Chapter 1

Semiconductor Theory

CHAPTER HIGHLIGHTS

- *Atomic Structure*
- *Energy Band Diagrams*
- *Intrinsic and Extrinsic Semiconductors*
- *Conductivity of Semiconductor*
- *Fermi – Dirac Function*
- *Fermi Level in an Intrinsic Semiconductor*
- *Mass Action Law*
- *Energy Band Gap (E_G)*
- *Drift and Diffusion Currents*
- *Einstein Relationship for Semiconductors*
- *The Hall Effect*

Introduction

Atomic Structure

All the materials are composed of very small particles called atoms. An atom consists of a central nucleus of positive charge around which small negatively charged particles called electrons revolves in different orbits.

1. **Nucleus:** It is the central part of an atom. It contains protons and neutrons. A proton is a positively charged particle. While the neutron has the same mass of the proton, but has no charge, that is, the nucleus of an atom is positively charged. The sum of protons and neutrons constitutes the entire weight of an atom and is called atomic weight, and electrons have negligible weight as compared to protons or neutrons.
2. **Extra Nucleus:** It is the outer part of an atom and contains electrons only. An e^- is a negatively charged particle having negligible mass. The charge on an e^- is equal but opposite to that on a proton. Therefore, an atom is neutral as a whole. The number of electrons or protons in an atom is called atomic number.
   The e^- in an atom revolves around the nucleus in the different orbits. The number of e^- in any orbit is given by $2n^2$, where n is the number of the orbit.
   The first orbit contains $= 2 \times 1^2 = 2$ e^-s
   The third orbit contains $= 2 \times 3^2 = 18$ e^-s
   ……..etc.
   The last orbit cannot have more than 8 e^-s and the last but one orbit cannot have more than 18 e^-s.

Atomic Structure of Copper

Copper atomic weight = 64
Atomic number = 29
Number of protons = e^-s = 39 and number of neutrons = 64 – 29 = 35

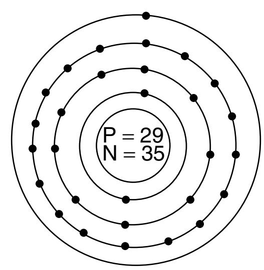


Figure 1 Structure of copper atom

It has 29 e^-s that are arranged in different orbits as follows.

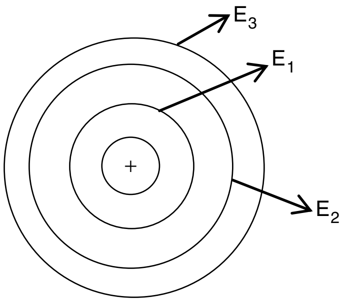
$$Cu \rightarrow 29 \Rightarrow 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^1$$

Therefore, the number of Valence e^-s in Cu is equal to one.

Some of the important properties of an electron are as follows

1. Charge on an $e^- = 1.602 \times 10^{-19}$ C $= q$
2. Mass of an e^- $m = 9 \times 10^{-31}$ kg
3. Radius of an $e^- = r = 1.9 \times 10^{-15}$ m.

An e^- moving around the nucleus posses two types of energies: kinetic energy due to its motion and potential energy due to the charge on the nucleus. The total energy of the electron is the sum of the two energies. The energy of an e^- increases as its distance from the nucleus increases. Thus, an e^- in the second orbit has more energy than the e^- in the first orbit. Therefore, the e^- in the last orbit possesses very high energy as compared to the inner orbits.



Energy = K. E + P. E

For any atom, the energy of an nth orbit is given by $E_n = \frac{-13.56}{n^2}$ eV

If $n = 1 \Rightarrow E_1 = -13.56$ eV

$n = 2 \Rightarrow E_2 = -3.5$ ev, etc.,

$\Rightarrow E_1 < E_2 < E_3 \ldots\ldots E_n$.

Valence shell will have the highest energy.

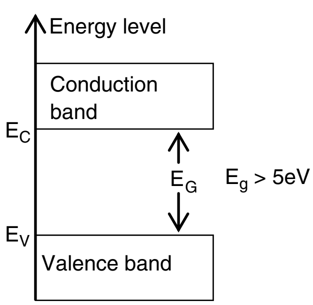
The electrons in the outermost orbit of an atom are known as valence electrons. The outermost orbit can have a maximum of 8 electrons. For a stable atom, the number of valence e^- is equal to 8.

Materials classified based on the conductivity (number of valence e^-) are of three categories: insulators (>4 e^-s), semiconductors (4 e^- s), and conductors (< 4 e^-s).

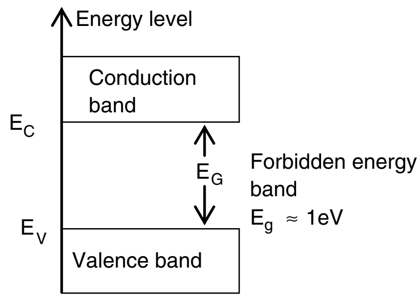
1. When the number of valence electrons of an atom is less than 4, the material is usually a metal and a conductor. For example, Cu, Al, sodium, Mg, cl, and gold
2. When the number of valence electrons of an atom is 4, the material has both metal and non-metal properties and it is called a semiconductor. For example, Si and Ge.
3. When the number of valence electrons of an atom is more than 4, the material is usually a non-metal and an insulator. For example, N, sulphur, neon, Br, As, etc., and wood, plastic, mica, etc.
   (a) The resistance of a good conductor increases with an increase in the temperature, that is, it is a positive temperature coefficient (PTC).
   (b) The resistance of a semiconductor material is decreased with an increase in temperature, that is, it is negative temperature coefficient (NTC).
   (c) Insulators also have NTC.

