fig. 2.11** Fermi level in *p*-type semiconductor (a) at 0°K (b) as function of temperature.

## 2.14 Hall Effect

When a magnetic field is applied perpendicular to a conductor carrying current, a voltage is developed across the specimen in the direction perpendicular to both the current and magnetic field. This phenomenon is known as Hall effect.

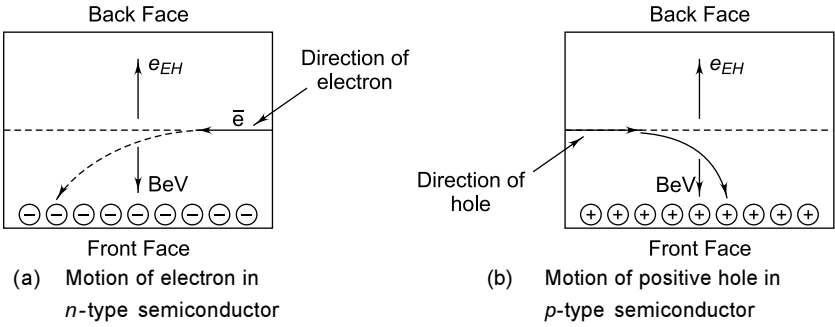
Let us consider that an electric field is applied along the axis of a specimen ( $E_x$  is applied along the axis of a specimen ( $x$ -axis), then electrons drift in opposite direction. Let the magnetic field ( $H_z$ ) be applied along  $z$ -axis, perpendicular to the axis of the specimen then the electrons will tend to be deflected to one side ( $y$ -axis) (Fig. 2.12). These electrons will not drift into the space but a surface charge is developed. The surface charge then gives rise to a transverse electric field which causes a compensating drift such that the carriers remain in the specimen. The effect is known as Hall effect.



**Fig. 2.12** Schematic of Hall effect setup.

Suppose in a specimen  $n$ -type semiconductor by electrons of charge  $-e$ . Under the influence of magnetic field the electrons will be subjected to a Lorentz force such that front surface collects a negative charge. Ultimately, a stationary state is obtained in which current along  $y$  direction vanishes and a field is set up. If the charge carriers were ( $p$ -type semiconductors) positive the front surface would become positive and back surface negative and a field  $F_y$  is set up. When specimen is  $n$ -type semiconductor the direction of electric field will be front from to rear (back) face. It is such that it opposes further piling up of holes on the front face  $F$ . A condition of equilibrium when force  $F_y$  due to transverse electric field  $E_y$  balances Lorentz force. The transverse electric field  $E_y$  is known as Hall Field and it is denoted by  $E_H$ .





**Fig. 2.13** Direction of Lorentz force.

Electric force on an electron having due to electric field  $E_H$  is

$$F_E = -eE_H \quad (1)$$

Force due to magnetic field  $H$ ,

$$F_M = Bev_d \quad (2)$$

where  $v_d = \text{drift velocity} = \frac{J_x}{ne}$

where  $J_x$  is current density along  $x$  direction

$$F_M = Be \frac{J_x}{ne} = \frac{BJ_x}{n} \quad (3)$$

From Eq. (1)  $F_E = -eE_H$

$$F_E = \frac{-eV_H}{w} \quad (4)$$

where  $V_H$  is Hall voltage developed between front and back surface and  $w$  is distance between front and back surface

Equating Eqns. (3) and (4)

$$\begin{aligned} -\frac{eV_H}{w} &= \frac{BJ_x}{n} \\ V_H &= -\frac{wBJ_x}{ne} \\ &= -\frac{wBI}{neA} \quad \therefore J_x = \frac{I}{A} \text{ current per unit area} \end{aligned} \quad (5)$$

If  $t$  is the thickness of the specimen the  $A = wt$

$$\therefore V_H = -\frac{wBI}{newt} = -\frac{BI}{net} \quad (6)$$

**Hall coefficient** Hall field per unit current density per unit magnetic induction is called Hall coefficient ( $R_H$ )

$$R_H = \frac{E_H}{J_x B} = \frac{V_H/w}{J_x B} = -\frac{BJ_x}{ne} \times \frac{1}{J_x B}$$

$$R_H = \frac{-1}{ne} \quad (7)$$

Hall coefficient is inversely proportional to  $n$ , the number of electrons per unit volume.

For  $p$ -type semiconductor this expression becomes

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

where  $p$  denotes number of holes unit volume.

Putting (7) in (6) gives

$$V_H = -R_H \cdot \frac{B \cdot I}{t} \quad (8)$$

**Knowing the thickness of the semiconductor ( $t$ ) by measuring Hall voltage  $V_H$  with voltmeter.** For given current and with known magnetic field, the Hall coefficient  $R_H$  can be determined. Depending upon the polarity of the Hall voltage is the Hall coefficient will be either positive or negative. Hall coefficient decreases with a rise in temperature because the concentration of free electrons increases with the temp.

**Concentration of charge carriers.**

$$n = \frac{-1}{R_H \cdot e} = \frac{-BI}{V_H \cdot t \cdot e} \quad (9)$$

For  $p$ -type semiconductor

$$p = \frac{1}{R_H e} = \frac{BI}{V_H \cdot t \cdot e} \quad (10)$$

**Hall angle** The net electric field  $E$  in the semiconductor is a vector sum of  $E_x$  and  $E_H$ . It acts at an angle  $\theta_H$  to the  $x$  axis.  $\theta_H$  is called the Hall angle.

$$\tan \theta_H = \frac{E_H}{E_x} \quad (11)$$

$$E_H = \frac{V_H}{w} = \frac{-BJ_x}{ne} \quad (12)$$

$$E_x = \rho J_x \quad (13)$$

$$\tan \theta_H = \frac{-BJ_x}{ne}$$

$$= \frac{-B}{ne\rho}$$

$$= B \cdot R_H \cdot \sigma$$

$$\tan \theta_H = \mu_H B$$

$$\therefore R_H = \frac{-1}{ne} \quad \sigma = 1/\rho$$

$$(14)$$

$\mu_h = R_H \sigma =$  mobility of hole

$$\theta_H = \tan^{-1} (\mu_h B) \quad (15)$$

### Importance of Hall effect

1. It differentiates between positive charges moving in one direction and negative charges moving in the opposite.
2. Hall effect offered the first real proof that electric current in metals is carried by moving electrons and not by protons.
3. The Hall effect also showed that in some substances (especially semiconductors), it is more appropriate to think of the current as positive holes moving rather than negative electrons.
4. The Hall effect can be used to measure magnetic field with Hall probe.

### Applications of Hall effect

1. *Determination of semiconductors type:* The sign of Hall coefficient can be used to determine whether a given semiconductor is  $n$ - or  $p$ -type.
2. *Calculation of carrier concentration*

$$n = \frac{-1}{eR_H} = \frac{-BI}{V_H \cdot t \cdot e} \quad \text{or} \quad p = \frac{1}{eR_H} = \frac{BI}{V_H \cdot t \cdot e}$$

measuring Hall voltage, current, magnetic field and thickness of conductor carrier concentration can be found out in  $n$ -type or  $p$ -type semiconductors.

3. *Determination of mobility*

$$\mu_e = \frac{\sigma}{ne} = \sigma R_H = \sigma \left( \frac{V_H t}{B \cdot I} \right)$$

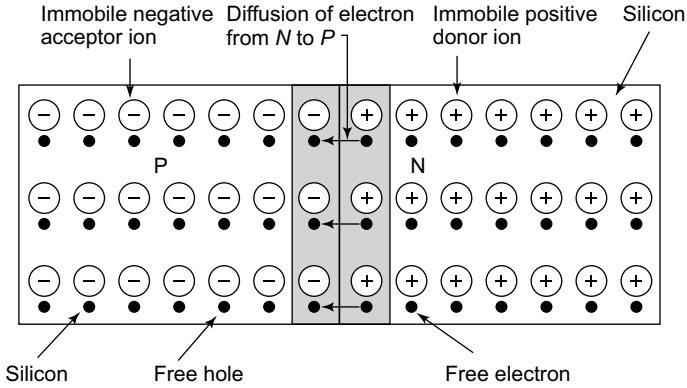
Mobility of electrons or hole can be found out by knowing  $\sigma$  and Hall coefficient.

4. *Measurement of magnetic flux density.* Since Hall voltage  $V_H$  is proportional to the magnetic flux density  $B$  for a given current  $I_x$  through the sample, the Hall effect can be used as the basis for the design of a magnetic flux density meter.
5. *Measurement of power in an electromagnetic wave*—If an electromagnetic wave moves in free space, the magnetic field  $H$  and the electric field  $E$  are at right angles. Thus, if a semiconductor sample is placed parallel to  $E$  it will drive a current  $I$  in the semiconductors. The semiconductor is subjected simultaneously to a transverse magnetic field  $H$  producing a Hall voltage across the sample which is proportional to the product  $E$  and  $H$ , i.e., to the magnitude of pointing vector of the electromagnetic wave. Thus, the Hall effect can be used to determine the power flow in an electromagnetic wave.

### Experimental Determination of Hall Coefficient ( $R_H$ )

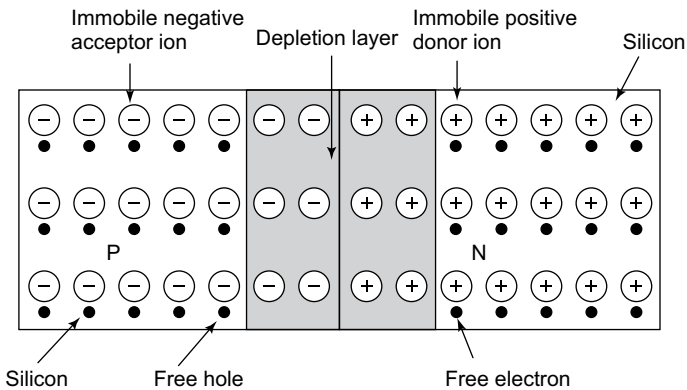
In experimental determination of Hall coefficient of a thin strip of specimen of thickness  $t$  and width  $w$  is taken and placed in a magnetic field ( $B$ ) in the  $z$  direction. Current  $I$  amp is allowed to pass through this sample by connecting it to a battery

and cross the junction to the  $N$ -side under the concentration gradient  $dp/dx$ , where  $dp$  = number of holes along the distance  $dx$ . Similarly, electrons from the  $N$ -region cross the junction to the  $P$ -region under the influence of  $dn/dx$ , where  $dn$  = number of electrons along the distance  $dx$ . This situation is depicted in Fig. 2.16.



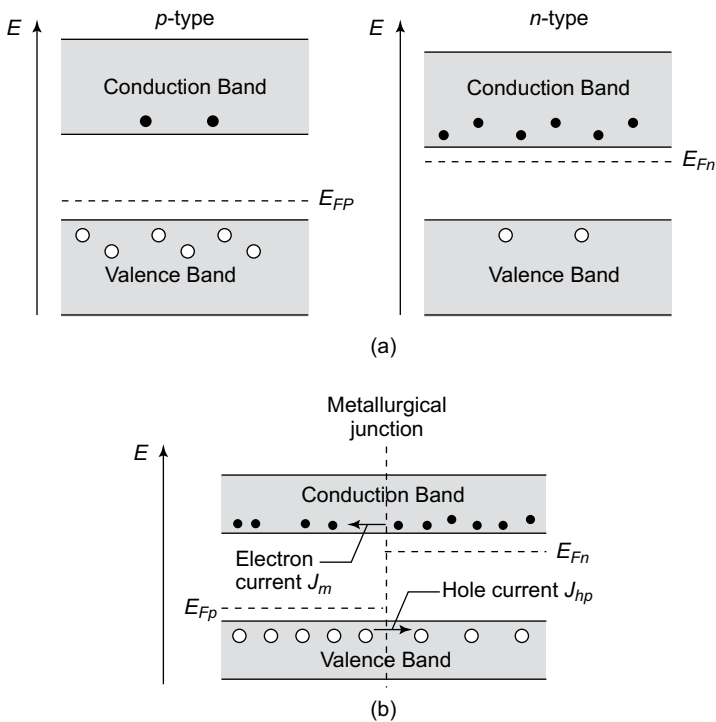
**Fig. 2.16** Electron-hole diffusion across the junction.

Due to this process, electrons and holes, which cross the junction, get recombined with each other near the junction. When an electron leaves the  $N$ -region close to the junction, one immobile positive donor ion is left uncovered in that region. Similarly, when a hole leaves the  $P$ -region, an immobile negative acceptor ion is left uncovered there. Therefore, each electron-hole recombination leaves one positive ion in the  $N$ -region and one negative ion in the  $P$ -region close to the junction uncovered. This situation is depicted in Fig. 2.17, which also shows the concentration of immobile negative and positive ions on either side of the junction. Finally, the process of diffusion of electrons and holes stops when sufficient numbers of immobile ions are uncovered near the junction.



**Fig. 2.17**  $P$ - $N$  junction after equilibrium state is reached.

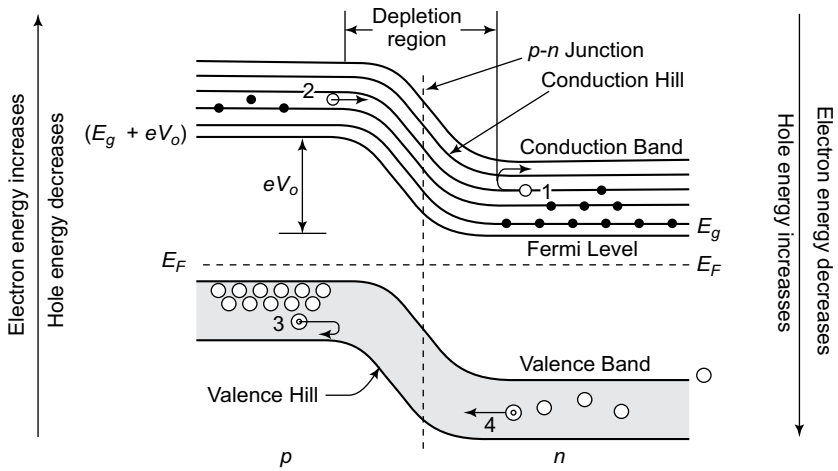
on  $p$ -side. Similarly, the probability of occupancy of valence band levels by holes on  $p$ -side is high whereas it is low on  $n$ -side. As a result, holes tend to migrate into the valence band levels on  $n$ -side. Current flows due to such migration of carriers. As high energy electrons leave  $n$ -region, the Fermi level  $E_{Fn}$ , which represents the average energy of electrons, moves downward since the Fermi level is fixed relative to the band structure of the region, its movement causes downward shift of the entire band structure of the  $n$ -region. On the  $p$ -side holes having higher energy leave the region. As the direction of decrease in hole energy is upward, the Fermi level  $E_{Fp}$  shifts upward. Along with  $E_{Fp}$  the entire band structure of  $p$ -region shifts upward. The shifting of energy bands continues till the energy levels  $E_{Fp}$  and  $E_{Fn}$  are equalised. When they come to the same level the carrier migration ceases and equilibrium condition is attained.



**Fig. 2.18**  $p$ - $n$  junction at the instant of formation—(a) Energy band diagrams of  $p$ -type and  $n$ -type semiconductors (b) Energy band diagram at the instant of joining which illustrates the position of Fermi levels on each side and consequent carrier migration across the junction.