Energy Band Diagrams

1. Insulators



2. Semiconductors



3. Conductors

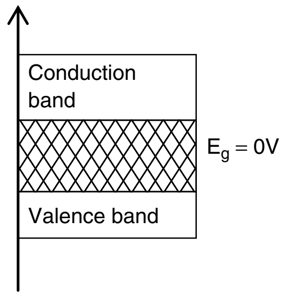


Figure 2 Energy band diagrams

In an insulator, the conduction band is practically empty and the valence band is full, and therefore, enormous energy would be required to push electrons from the valence band into conduction band, that is, the forbidden energy gap. It is not possible in the normal working temperatures. Hence, an insulator cannot conduct even if a strong electric field is applied.

Insulators ⇒ Ionic bond

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator. The valence band is not saturated. Since there are only four e^- and the conduction band is practically empty at low temperatures (insulator).

However, with the increase in temperature, more and more valence electrons are jumped into the conduction band. This increases the conductivity of the material, that is, at high temperatures, a semiconductor behaves like a good conductor.

Semi conductor ⇒ covalent bonds

In conductors, the valence and conduction band overlap (i.e., $E_G = 0$), and therefore, a large number of free electrons are available even at low temperatures.

⇒ Conductors ⇒ Metalic bond

Intrinsic and Extrinsic Semiconductors

Intrinsic Semiconductor

Intrinsic semiconductor is a semiconductor material in its purest form, for example silicon and germanium. Both Si and Ge are tetravalent (IVth group), and they are crystalline. Each atom is shared by the four surrounding atoms, as shown in the figure.

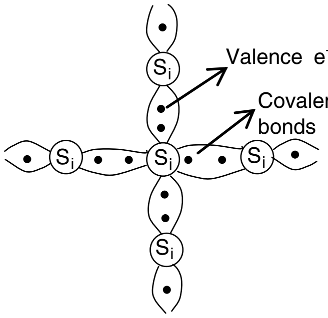


Figure 3 crystalline structure of Si

At low temperatures, the covalent bonds are intact, and the valence electrons are strongly bound to the parent atoms, that is, no free e^-s are available for conduction at room temperature. As temperature increases, the valence e^- acquires energy and create e^--hole pairs or some of the covalent bonds break; further, these free e^- s contribute to conduction. When a covalent bond breaks, a hole is created in the crystal lattice. A hole is nothing but missing electron, and hence, it represents a positive charge.

If the temperature is further increased, it creates more and more new e^-–hole pairs. This means the conductivity of the material increases with the temperature increase, but the total conductivity is poor.

Extrinsic Semiconductors

The conductivity of a pure semiconductor material can be increased by the addition of a small amount of suitable impurity to a semiconductor. The process of adding impurities to a semiconductor is known as doping.

The purpose of adding impurity is to increase either the number of free e^-s or holes in the semiconductor crystal. Depending on the type of impurity added, extrinsic semiconductor are divided into n-type semiconductors and p-type semiconductors

n-type Semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as n-type semiconductor.

The addition of pentavalent impurity provides a large number of free e^-s in the semiconductor crystal. For example, P, As, antimony, and Bi (Vth group elements).

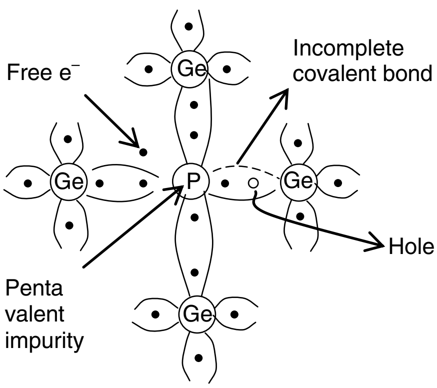


Figure 4 Crystalline structure of N-type semiconductor

Such impurities are known as donor impurities because they donate or provide free e^-s to the semiconductor crystal. In N-type semiconductor, e^-s are majority charge carriers and holes are the minority charge carriers.

P-type Semiconductor

P-type semiconductor is formed by doping pure Si or Ge with trivalent impurities such as B, indium, gallium, or Al. In P-type semiconductor, holes (which are present in large numbers) are majority charge carriers and e^-s are minority charge carriers.

The acceptor atoms can be represented as negative ions. In extrinsic semiconductor, conduction is due to both majority and minority charge carriers.

Conductivity of Semiconductor

In a pure semiconductor, the number of holes is equal to the number of electrons. Thermal agitation continues to produce new electron–hole pairs and they disappear because of recombination.

The total current density J within the semiconductor is given by

$$J = J_n + J_p$$
$$= q.n.\mu_n E + q.p.\mu_p.E$$
$$= (n\mu_n + p\mu_p)q.E$$
$$J = \sigma E$$
$$\therefore \boldsymbol{\sigma = (n\mu_n + p\mu_p)q}$$

For pure semiconductor, $n = p = n_i$.

$$\therefore \sigma_i = n_i(\mu_n + \mu_p)q$$

Where

$n \rightarrow$ No. of e^- 's per unit volume

$p \rightarrow$ No. of holes per unit volume

$E \rightarrow$ applied electric field strength V/m.