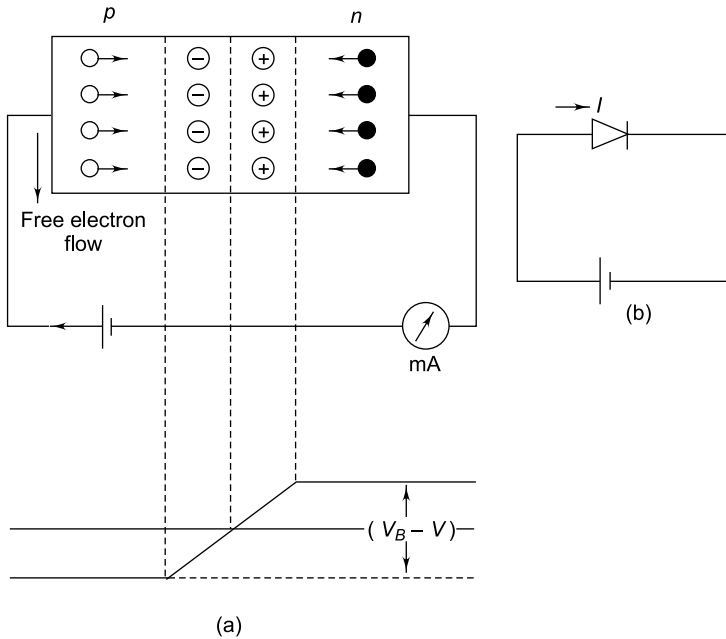
The mutual displacement of the energy levels on both the sides causes a bending of the energy bands in the region around the metallurgical junction as illustrated in Fig. 2.19. Each side takes up a different electrostatic potential. It results in a potential barrier  $V_o$  or an energy hill of height  $eV_o$ . Electrons in the conduction band of  $n$ -region face a raising energy hill which may be called a *conduction hill*. As the direction of increasing energy is downward for holes, the holes in the valence band of  $p$ -region encounter an energy hill which may be called a *valence hill*.

Many of the electrons from the  $n$ -region move toward the junction region but cannot mount the conduction hill and return back to the  $n$ -region. For example, the electron marked 1 in Fig. 2.19 fails to climb conduction hill. Occasionally, a few of the electrons which have extra energy succeed in overcoming the conduction hill and go into  $p$ -region. On the other hand, the electrons in  $p$ -region can roll down the conduction hill effortlessly and pass into  $n$ -region. For example, the electron marked 2 in Fig. 2.19 rolls down the conduction hill. The two current components due to such migration of electrons are in opposite direction and balance each other. Similarly, the moving from  $p$ -region toward the junction encounter the valence hill and return back.



**Fig. 2.19** Energy band diagram of  $p$ - $n$  junction at equilibrium.

For example, the hole marked 3 in figure fails to surmount the valence hill. However, a few energetic holes succeed in going into  $n$ -region. The holes in the  $n$ -region readily float up the valence hill regardless of the energy of the  $p$ -region. For example, the hole marked 4 in Fig. 2.19 floats up the valence hill. The two current components due to opposite flow of holes balance each other. The net current across the junction is therefore zero, which is characteristic of the junction at equilibrium.



**Fig. 2.21** (a) Forward biasing (b) Symbolic representation of  $p$ - $n$  junction.

When barrier potential is reduced the drift and diffusion currents will not be balanced and net current flows across the junction. The reverse saturation current ( $I_R$ ) due to minority charge carriers flows along with the forward current  $I_F$ . The net forward current,  $I = I_F - I_R$ , flows from region  $p$  to region  $n$

$$I = I_R e^{eV/KT}$$

Due to forward bias width of depletion layer decreases.

### Reverse Bias

Here the positive terminal is connected to  $n$  region and negative terminal is connected to  $p$  region. The effective junction voltage is greater than the equilibrium voltage  $V_0$  by an amount equal to the applied voltage  $V$ . Thus, the applied voltage increase the height of potential barrier to  $(V + V_0)$ . Hence, the majority carriers in the two regions find it more difficult to cross the junction (Fig. 2.22).

Because of the increase in the height of potential barrier, the electric field due to it increases. As it assists the minority carriers to cross the junction, the current flow through the junction is only due to minority carriers and conventional current flows from  $n$  to  $p$  region. Its magnitude depends on the maximum number of minority carrier present (which in turn depends upon the temperature and forbidden energy gap of semiconductor). The maximum value of the reverse current is the reverse saturation current  $I_R$ .

$$I = I_R \left[ 1 - e^{-\frac{eV}{KT}} \right]$$

for large  $V$ ,  $I = -I_R$

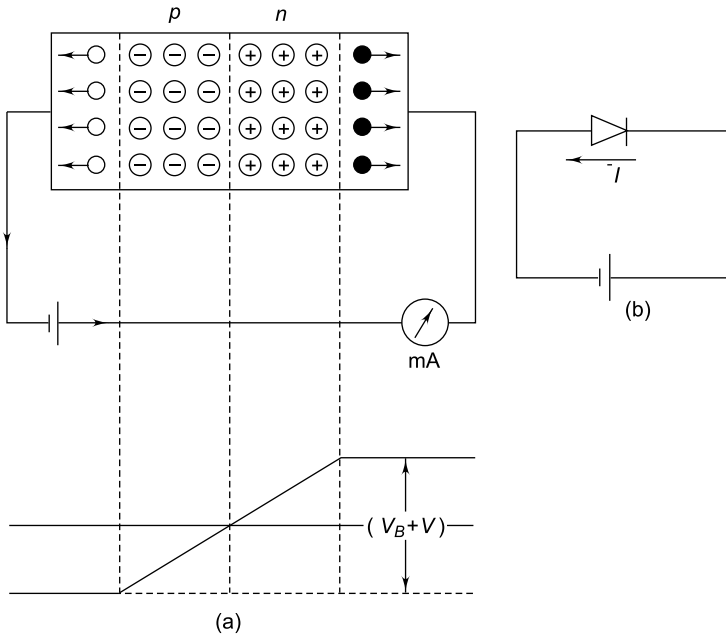


Fig. 2.22 (a) Reverse biasing (b) Symbolic representation of  $p$ - $n$  junction.

## 2.18 Drift and Diffusion Currents in Semiconductors

In semiconductors, there exists a hole current and an electron current. In each of these categories, there exist two other distinct forms of currents, viz., the drift current and diffusion currents. Thus we have the hole drift current and the hole diffusion current. Similarly, we also have the electron drift and diffusion currents.

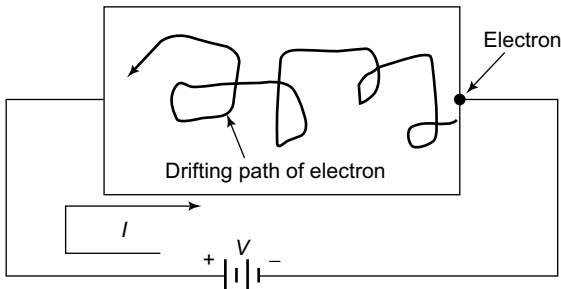


Fig. 2.23 Drift current in a semiconductor.

**Drift Current** The nature of the drift current is shown in Fig 2.23. It is the current obtained by the random motion of an electron (or hole) under the influence of an applied electric voltage  $V$ . The electron (or hole) moves from the negative (positive) terminal through the semiconductor bar in a zigzag fashion to the positive



**Diffusion Current** In semiconductors, the concentration of charge carriers, i.e., electrons and holes may not be the same throughout the material. The presence of concentration gradient results in the flow of charge carriers and hence an electric current. **The charge carriers flow from a region of higher concentration to a region of lower concentration. This phenomenon is called diffusion.**

Suppose that the density of carriers (electrons or holes) increases along positive  $X$  direction. Then the flow of particles due to diffusion will be along the negative  $X$  direction. According to diffusion theory, the net flow of carriers through a unit area perpendicular to  $x$  axis (i.e., flux  $\phi$ ) is proportional to  $-dn/dx$ , where  $n$  is density of carriers.

$$\phi \propto -\frac{dn}{dx}$$

$$\phi = -D \cdot \frac{dn}{dx}$$

where  $D$  is diffusion const. Unit of  $D$  is  $\text{cm}^2/\text{sec}$ .

The diffusion current  $\phi$  is proportional to the rate of change of carrier concentration per unit length, i.e., concentration gradient ( $dn/dx$ ).

Considering the diffusion process for the electrons, we have current density,  $J(n)$  diffusion given by,

$$J(n)_{\text{diffusion}} \propto e \frac{dn}{dx} \quad (\text{x})$$

where  $dn/dx$  is the concentration gradient and  $e$  is the electron charge. Using the constant of proportionality  $D_n$  called the diffusion constant for electrons, we have

$$J(n)_{\text{diffusion}} = D_n e \frac{dn}{dx} \quad \text{A/m}^2 \quad (\text{xi})$$

For holes we can write a similar expression. Therefore, hole diffusion current is

$$J(p)_{\text{diffusion}} = -D_p e \frac{dp}{dx} \quad \text{A/m}^2 \quad (\text{xii})$$

where  $D_p$  = diffusion constant for holes and  $dp/dx$  = hole concentration gradient. The negative sign indicates that the movement of holes is against the direction of the concentration gradient.

## 2.19 Total Carrier Current Densities in $p$ - $n$ Junction in Equilibrium

The total current in a semiconductor is a total of 'four components' of the majority carrier current in a semiconductor, viz., the drift and diffusion electrons currents and the drift and diffusion hole currents. Therefore, the total current density is expressed as

$$J = J(p) + J(n) \quad (\text{xiii})$$

$$J = J(p)_{\text{drift}} + J(n)_{\text{drift}} + J(p)_{\text{diffusion}} + J(n)_{\text{diffusion}} \quad (\text{xiv})$$

where the total hole current

$$J(p) = pe\mu_{phair}E - D_p e \frac{dp}{dx} \quad (\text{xv})$$

and the total electron current

$$J(n) = ne\mu_{nhair}E + D_n e \frac{dn}{dx} \quad (\text{xvi})$$

Therefore, the total current is given by the expression

$$J = pe\mu_p E - D_p e \frac{dp}{dx} + ne\mu_n E + D_n e \frac{dn}{dx} \quad (\text{xvii})$$

## 2.20 Light Emitting Diode

A Light Emitting Diode (LED) is a junction diode which emits light when it is forward biased. The principle behind LED is electroluminescence. The process of injecting electrons and holes into the  $n$ -type and  $p$ -type materials is known as injection electroluminescence.

### Principle

Electrons are charge carriers in a semiconductor and it absorbs energy when an electric energy is applied. The total energy of the charge carrier electrons increases and hence, they are excited to the higher energy state ( $E_2$ ). The excited electrons in the higher energy states stay there only for a few seconds, and after the mean lifetime eventually return back to the ground state energy level ( $E_1$ ). During this process, a spontaneous emission of the radiation of light takes place. The energy of the emitted photon ( $h\nu$ ) is equal to the energy of band gap ( $E_g$ ) of materials, i.e.,

$$E_g = h\nu = \frac{hc}{\lambda} \quad (\text{i})$$

where  $h$  is the Planck's constant and  $\nu$ , the frequency of the emitted radiation.

where  $c$  is the velocity of light and  $\lambda$ , the wavelength of light.

Equation (i) can be written as,

$$\lambda = \frac{hc}{E_g} \quad (\text{ii})$$

Equation (ii) gives wavelength of emitted photon.

Substituting the values of  $h = 6.62 \times 10^{-34}$  J s and  $c = 2.998 \times 10^8$  m s<sup>-1</sup> in Eq. (ii), we get,

$$\text{The wavelength of emitted photon } \lambda = \frac{6.62 \times 10^{-34} \times 2.998 \times 10^8}{E_g}$$

$$\lambda = \frac{12400}{E_g \text{ (eV)}} \text{ \AA} \quad (\text{iii})$$

Equation (iii) indicates that the wavelength of emitted photons depends on the energy gap in the semiconductor. Thus, the energy gap of a semiconductor plays a major role in selecting a suitable material for LED applications. The type of material is also an important factor to be considered for the materials selection.

## Operation

LED is a forward biased  $p$ - $n$  junction (Fig. 2.24). When it is forward biased suitably, it emits visible light. During the forward biasing, the charge carriers, namely, electrons and holes, are injected respectively into the anode and cathode regions. The recombination of the charge carriers, namely, the electrons from the  $n$ -side and the holes from the  $p$ -side, takes place at the junction. During the recombination the difference in the energy is given up in the form of heat and light radiation, i.e., photons. The energy of light radiation depends on the strength of recombination. Thus, the diode current controls electroluminescent efficiency of the LED. The emitted light is very small in intensity and is of the order of microampere range. The emitted light colour depends on the types of materials used. For example, materials like GaAs, GaP and GaAsP are used to produce infrared, red or green and red or yellow colours.

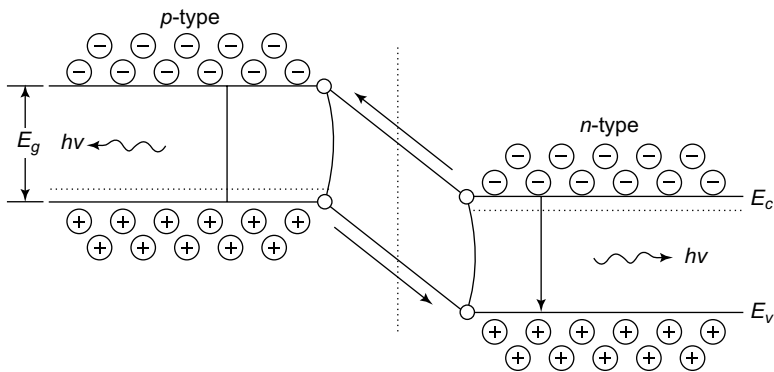


Fig. 2.24  $p$ - $n$  Junction spontaneous emission.

## LED Materials

The material selection for the fabrication of LED is essential due to the emission of different colours (wavelength). The emission of light with different colours depends on the semiconductor materials. The essential factors such as energy gap, both  $n$ - and  $p$ -type with efficient pathways are to be considered for the fabrication of LEDs. The wavelength of the light emitted depends on the energy gap of the semiconducting materials. For example, infrared and far infrared lights are emitted by lower band gap materials, while visible light is emitted by larger band gap ( $\approx 2$  eV) materials. Due to the high melting point, high resistivity and low structural stability, the high band gap materials have advantages in LED applications than low

available for conduction. This is an example of an extrinsic semiconductor. Photoconductor are basically photocells.

Photoconductors come in many different types. Inexpensive **cadmium sulphide** cells can be found in many consumer items such as camera light meters, street lights, clock radios, alarm devices, outdoor clocks, solar street lamps and solar road studs, etc. They are also used in some dynamic compressors together with a small incandescent lamp or light emitting diode to control gain reduction and are also used in bed lamps, etc.

**Lead sulphide (PbS) and Indium Antimonide (InSb) LDRs** (light dependent resistors) are used for the mid infrared spectral region. **Ge:Cu photoconductors** are among the best far-infrared detectors available, and are used for infrared astronomy and infrared spectroscopy. **Selenium**, employed in early television and xerography. Conductive polymer **Polyvinylcarbazole**, is used extensively in photocopying (xerography).

## 2.22 Photovoltaic Cell or Solar Cells

Photovoltaics is the direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When these free electrons are captured, an electric current results which can be used as electricity.

A **solar cell** is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of **photoelectric cell** (in that its electrical characteristics—current, voltage, or resistance—vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source.

**Photovoltaics** is the field of technology and research related to the practical application of photovoltaic cells producing electricity from light, though it is often used specifically to refer to the generation of electricity from sunlight. Cells can be described as **photovoltaic** even when the light source is not necessarily sunlight (lamplight, artificial light, etc.). In such cases the cell is sometimes used as a photodetector (for example, infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity.