$q \rightarrow$ charge of e^- C

$J_n \Rightarrow$ electron drift current density

$J_p \Rightarrow$ hole drift current density

$\sigma \rightarrow$ conductivity of semiconductor

The resistivity of a semiconductor is the reciprocal of conductivity.

i.e., $\rho = \dfrac{1}{\sigma}$

Semiconductors have negative temperature coefficient.

i.e., $T\uparrow R\downarrow$ (NTC)

1. **For N-type semiconductor:** For N-type semiconductor, as n > > p, then the conductivity

$$\sigma_n \approx q{\cdot}n{\cdot}\mu_n$$
$$n \approx N_D$$
$$\therefore J_n \approx N_D{\cdot}\mu_n{\cdot}q{\cdot}E$$

where N_D is the total no. of donor atoms/units volume.

2. **For P-type semiconductor:** $p >> n$ and $p \approx N_A$.

$$\therefore \sigma_P = p{\cdot}\mu_p{\cdot}q$$
$$J_p \approx N_A{\cdot}\mu_p{\cdot}q{\cdot}E$$

NOTES

(i) for Ge semiconductor
'ε_r' (Ge) = 16,
n_i (Ge) = 2. 5 × 10^{13} cm^{-3}
(ii) for Si Semiconductors
n_i (Si) = 1. 5 × 10^{10} cm^{-3}
'ε_r' (Si) = 12

Solved Examples

Example 1

The resistivity of a uniform doped N-type Si sample is 0.5 Ω-cm. If the electron mobility (μ_n) is 1,250 cm^2/v-s and the charge of an election is 1.6 × 10^{-19} Coulomb, then the donor impurity concentration (N_D) in the sample is

(A) 1×10^{16} cm^{-3}
(B) 2×10^{16} cm^{-3}
(C) 2.5×10^{15} cm^{-3}
(D) 2×10^{15} cm^{-3}

Solution

From the given data $\rho = 0.5$ Ω-cm.

$$\mu_n = 1{,}250 \text{ cm}^2/\text{v-s}$$

$$\sigma = \frac{1}{\rho} = N_D \cdot \mu_n \cdot q$$

$$N_D = \frac{1}{\rho \cdot \mu_n \cdot q} = \frac{1}{0.5 \times 1250 \times 1.6 \times 10^{-19}}$$

$$= 10^{16} \text{ cm}^{-3}$$

Example 2

A sample of Si at a given temperature T in intrinsic condition has a resistivity of 25 × 10^4 Ω-cm. The sample is now doped to the extent of 4.5 × 10^{10} donor atoms/cm^3 and 0.5 × 10^{10} acceptor atoms/cm^3. Find the total conduction current density if an electric field of 5 V/cm is applied, given that μ_n = 1,500 cm^2/v-s and μ_p = 300 cm^2/v-s at the given temperature.

Solution

$$\sigma = n_i(\mu_n + \mu_p) \cdot q$$

$$\rho_i = 25 \times 10^4 \ \Omega\text{-cm}$$

$$\therefore n_i = \frac{\sigma_i}{(\mu_n + \mu_p) \cdot q} = \frac{1}{25 \times 10^4 \times 1800 \times 1.6 \times 10^{-19}}$$

$$= \frac{1}{72} \times 10^{12} = 1.388 \times 10^{10} \text{ cm}^{-3}$$

Net donor density (N_D)

$$= 4.5 \times 10^{10} - 0.5 \times 10^{10} = 4 \times 10^{10} \text{ atoms/cm}^3$$

$$\text{Minority carrier concentration} = \frac{n_i^2}{N_D}$$

$$= \frac{(1.388 \times 10^{10})^2}{4 \times 10^{10}} = 0.48 \times 10^{10} \text{cm}^{-3}$$

$$\sigma = (n\mu_n + p\mu_p) \cdot q$$

$$= (4 \times 10^{10} \times 1500 + 0.48 \times 10^{10} \times 300)1.6 \times 10^{-19}$$

$$= (60 \times 10^{12} + 1.44 \times 10^{12}) \times 1.6 \times 10^{-19}$$

$$\sigma = 98.3 \times 10^{-7} \ (\Omega\text{-cm})^{-1}$$

$$J = \sigma E = 98.3 \times 10^{-7} \times 5 = 49.15 \times 10^{-6} \text{ A/cm}^2$$

Fermi–Dirac Function

The probability of occupation $f(E)$ of an energy level (E) by an electron is given by

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

where K is Boltzmann constant in eV/°K.

The Fermi level represents the energy state with 50% probability of being filled, if no forbidden band exists. Therefore, if $E = E_F$, then $f(E) = 1/2$ for any temperature.

Case (i): At T = zero (0°K)

$$F(E) = \frac{1}{(1 + e^{\infty})} = 0 \text{ ; when } E > E_F.$$

$$F(E) = \frac{1}{1 + e^{-\infty}} = 1; \text{ when } E < E_F.$$

Intrinsic semiconductor acts like an insulator at 0°K.