The operation of a photovoltaic cell requires 3 basic attributes:

- The absorption of light, generating either electron-hole pairs or excitons
- The separation of different types of charge carriers
- Separate extraction of those carriers to an external circuit

The diagram below illustrates the operation of a basic **solar cell**. Solar cells are made of the same kinds of semiconductor materials, such as silicon, used in the microelectronics industry. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be

Today's most common PV devices use a single junction, or interface, to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to or greater than the band gap of the cell material can free an electron for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used.

One way to get around this limitation is to use two (or more) different cells, with more than one band gap and more than one junction, to generate a voltage. These are referred to as "multijunction" cells (also called "cascade" or "tandem" cells). Multijunction devices can achieve a higher total conversion efficiency because they can convert more of the energy spectrum of light to electricity.

As shown below, a multijunction device is a stack of individual single-junction cells in descending order of band gap ( $E_g$ ). The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells.

Much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells. Such cells have reached efficiencies of around 35% under concentrated sunlight. Other materials studied for multijunction devices have been amorphous silicon and copper indium diselenide.

As an example, the multijunction device below uses a top cell of gallium indium phosphide, "a tunnel junction," to aid the flow of electrons between the cells, and a bottom cell of gallium arsenide.

The first practical photovoltaic cell was developed in 1954 at Bell Laboratories by Daryl Chapin, Calvin Souther Fuller and Gerald Pearson. They used a diffused silicon  $p$ - $n$  junction that reached 6% efficiency, compared to the selenium cells that found it difficult to reach 0.5%. At first, cells were developed for toys and other minor uses, as the cost of the electricity they produced was very high; in

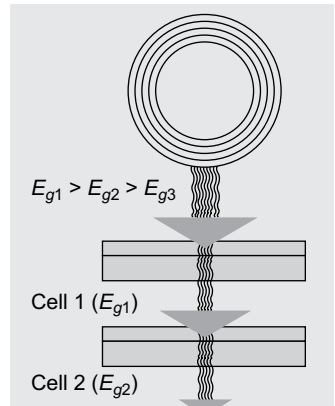


Fig. 2.28

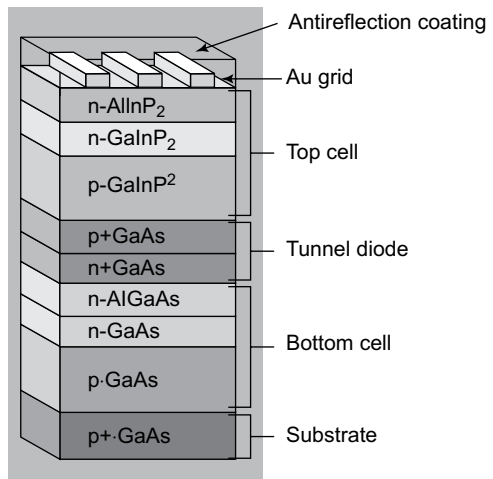


Fig. 2.29 A multijunction device.

- As electrons and holes are simultaneously generated, in an intrinsic semiconductor their concentrations will be equal. Thus,

$$n = p = n_i$$

- Thermal process is the only process that generates carriers in an intrinsic semiconductor.
- Electrons move in conduction band and holes move in the valence band. Both of them contribute to electrical conduction in the material. The electrical conductivity of an intrinsic semiconductor is given by

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

- Semiconductors doped with pentavalent (donor) impurities become  $n$ -type semiconductors. Semiconductors doped with trivalent (acceptor) impurities are known as  $p$ -type semiconductors.
- The motion of electrons and holes in a solid does not occur freely. The particle mass is to be replaced by an effective mass for their proper description.
- The electron concentration in a semiconductor is given by

$$n = 2 \left[ \frac{2\pi m_e^* kT}{h^2} \right]^{3/2} e^{-(E_C - E_F)/kT}$$

- The hole concentration is given by

$$p = 2 \left[ \frac{2\pi m_h^* kT}{h^2} \right]^{3/2} e^{-(E_F - E_V)/kT}$$

- In  $n$ -type semiconductors, donor levels form near the edge of conduction band. Donor impurities donate electrons to the conduction band. The Fermi level in  $n$ -type semiconductor at 0 K lies between donor level and conduction band bottom edge.
- In  $p$ -type semiconductors, acceptor levels form near the edge of valence band. Acceptor impurities accept electrons from the valence band. It causes generation of holes in the valence band. The Fermi level in  $p$ -type semiconductors at 0K lies between the acceptor level and top edge of the valence band.
- In extrinsic semiconductors, charge carriers are produced through two processes. They are: (i) due to impurities and (ii) due to thermal (intrinsic) process.
- Electrons are majority carriers and holes are minority carriers in an  $n$ -type material. Holes are majority carriers and electrons are minority carriers in a  $p$ -type semiconductor.
- In metals conduction takes place only due to drift of electrons in an externally applied electric field. In semiconductors conduction takes place due to drift and also without the help of electric field. Whenever a carrier concentration gradient occurs in semiconductors, conduction takes place through the process of diffusion of carriers.

- Excess free carriers generated (or introduced) in a region tend to diffuse into regions of lower concentration.
- When a semiconductor carries a current and a magnetic field applied normal to the current direction generates a voltage in a direction perpendicular to both the magnetic field and current directions. This is called Hall effect.

- The Hall coefficient  $R_H = -\frac{1}{ne}$

- The Hall angle is given by

$$\theta = \tan^{-1} (\mu_h B)$$

or 
$$\theta = \tan^{-1} (\mu_e B)$$

- The mobility is given by

$$\mu_h = \sigma R_H \quad \text{or} \quad \mu_e = \sigma R_H$$

- Hall effect measurements help us in identifying the type of majority carrier, in determining carrier concentration and carrier mobility.
- The occupancy of energy levels in conductors is described by Fermi-Dirac Distribution function.
- Fermi level in intrinsic semiconductor is located exactly halfway between valence and conduction band.
- Fermi energy for *n*-type semiconductor lies halfway between the donor levels and the bottom of conduction band.
- Fermi energy for *p*-type semiconductor lies halfway between the acceptor levels and the top of valence band.
- The concentration of immobile negative and positive ions on either side of the junction is called depletion layer.
- The phenomenon of flow of charge carriers from region of higher concentration to a region of lower concentration is called diffusion.
- The total current density in *p-n* junction is combination of drift current density and diffusion current density.
- Light emitting diode is a junction diode which emits light when it is forward biased.
- The devices making use of photovoltaic effect to convert solar energy into electrical energy are known as solar cells.

### IMPORTANT FORMULAE

1. Conductivity for intrinsic semiconductor  $\sigma$ :

$$\sigma = n_i \times e \cdot (\mu_e + \mu_h)$$

where  $n_i$  is intrinsic density

$e$  is charge on electron (hole)