Case (ii): for $T > 0$°K

$F(E) = 0$ when $E >> E_F$
$F(E) = 1$ when $E << E_F$

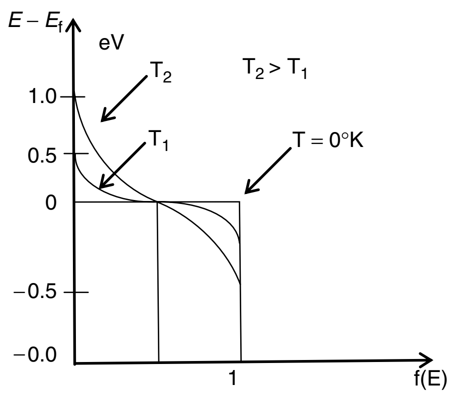


Figure 5 Fermi–Dirac distribution function $f(E)$

The concentration of free electrons n and the concentration of free holes is p.

$$\therefore n = N_C e^{-(E_c - E_F)/KT}$$

$$p = N_V e^{-(E_F - E_v)/KT}$$

Fermi Level in an Intrinsic Semiconductor

In the case of intrinsic material, the crystal must be electrically neutral.

$$n_i = p_i$$

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

$$\Rightarrow \qquad E_F = \frac{E_C + E_V}{2} - \frac{KT}{2}.\ln\left(\frac{N_C}{N_V}\right)$$

If the effective mass of a free electron and hole are same, then

$$N_C = N_V$$

$$E_F = \frac{E_C + E_V}{2}$$

In intrinsic semiconductor, the Fermi level lies in the middle of the forbidden energy band.

Donor Impurities

If pentavalent substances (phosphorous, antimony, As) are added as impurities to a pure germanium or Si, four of the five valence electrons of the impurity atoms will occupy covalent bonds and the fifth e^- will be available as a carrier of current. These impurities donate excess electron carriers, and hence, these are called donor or N-type impurities.

Acceptor Impurities

If a trivalent impurity (B, Al, Ga, In) is added to an intrinsic semiconductor, only three covalent bonds are filled, and the vacancy in the fourth bond constitutes a hole. These impurities are known as acceptor or P-type impurities.

Acceptor ion is indicated by a '–ve' sign because after this atom accepts an electron, it converts into a negative-ion.

Fermi level in an N-type material is given by

We know $n = N_C.\ e^{-(E_C - E_F)/KT}$

But $\quad n \approx N_D$

$$N_D = N_C.\ e^{-(E_C - E_F)/KT}$$

$$E_{F_n} = E_C - KT.\ln\left(\frac{N_C}{N_D}\right)\text{eV}$$

where

$N_D \Rightarrow$ concentration of donor atoms

N_C = effective density states

The Fermi level in a P-type material is given by

$$E_{F_p} = E_V + KT.\ln\left(\frac{N_V}{N_A}\right)\text{eV}$$

where $N_A \Rightarrow$ concentration of acceptor atoms

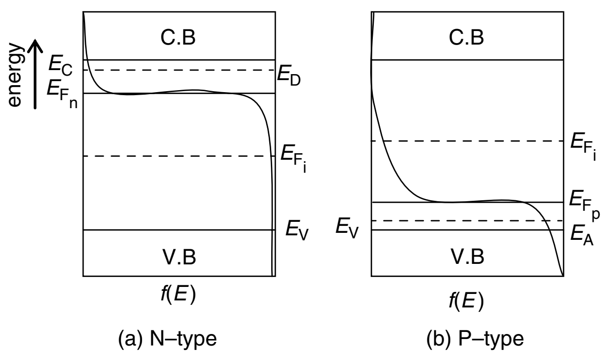


Figure 6 Positions of semiconductor Fermi levels in an extrinsic semiconductor

From the abovementioned figure, it shows the Fermi level in N-type semiconductor is just below the conduction band (E_C), and in p-type semiconductor, the Fermi level lies just above the valence band (E_V).

Example 3

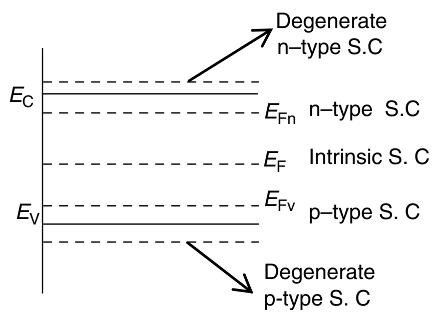
Match List-I (type of conductor) with List-II (position of Fermi level) and select the correct answer using the codes given in the following lists.