$\mu_e$  is mobility of electron

$\mu_h$  is mobility of hole

$\sigma$  is conductivity

2. Resistivity:

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

3. Conductivity of  $n$ -type semiconductor:

$$\sigma_n = N_d \cdot e \cdot \mu_e$$

where  $N_d$  is the concentration of donor atoms

4. Conductivity of  $p$ -type semiconductor:

$$\sigma_p = N_a \cdot e \cdot \mu_h$$

where  $N_a$  is the concentration of acceptor atoms

5. Hall voltage:

$$V_H = \frac{JBW}{ne} = \frac{BI}{net}$$

where  $V_H$  is Hall voltage

$J$  is current density

$B$  is strength of magnetic field

$n$  is concentration of charge carrier

$w$  is width of specimen

$t$  is thickness of specimen

$I$  is current

6. Hall coefficient:

$$R_H = \frac{1}{ne} = \frac{\mu}{\sigma}$$

7. Hall angle:

$$\tan \theta_H = \mu_h B$$

8. Carrier concentration:

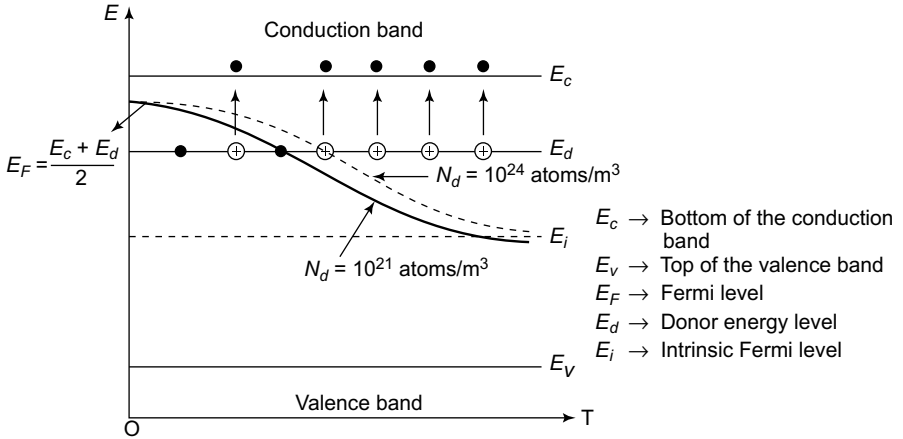
$$n = \frac{-1}{eR_H} = \frac{-BI}{V_H \cdot t \cdot e}$$

$$p = \frac{1}{eR_H} = \frac{BI}{V_H \cdot t \cdot e}$$

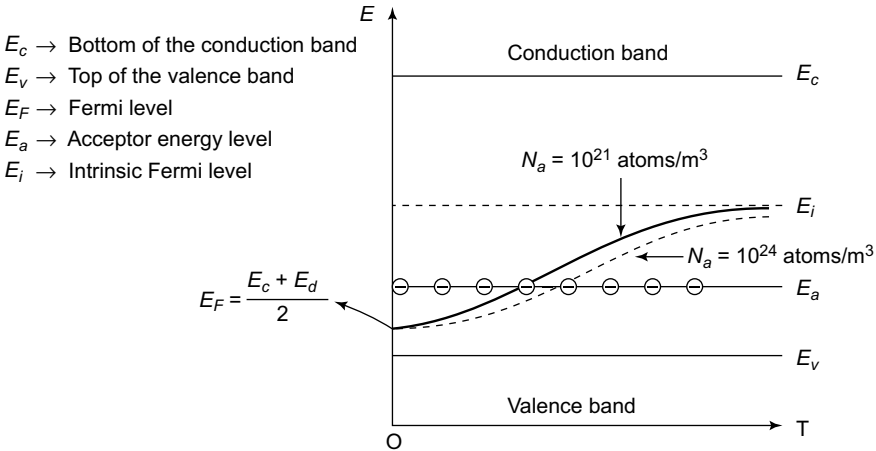
9. Mobility:

$$\mu_e = \sigma R_H = \sigma \left( \frac{V_H t}{BI} \right)$$





10. Draw a neat sketch to represent the variation of Fermi level with temperature in the case of *p*-type semiconductor for high and low doping levels.



11. What are acceptor and donor levels.

The discrete energy levels formed by the doped acceptors are called acceptor levels. This acceptor level lies just above the valence band.

The discrete energy levels formed by the doped donors are called donor levels. This donor level lies just below the conduction band.

12. Explain, why holes are majority carriers and electrons are minority carriers in a *p*-type semiconductor.

In the formation of a *p*-type semiconductor trivalent impurities like Ga or boron is doped to a pure semiconductor like Ge or Si.

**Solution:**

Given Data:  $\sigma_i = 4 \times 10^{-4} \Omega^{-1} \text{m}^{-1}$ ;  $\mu_e = 0.14 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ ;  $\mu_h = 0.04 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ ;  
 $n_e = ?$  and  $n_h = ?$

**Formula**

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

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

$$= \frac{4 \times 10^{-4}}{1.6 \times 10^{-19} (0.14 + 0.04)}$$

$$n_i = \frac{4 \times 10^{-4}}{2.88 \times 10^{-20}}$$

$$\therefore n_i = 1.388 \times 10^{16} \text{ m}^{-3}$$

Since  $n_e = n_h = n_i$  from law of mass action the electron and hole concentrations are  $1.38 \times 10^{16} \text{ m}^{-3}$ .

3. The resistivity of intrinsic germanium at  $27^\circ\text{C}$  is equal to  $0.47 \Omega \text{ m}$ . Calculate the intrinsic carrier density  $n_i$  at  $27^\circ\text{C}$  (Electron mobility =  $0.38 \text{ m}^2/\text{V sec}$  and hole mobility =  $0.18 \text{ m}^2/\text{V sec}$ .)

**Solution:**

Given Data:

$$\mu_e = 0.38 \frac{\text{m}^2}{\text{V}} \quad \mu_h = 0.18 \frac{\text{m}^2}{\text{V}}, \quad \rho = 0.47 \Omega \text{ m},$$

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

$$n_i = \frac{\sigma}{e(\mu_e + \mu_h)} = \frac{1}{\rho \cdot e \cdot (\mu_e + \mu_h)}$$

$$= \frac{1}{0.47 \times 1.6 \times 10^{-19} \times 0.56}$$

$$n_i = 2.375 \times 10^{19} / \text{m}^3$$

4. The electron and hole mobilities in In - Sb semiconductor are band  $0.2 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$  respectively. At room temperature, the resistivity of In - Sb is  $2 \times 10^{-4} \Omega \text{ m}$ . Assuming that the material is intrinsic, determine its intrinsic carrier density at room temperature.

**Solution:**

Given Data:  $\rho = 2 \times 10^{-4} \Omega \text{ m}$ ;  $\mu_e = 6 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ ;  $\mu_h = 0.2 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ ;  $n_i = ?$

**Formula**

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

$$\therefore n_i = \frac{\sigma_i}{e(\mu_e + \mu_h)}$$

$$\text{or } n_i = \frac{1}{\rho e(\mu_e + \mu_h)} \quad \left[ \because \sigma = \frac{1}{\rho} \right]$$

$$\begin{aligned} \therefore n_i &= \frac{1}{2 \times 10^{-4} \times 1.6 \times 10^{-19} \times (6 + 0.2)} \\ &= \frac{1}{2 \times 10^{-4} \times 1.6 \times 10^{-19} \times 6.2} = \frac{1}{1.984 \times 10^{-22}} \end{aligned}$$

$$\therefore n_i = 5.040 \times 10^{21} \text{ m}^{-3}$$

5. The mobilities of electrons and holes in a sample of intrinsic Ge at room temperature are 0.38 and 0.17  $\frac{\text{m}^2}{\text{Vs}}$  respectively. If the electron and hole

densities are each equal to  $2.5 \times 10^{19}/\text{m}^3$ , calculate the electrical conductivity and resistivity of germanium.

**Solution:**

Given Data:

$$\mu_e = 0.38 \text{ m}^2/\text{vs}$$

$$\mu_h = 0.17 \text{ m}^2/\text{vs}$$

$$n_i = 2.5 \times 10^{19}/\text{m}^3$$

$$\sigma = ?$$

$$\rho = ?$$

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

$$= 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.38 + 0.17)$$

$$= 2.2 \frac{\text{C/m}}{\text{V sec}} \quad \because \text{ volt-sec} = \Omega \cdot \text{c}$$

$$= 2.12/\Omega\text{m}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{2.2} = 0.4545 \Omega\text{m}$$

6. Find the resistance of an intrinsic Ge rod 1 cm  $\times$  1 mm  $\times$  1 mm at 300 K. For Ge :  $n_i = 2.5 \times 10^{13}/\text{cm}^3$ ,  $\mu_e = 3900 \text{ cm}^2/\text{Volt-sec}$ ,  $\mu_h = 1900 \text{ cm}^2/\text{Volt-sec}$  at 300°K

**Solution:**

Given Data:

$$n_i = 2.5 \times 10^{19}/\text{m}^3$$

$$\mu_e = 0.39 \text{ m}^2/\text{V sec}$$

$$= 0.19 \text{ m}^2/\text{V sec}$$

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

$$l = 10^{-2} \text{ m}$$

$$A = bd = 10^{-6} \text{ m}^2$$

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

$$= (2.5 \times 10^{19})(1.6 \times 10^{-19})(0.39 + 0.19)$$

$$= 2.32/\Omega\text{m}$$

$$\rho = 1/\sigma = \frac{1}{2.3} = 0.431 \Omega \text{ m}$$

$$R = \rho \frac{l}{A} = (0.431 \Omega \text{ m}) \times \frac{10^{-2}}{10^{-6}} = 4.31 \times 10^3 \Omega$$

7. The energy gap of silicon is 1.1 eV. Its electron and hole mobilities at room temperature are 0.48 and 0.13  $\text{m}^2 \text{V}^{-1} \text{s}^{-1}$ . Evaluate its conductivity.

**Solution:**

Given Data:  $E_g = 1.1 \text{ eV} = 1.1 \times 1.6 \times 10^{-19} \text{ J}$ ;  $\mu_e = 0.48 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ ;

$$\mu_h = 0.13 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}; \sigma_i = ?$$

**Formula**

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

But,  $n_i$  has to be calculated. Hence,

$$n_i = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{-E_g}{2k_B T} \right)}$$

Assuming  $m_e^* = m_h^* = m_o$

$$\therefore n_i = 2 \left( \frac{2 \times 3.14 \times 9.11 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{(6.625 \times 10^{-34})^2} \right)^{3/2} e^{\left( \frac{-1.1 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300} \right)}$$

$$= 2 \times (5.3964 \times 10^{16})^{3/2} \times e^{(-21.25)}$$

$$= 2 \times 1.25359 \times 10^{25} \times 5.90530 \times 10^{-10}$$

$$n_i = 1.48056 \times 10^{16} \text{ m}^{-3}$$

$$\therefore \sigma_i = 1.4805 \times 10^{16} \times 1.6 \times 10^{-19} (0.48 + 0.13)$$

$$= 1.4805 \times 10^{16} \times 1.6 \times 10^{-19} \times 0.61$$

$$\text{or } \sigma_i = 1.4449 \times 10^{-3} \Omega^{-1} \text{m}^{-1}$$

8. Find the resistance of an intrinsic Ge rod 1 cm long, 1 mm wide and 1 mm thick at 300 K. For Ge,  $n_i = 2.5 \times 10^{19}/\text{m}^3$ ,  $\mu_e = 0.39 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$  and  $\mu_h = 0.19 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ .

**Solution:**

Given Data:  $l = 1 \times 10^{-2} \text{ m}$ ; breadth =  $1 \times 10^{-3} \text{ m}$ ; thickness =  $1 \times 10^{-3} \text{ m}$ ;  
 $T = 300 \text{ K}$   $\mu_e = 0.39 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ ;  $\mu_h = 0.19 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ ;  $R = ?$

**Formula**

$$\begin{aligned}\sigma_i &= n_i e (\mu_e + \mu_h) \\ &= 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.39 + 0.19) \\ &= 2.5 \times 10^{19} \times 1.6 \times 10^{-19} \times .58\end{aligned}$$

$$\therefore \sigma_i = 2.32 \Omega^{-1} \text{ m}^{-1}.$$

We know resistance  $R = \frac{\rho l}{A}$

$$R = \frac{l}{\sigma A}$$

$$\begin{aligned}R &= \frac{1 \times 10^{-2}}{2.32 \times (1 \times 10^{-3} \times 1 \times 10^{-3})} \left[ \because \text{Area} = \text{Breadth} \times \text{Thickness} \right] \\ &= \frac{1 \times 10^{-2}}{2.32 \times 10^{-6}}\end{aligned}$$

$$R = 4310 \Omega.$$

9. In an intrinsic semiconductor the energy gap is 1.2 eV. What is the ratio between its conductivity at 600 K and that at 300 K.

**Solution:**

Given Data:  $E_g = 1.2 \text{ eV} = 1.2 \times 1.6 \times 10^{-19} \text{ J}$ ;  $T_1 = 600 \text{ K}$ ;  $T_2 = 300 \text{ K}$ ;  $\frac{\sigma_1}{\sigma_2} = ?$

**Formula**

$$\sigma = C e^{\left( \frac{-E_g}{2k_B T} \right)}$$

Let  $\sigma_1$  be the electrical conductivity at  $T_1 \text{ K}$  and  $\sigma_2$  the electrical conductivity at  $T_2 \text{ K}$ .

$$\therefore \sigma_1 = C e^{\left( \frac{-E_g}{2k_B T_1} \right)}$$

and, 
$$\sigma_2 = C e^{\left( \frac{-E_g}{2k_B T_2} \right)}$$

$$\begin{aligned}\text{Hence, } \frac{\sigma_1}{\sigma_2} &= e^{\left[ \frac{-E_g}{2k_B} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \right]} = e^{\left[ \frac{-1.2 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23}} \times \left( \frac{1}{600} - \frac{1}{300} \right) \right]} \\ &= e^{\left[ \frac{-1.2 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23}} \times (-1.666 \times 10^{-3}) \right]} = e^{\left( \frac{3.19872 \times 10^{-22}}{2 \times 1.38 \times 10^{-23}} \right)} = e^{11.59} \\ &= 108416.886\end{aligned}$$

specimen, the voltage measured across its width is found to be  $37 \mu\text{V}$ . What is the Hall coefficient of semiconductor and the density of charge carrier.

**Solution:**

Given Data:

$$l = 12 \text{ mm} = 12 \times 10^{-3} \text{ m}; t = 1 \text{ mm} = 1 \times 10^{-3} \text{ m}$$

$$b = 1 \text{ mm} = 1 \times 10^{-3} \text{ m}, I = 20 \text{ mA} = 20 \times 10^{-3} \text{ A}$$

$$V_H = 37 \mu\text{V} = 37 \times 10^{-6} \text{ V}, B = 0.5 \text{ wb/m}^2.$$

$$R_H = ? \text{ and } n = ?$$

We know

$$\begin{aligned} R_H &= \frac{V_H t}{IB} \\ &= \frac{37 \times 10^{-6} \times 1 \times 10^{-3}}{20 \times 10^{-3} \times 0.5} = \frac{3.7 \times 10^{-8}}{0.01} \end{aligned}$$

$$R_H = 3.7 \times 10^{-6} \text{ C}^{-1} \text{ m}^3.$$

15. A sample of a  $p$ -type silicon has an acceptor density of  $10^{20}$  per  $\text{m}^3$ . It is used in the Hall effect experiment. The magnetic field used is  $0.6 \text{ T}$  and the current passed is  $500 \text{ A/m}^2$ . The thickness of the sample is  $5 \text{ mm}$ . Find the Hall voltage developed.

**Solution:**

Given Data:

$$n_a = 10^{20}/\text{m}^3$$

$$B = 0.6 \text{ T}$$

$$J = 500 \text{ A/m}^2$$

$$W = 5 \text{ mm} = 5 \times 10^{-3} \text{ m}$$

The Hall voltage is given by

$$\begin{aligned} V_H &= \frac{J \cdot B \cdot W}{n_a \cdot e} = \frac{500 \times 0.6 \times 5 \times 10^{-3}}{10^{20} \times 1.6 \times 10^{-19}} \\ &= 9.375 \times 10^{-3} \end{aligned}$$

$$V_H = 9.375 \text{ mV}$$

16. A rectangular plane sheet of doped silicon has dimensions of  $1 \text{ cm}$  along  $Y$ -direction, and  $0.5 \text{ m}$  along  $Z$ -direction. Hall probes are attached on its two surfaces parallel to  $X$ - $Z$  plane and a magnetic field of flux density  $0.7 \text{ wb/m}^2$  is applied along  $Z$ -direction. A current of  $1 \text{ mA}$  is flowing in it in the  $X$ -direction. Calculate the Hall voltage measured by the probes if the Hall coefficient of the material is  $1.25 \times 10^{-3} \text{ m}^3 \text{ C}^{-1}$ .