List-I	List-II
P. N-type semiconductor	1. Middle of band gap
Q. P-type semiconductor	2. Above the conduction band
R. Intrinsic semiconductor	3. Near but below conduction band
S. Degenerative n-type semiconductor	4. Near but above valence band

Codes:

	P	Q	R	S
(A)	1	2	3	4
(B)	3	4	1	2
(C)	2	1	3	3
(D)	3	2	1	4

Solution



If temperature T increases, the Fermi levels of p-type and n-type semiconductor moves towards the middle of the forbidden energy band.

$$E_{Fn} - E_{Fi} = \text{Shift} = \text{KTln}\left[\frac{N_D}{n_i}\right]\text{eV.}$$

Example 4

In a p-type semiconductor, the Fermi level is 0.2 eV above the valence band at a room temperature of 300 K. The new position of the Fermi level at $T = 400$ K is

(A) 0.153 V (B) 0.2 V
(C) 0.265 V (D) 0.32 V

Solution

We know the Fermi level in P-type materials is

$$E_F = E_V + \text{KTln}\left(\frac{N_V}{N_A}\right)$$

$$\frac{E_{F_2} - E_V}{E_{F_1} - E_V} = \frac{T_2}{T_1}$$

$$E_{F_2} - E_v = 0.2 \times \frac{400}{300} \text{eV} = 0.266 \text{ V}$$

If the concentration impurity increases, the Fermi level of heavily doped p-type and n-type semiconductor moves away from the middle of the energy band.

Shift in Fermi level = $E_{Fi} - E_{FP}$

$$\text{Shift} = KT \ln\left(\frac{N_A}{n_i}\right) \text{ev}$$

Example 5

Si is doped with boron to a concentration of 4×10^{15} atoms/cm^3. Assume the intrinsic carrier concentration of Si to be 1.5×10^{10} cm^{-3} and V_T = 26 mV at 300° K compared to undoped Si, then the Fermi level of doped silicon

(A) goes down by 0.25 eV
(B) goes up by 0.325 eV
(C) goes down by 0.325 eV
(D) goes up by 0.25 eV

Solution

Boron is P-type impurity.

∴ Fermi level goes down to the centre.

$$\text{Shift in Fermi level} = E_{Fi} - E_{Fv} = KT \ln\left(\frac{N_A}{n_i}\right)$$

$$\text{Shift} = 26 \times 10^{-3}. \ln\left[\frac{4 \times 10^{15}}{1.5 \times 10^{10}}\right] = 0.325 \text{ eV.}$$

Mass Action Law

It states that under thermal equilibrium for any semiconductor, the product of the number of electrons and the number of holes is constant and is independent of the amount of donor and acceptor impurities.

i.e., $n\,p = n_i^2$

The semiconductor is electrically neutral, and the magnitudes of the positive charge density must be equal to that of the negative concentration.

$$N_D + p = N_A + n$$

For N-type semiconductors of $N_A = 0$,

$$\therefore \quad n = N_D + p \Rightarrow n \approx N_D$$

Let N_D be the concentration of donor atoms in an N-type semiconductor.

$$\Rightarrow \quad n\,.p = n_i^2$$

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

$$\Rightarrow \quad p_n \propto \frac{1}{N_D}$$

∴ The minority carrier concentration is inversely proportional to the majority charge carrier concentration.

In P-type semiconductor $N_D = 0$.

$$\therefore N_A + n = p$$

$$P \approx N_A,$$

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

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

where $n_p << p_p$ or N_A

$n_i^2 = A_0 \cdot T^3 \,.\, e^{-E_{G_0}/KT}$

$\therefore n_i^2 \,\alpha\, T^3$

Energy Band Gap (E_G)

Energy required to break a covalent bond, that is, it is the difference between the conductance band (E_C) to valence band energy (E_V). The energy gap decreases with the increase in temperature and is given by

$$E_G(T) = E_{G0} - \beta T$$

where β = Constant

$\beta_{Si} = 3.6 \times 10^{-4}$ eV/°k and $\beta_{Ge} = 2.23 \times 10^{-4}$ eV/°k

E_{G0} = energy gap at 0°K

E_{g_o} = 1.21eV for Si

E_{g_o} = 0.785 eV for Ge at 0° K

and

E_G = 1.1eV for Si

E_G = 0.72 eV for Ge at room temperature (300 K)

Drift and Diffusion Currents

The flow of charge, that is, current through a semiconductor material is of two types, namely drift and diffusion. Since the net current flows through a PN junction, diode has two components: drift current and diffusion current

Drift Current

When an electric field is applied across the semiconductor material, the charge carriers attain a certain drift velocity v_d, which is equal to the product of the mobility of the charge carriers and the applied electric field intensity E. This means the drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

Drift velocity $V_d = \mu$E m/s

E = applied electric field intensity in V/cm

∴ The drift current density

$$J = J_n + J_p = (n\,\mu_n + p\,\mu_p)\,qE \text{ A/cm}^2$$

Diffusion Current

It is possible for an electric current to flow in a semiconductor even in the absence of the electric field, provided a concentration gradient exists in the material. A concentration gradient exists if the number of either e$^-$'s or holes is greater.

In one region of a semiconductor as compared to the rest of the region, that is, diffusion current flows in semiconductor because of unequal distribution of charge carriers.

Diffusion current density due to holes, J_p is given by

$$J_P = -q.D_P.\frac{dp}{dx}\text{ A/cm}^2$$

Diffusion current density due to electrons is given by

$$J_n = +q.D_n.\frac{dn}{dx}\text{ A/cm}^2$$

where

$\frac{dn}{dx}$ ⇒ concentration gradients of e^-'s

$\frac{dp}{dx}$ ⇒ concentration gradients of holes

NOTE

$$J_{n(diff)} = (-q).D_n\left(-\frac{dn}{dx}\right)$$

$$= qD_n . dn/dx \Rightarrow \text{i.e., } J_{n(diff)} \Rightarrow +\text{Ve sign}$$

$$J_{P(diff)} = (+q).D_p\left(-\frac{dp}{dx}\right)$$

$$= -qD_p . \frac{dp}{dx} \Rightarrow \text{i.e., } J_{p(diff)} \Rightarrow -\text{Ve sign}$$

The total current in a semiconductor is the sum of drift current and diffusion current.

$$\boldsymbol{J = I/A \text{ A/cm}^2}$$

That is, for a P-type semiconductor, the total current per unit area is given by

$$J_P = \left(p\mu_p qE - q\, D_p.\frac{dp}{dx}\right)\text{ A/cm}^2$$

Similarly, the total current density for an N-type semiconductor is given by

$$J_n = \left(n\mu_n qE + q.D_n.\frac{dn}{dx}\right)\text{ A/cm}^2$$

Einstein Relationship for Semiconductors

The equation which relates the mobility (μ) and the diffusion coefficient (D) is known as the Einstein relationship. The relationship is expressed as

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

where

$$V_T = \frac{T}{11{,}600}\text{ V}$$

$V_T = 26$ mV; At $T = 300$°K

Diffusion Length (*L*)

The average distance that an excess charge carriers can diffuse during its life time (τ) is called the diffusion length L, which is given by

$$L = \sqrt{D\tau}$$

where

$$D = \mu\ V_T$$

$$\therefore L_n = \sqrt{\mu_n . V_T . \tau_n}$$

$$L_P = \sqrt{\mu_p . V_T . \tau_p}$$

Carrier Lifetime

In a pure semiconductor, the number of holes is equal to the number of free electrons. However, due to thermal agitation, it continues to produce new hole–electron pairs, while other e^-–hole pairs disappear as a result of recombination. On an average, an electron (a hole) will exist for $\tau_n(\tau_p)$ s before recombination. This time is called the mean life time of the electron and hole.

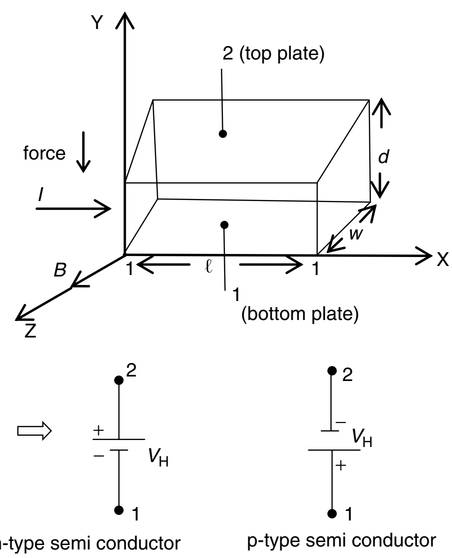
It ranges from few nanoseconds to hundreds of microseconds and depends on the temperature and impurity concentration in the semiconductor material. 'Gold' is extensively used as recombination agent.

Consider an N-type semiconductor having thermal equilibrium concentration p_{no} and n_{no} of holes and electrons. When the specimen is illuminated by light, as a result of this radiation, the new electron–hole pairs generate. Therefore, the hole and electron concentration will increase by the same amount.

$$\overline{P_{no}} - p_{no} = \overline{n_{no}} - n_{no}$$

Hall Effect

If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, then an electric field E is induced in the direction perpendicular to both I and B. This phenomenon is known as the Hall effect. This is used to determine whether a semiconductor is N-type or P-type and to find the carrier concentration.



Under the equilibrium condition, the electric field intensity E is due to the Hall effect must exist a force on the carrier charge q, which balances the magnetic force.

That is,

$$qE = B \cdot q \cdot V_d$$

$$E = B \cdot V_d \qquad (1.1)$$

Where

$v_d \Rightarrow$ drift velocity

$E \Rightarrow$ electric field due to Hall Effect

$$E = \frac{V_H}{d}$$

where d is the distance between the surfaces 1 and 2.

The current density $J = nq\,\mu_n E = \frac{I}{A}$

$$J = \rho V_d = \frac{I}{wd}$$

where $\rho \rightarrow$ charge density

$$V_H = E\,d = B \cdot d\,V_d \qquad (1.2)$$

Substituting $V_d = \frac{J}{\rho}$

$$V_H = B\,d.\frac{J}{\rho} = \frac{B\,.\,d}{\rho}\,\frac{I}{Wd}$$

$$V_H = \frac{B.I}{\rho.W}$$

Where 'ρ' $\rightarrow$ charge density

The Hall coefficient, R_H is defined by

$$R_H = \frac{1}{\rho} = \frac{1}{n\,.q}$$

$\Rightarrow$ for n-type semiconductor

$$\therefore V_H = \frac{R_H\,.B.I}{W}$$

The Hall coefficient (R_H) for a p-type semiconductor is positive and –Ve for n-type semiconductor.