**Solution:**

$$\text{Given Data: } B = 0.7 \text{ wb/m}^2, I = 1 \times 10^{-3} \text{ A}; R_H = 1.25 \times 10^{-3} \text{ C}^{-1},$$

$$b = 1 \text{ cm} = 1 \times 10^{-2} \text{ m}, t = 0.5 \text{ mm} = 0.5 \times 10^{-3} \text{ m}; V_H = ?$$

We know  $\sigma = n_e e \mu_e$

$$\therefore \mu_e = \frac{\sigma}{n_e e} = \frac{180}{1.772 \times 10^{22} \times 1.6 \times 10^{-19}}$$

$$\therefore \mu_e = 0.03809 \text{ m}^2\text{V}^{-1}\text{s}^{-1}.$$

19. An electric field of 100 V/m is applied to a sample of  $n$ -type semiconductor whose Hall coefficient is  $-0.0125 \text{ m}^3\text{C}^{-1}$ . Determine the current density in the sample, assuming electron mobility to be  $0.36 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ .

**Solution:**

Given Data:  $R_H = -0.0125 \text{ m}^3\text{C}^{-1}$ ;  $\mu = 0.36 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ ;  $E_H = 100 \text{ V/m}$ ;  $J = ?$

We know

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

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

$$n_i = \frac{\sigma_i}{e(\mu_e + \mu_h)}$$

or

$$n_i = \frac{1}{\rho e (\mu_e + \mu_h)} \quad \left[ \because \sigma = \frac{1}{\rho} \right]$$

$$\begin{aligned} n_i &= \frac{1}{2 \times 10^{-4} \times 1.6 \times 10^{-19} \times (6 + 0.2)} \\ &= \frac{1}{2 \times 10^{-4} \times 1.6 \times 10^{-19} \times (6.2)} = \frac{1}{1.984 \times 10^{-22}} \\ n_i &= 5.040 \times 10^{21} \text{ m}^{-3}. \end{aligned}$$

20. The Hall coefficient of a specimen of a doped silicon is found to be  $3.66 \times 10^{-4} \text{ m}^3\text{C}^{-1}$ . The resistivity of the specimen is  $8.93 \times 10^{-3} \text{ m}$ . Find the mobility and density of the charge carrier.

**Solution:**

Given Data:  $R_H = 3.66 \times 10^{-4} \text{ m}^3\text{C}^{-1}$ ;  $\rho = 8.93 \times 10^{-3} \Omega\text{m}$ ;  $\mu = ?$  and  $n = ?$

**Formula**

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

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

$$n = 1.7076 \times 10^{22} \text{ m}^{-3}.$$

$$\text{Mobility} \quad \mu = \sigma R_H$$

$$\text{or} \quad \mu = \frac{R_H}{\rho}$$

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

$$\text{or} \quad \mu = 0.0409 \text{ m}^2\text{V}^{-1}\text{s}^{-1}.$$

21. Find the concentration of holes and electrons in  $n$ -type silicon at 300 K, if the conductivity is  $3 \times 10^4 \Omega^{-1} \text{ m}^{-1}$ . Also find these values for  $p$ -type silicon.

[Given  $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$ ,  $\mu_e = 1300 \times 10^{-4} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$  and  $\mu_h = 500 \times 10^{-4} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ ]

**Solution:**

Given Data:  $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$ ;  $\mu_e = 1300 \times 10^{-4} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$

$\mu_h = 500 \times 10^{-4} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ ;  $\sigma = 3 \times 10^4 \Omega^{-1}\text{m}^{-1}$ ;  $n_e = ?$  and  $n_h = ?$

The density of electrons in  $n$ -type silicon is

$$n_e = \frac{\sigma}{e\mu_e} = \frac{3 \times 10^4}{1.6 \times 10^{19} \times 1300 \times 10^{-4}} = \frac{3 \times 10^4}{2.08 \times 10^{-20}}$$

$$n_e = 1.4423 \times 10^{24} \text{ electrons/m}^3.$$

$\therefore$  The density of holes is

$$n_h = \frac{n_i^2}{n_e} = \frac{(1.5 \times 10^{16})^2}{1.4423 \times 10^{24}}$$

$$n_h = 1.56 \times 10^8 \text{ holes/m}^3.$$

Density of holes in  $p$ -type silicon is

$$n_h = \frac{\sigma}{e\mu_h} = \frac{3 \times 10^4}{1.6 \times 10^{-19} \times 500 \times 10^{-4}} = \frac{3 \times 10^4}{8 \times 10^{-21}}$$

$$n_h = 3.75 \times 10^{24} \text{ holes/m}^3.$$

Hence, density of electrons is

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5 \times 10^{16})^2}{3.75 \times 10^{24}}$$

$$n_e = 6 \times 10^7 \text{ electrons /m}^3.$$

22. If a sample of silicon is doped with  $3 \times 10^{23}$  arsenic atoms and  $5 \times 10^{23}$  atoms of boron, determine the electron concentration if the intrinsic charge carriers are  $2 \times 10^{16}/\text{m}^3$ .



$$\begin{aligned} \therefore N_a &= \frac{\sigma}{e\mu_h} = \frac{1}{\rho e\mu_h} = \frac{1}{10 \times 10^{-2} \times 1.6 \times 10^{-19} \times 480 \times 10^{-4}} \\ &= \frac{1}{7.68 \times 10^{-22}} \end{aligned}$$

$$\therefore N_a = 1.3020 \times 10^{21} / \text{m}^3.$$

The minority carrier concentration is

$$n_e = \frac{n_i^2}{n_h}$$

$$\therefore n_e = \frac{(1.5 \times 10^{16})^2}{1.3 \times 10^{21}}$$

$$\text{or } n_e = 1.728 \times 10^{11} \text{ electrons/m}^3.$$

**For  $n$ -type**

$$\text{Assuming } n_e = N_d$$

$$\sigma = n_e e\mu_e$$

$$\text{or } \sigma = N_d e\mu_e$$

$$\begin{aligned} \therefore N_d &= \frac{\sigma}{e\mu_e} = \frac{1}{\rho e\mu_e} = \frac{1}{10 \times 10^{-2} \times 1.6 \times 10^{-19} \times 1350 \times 10^{-4}} \\ &= \frac{1}{2.16 \times 10^{-21}} \end{aligned}$$

$$\therefore N_d = 4.629 \times 10^{20} / \text{m}^3.$$

**24.** The Hall coefficient of a specimen is  $3.66 \times 10^{-4} \text{ m}^3/\text{c}$ . Its resistivity is  $8.93 \times 10^{-3} \Omega\text{m}$ . Find mobility and carrier concentration.

**Solution:**

$$\text{Given Data: } R_H = 3.66 \times 10^{-4} \text{ m}^3/\text{c}, \rho = 8.93 \times 10^{-3} \Omega\text{m}$$

$$R_H = \frac{1}{ne} = \frac{\mu}{\sigma}$$

$$\mu = R_H \cdot \sigma = \frac{R_H}{\rho}$$

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

$$\mu = 0.041 \text{ m}^2/\text{Vm}$$

current direction and the thickness of the strip in the direction of the magnetic field is 0.5 mm. The Hall voltage is found to be 100 V. Calculate the number of conduction electrons per  $\text{m}^3$  in the metal.

**(Ans.:  $n_e = 7.51 \times 10^{21}$  electrons/ $\text{m}^3$ )**

13. A *p*-type Ge has a donor density of  $10^{23}$  per  $\text{m}^3$ . It is used in Hall effect experiment in which a magnetic field of  $0.5 \text{ wb/m}^2$  is used and a current of  $300 \text{ Am}^{-2}$  is passed. If the thickness of the Ge is 4 mm find the Hall voltage developed.

**(Ans.:  $V_H = 37.5 \mu\text{V}$ )**