NOTE

Hall voltage V_H is positive for n-type and negative for p-type semiconductor.

$$\sigma = \mu\rho;\ \mu = \sigma R_H$$

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

Example 6

A current of 15 A is passed through a thin metal strip, which is subjected to a magnetic flux density of 1.5 wb/m^2. The magnetic field is directly perpendicular to the current. If the thickness of the strip in the direction of the magnetic field is 0.5 mm, then the Hall voltage V_H = 55V, the electron density is

(A) 4.5×10^{20} atoms/m^3
(B) 5.1136×10^{21} atoms/m^3
(C) 5.25×10^{19}atoms/m^3
(D) None of the above

Solution

From the given data

$$I = 15\text{ A},\ B = 1.5\text{ wb/m}^2$$

$$W = 0.5\text{ mm at } V_H = 55\text{ V}$$

$$N_D = ?$$

We know $\quad V_H = \frac{B.I}{\rho\,W}$

But, $\quad \rho = n \cdot q$

$$N_D = n = \frac{B\,.I}{V_H\,.q.w}$$

$$\therefore n = \frac{1.5\times15}{55\times1.6\times10^{-19}\times0.5\times10^{-3}}$$

$$N_D = 5.1136 \times 10^{21}\text{ atoms/m}^3.$$

Example 7

Mobility is defined as

(a) diffusion velocity per unit electric field.
(b) drift velocity per unit electric field.
(c) displacement per unit electric field.
(d) none of the above.

Solution

We know $V_d = \mu E$

$$\mu = \frac{V_d}{E}\ \text{m}^2\text{/V-s}$$

Example 8

Match List-I (equation) with List-II (relation)

List-I	List-II
P. Continuity equation	1. Relates diffusion constant with mobility
Q. Einstein's equation	2. Relates charge density with electric field
R. Poisson's equation	3. Concentration gradient
S. Diffusion current	4. Rate of charge of minority carrier density with time

Codes:

(A) P – 4 Q – 1 R – 3 S – 2
(B) P – 4 Q – 1 R – 2 S – 3
(C) P – 1 Q – 4 R – 2 S – 3
(D) P – 1 Q – 4 R – 3 S – 2

Solution: (B)

Example 9

A Hall effect transducer can be used to measure

(A) displacement, position, and velocity
(B) displacement, temperature, and magnetic flux
(C) position, pressure, and velocity
(D) None of the above

Solution: (B)

Example 10

The Hall constant in a P-type Si bar is given by 4×10^3 cm^3/coulomb. The hole concentration in the bar is given by

(A) 1.56×10^{15}/cm^3 (B) 1.25×10^{15}/cm^3
(C) 1.56×10^{14}/cm^3 (D) 1.6×10^{15}/cm^3

Solution

$$R_H = \frac{1}{\rho} = \frac{1}{n.q}$$

$$n_A = \frac{1}{R_H.q}$$

$$= \frac{1}{4\times10^3\times1.6\times10^{-19}} = 15.625 \times 10^{14}/\text{cm}^3$$

Example 11

An n-type Si bar 0.2 cm long and 200 μm^2 in cross-sectional area has a majority carrier concentration of 5×10^{19}/m^3 and carrier mobility is 0.23 m^2/V-s at 300 K. If charge of electron is 1.6×10^{-19} C, then resistance of bar is

Solution

$$\sigma = nq\,\mu_n = 5 \times 10^{19} \times 1.6 \times 10^{-19} \times 0.23 = 1.84$$

$$\rho = \frac{1}{\sigma} = 0.5434$$

$$R = \frac{\rho l}{A} = \frac{0.5434\times0.2\times10^{-2}}{200\times10^{-12}}$$

$$= 5.434 \times 10^6\ \Omega$$

Example 12

The resistivity of a uniformly doped n-type silicon sample is 0.6 Ω-cm. If the electron mobility is 1,250 cm^2/V-s and charge of an e$^-$ is 1.6×10^{-19} C, then the donor impurity concentration (N_D) in the sample is

Solution

$$\rho = \frac{1}{nq\mu};\ n = N_D$$

$$N_D = \frac{1}{q\mu\rho}$$

$$= \frac{1}{1.6\times10^{-19}\times1250\times0.6}$$

$$= 8.33 \times 10^{15}\ \text{atoms/cm}^3$$

Example 13

The neutral base width of a bipolar transistor biased in the active region is 0.8 mm. The maximum e$^-$ concentration and diffusion constant in base are 10^{15}/cm^3 and $D_n = 30$ cm^2/s, respectively. Assume negligible recombination in base, then the collector current density is

Solution

$$J = D_n q\frac{dn}{dx} = \frac{30\times1.6\times10^{-19}\times10^{15}}{0.8\times10^{-4}} = 60\ \text{A/cm}^2$$

Example 14

For a heavily doped n-type semiconductor, parameters are as follows:

(i) Hole–electron mobility ratio is 0.4.
(ii) Doping concentration is 4.3×10^8 atoms/m^3.
(iii) Intrinsic concentration is 1.6×10^5 atoms/s.

The ratio of conductance of n-type semiconductor to that of intrinsic semiconductor of same material and at same temperature is

Solution

For n-type S.C, $\sigma_n = nq\,\mu_n$

For intrinsic S.C, $\sigma_i = n_i q\,(\mu_n + \mu_p)$

$$\frac{\sigma_n}{\sigma_i} = \frac{n\mu_n}{n_i(\mu_n+\mu_p)} = \frac{4.3\times10^8}{1.6\times10^5(1+0.4)}$$

$$= \frac{4.3\times10^8}{2.24\times10^5} = 1.91 \times 10^3$$

Example 15

If a donor impurity is added to intrinsic, then Si and resistivity at room temperature is observed to be 8 Ω cm. The ratio of donor atoms to Si atoms/unit volume is given by ($\mu_n = 1{,}350$)

Solution

$$\rho = 8$$

$$\rho = \frac{1}{N_D\mu_n q}$$

$$N_D = \frac{1}{\rho\mu_n q} = \frac{1}{8\times1350\times1.6\times10^{-19}}$$

$$= 5.7 \times 10^{14}\ \text{atoms/m}^3$$

$$\frac{\text{Donor atoms}}{\text{Si atoms}} = \frac{5.7\times10^{14}}{5\times10^{28}}$$

$$= 1.14 \times 10^{-14} \approx 10^{-14}$$

Example 16

A sample of Ge is doped to the extend of 10^{16} donor atoms/cm^3 and 7×10^{14} acceptor atoms/cm^3. At room temperature, the resistivity of pure Ge is 60 Ω cm. If applied electric field is 4 V/cm, then the concentration of holes and of electrons are, respectively, $\mu_n = 3{,}800$, $\mu_p = 1{,}800$.

Solution

$$\rho = \frac{1}{\sigma} = \frac{1}{en_i(\mu_n+\mu_p)}$$

$$n_i = \frac{1}{\rho e(\mu_n+\mu_p)}$$

$$= \frac{1}{60\times1.6\times10^{-19}(3800+1800)} = 1.86 \times 10^{13}$$

$$n \cdot p = n_i^2$$
$$n - p = N_D - N_A = 9.3 \times 10^{15}$$
$$n \cdot p = 3.45 \times 10^{26}$$
$$3.45 \times 10^{26} - p^2 = 9.3 \times 10^{15}\, p$$
$$p^2 + 9.3 \times 10^{15}\, p - 3.45 \times 10^{26} = 0$$
$$p = 3.7 \times 10^{10} \text{ atoms/cm}^3$$
$$n = 9.3 \times 10^{15} \text{ atoms/cm}^3$$

Example 17

What is Hall voltage in a Ge (n-type) donor density $10^{18}/\text{cm}^3$, B = 0.6 wb/m^2, $J = 400$ A/m^2, that is 4 mm thick?

Solution

$$R_H = \frac{E_x}{J_Z B_Y} = \frac{3\pi}{8} \times \frac{1}{nq}$$

$$E_X = \frac{0.6 \times 400 \times 1.18}{1.6 \times 10^{-19} \times \dfrac{10^{18}}{10^{-6}}} = 1.77 \times 10^{-3} \text{ V/m}$$

$$V = E \times t$$
$$= 1.77 \times 10^{-3} \times 4 \times 10^{-3} = 7.08\ \mu\text{V}$$

Exercises

Practice Problems I

Direction for questions 1 to 22: Select the correct alternative from the given choices.

1. If donor impurity is added to the extent of 1 impurity atom in 10^7 Ge atoms, then the conductivity changes to________
   (A) 30.4 ℧/cm (B) 3.04 ℧/cm
   (C) 1.275 ℧/cm (D) 12.75 ℧/cm
2. Find the ratio of conductivity of n-type silicon doped with 1 in 10^8 Si atoms to that of intrinsic Si at room temperature.
   (A) 204 (B) 20,400
   (C) 2,040 (D) 2,400
3. Find the conductivity of Ge, when doped simultaneously with 1 donor in 10^6 Ge atoms and 1 acceptor in 10^7 Ge atoms.
   (A) 24.08 ℧/cm (B) 2.408 ℧/cm
   (C) 26.57 ℧/cm (D) 2.657 ℧/cm
4. Calculate the electron and hole concentrations of extrinsic Si sample, when the conductivity is minimum, given $\mu_n = 1{,}350$ and $\mu_p = 450$ cm^2/vs.
   (A) 86.6×10^7 and 2.6×10^{10} per cm^3
   (B) 866×10^7 and 2.6×10^{10} per cm^3
   (C) 866×10^7 and 26.6×10^{10} per cm^3
   (D) 2.6×10^{10} and 866×10^7 per cm^3
5. If the resistivity of p-type Si bar is 0.12 Ω cm, then electron and hole concentrations per cm^3______, respectively.
   (A) 1.69×10^5, 2.06×10^5
   (B) 1.96×10^5, 2.06×10^5
   (C) 2.06×10^5, 1.69×10^5
   (D) 2.06×10^5, 1.96×10^{15}
6. A 1-kΩ resistor is to be fabricated using a p-type silicon bar with 4 mm thick, 20 μm wide, and 400 μm long. The required acceptor concentration is ________
   (A) 65×10^{22} per m^3 (B) 65×10^{21} per m^3
   (C) 6.5×10^{22} per m^3 (D) 6.5×10^{21} per m^3
7. A sample of Ge is doped to the extent of 2×10^{14} donor atoms/cm^3 and 1.5×10^{14} acceptors/cm^3. At temperature of sample, the resistivity of pure Ge is 80 Ω cm. If the applied electric field is 5 v/cm. Find the total current density?
   (A) 0.168 A/m^2 (B) 1.68 A/cm^2
   (C) 0.168 A/cm^2 (D) 1.68 A/m^2
8. A block of silicon is doped with a donor atom density of $3 \times 10^{14}/\text{cm}^3$ and acceptor atom density of $0.5 \times 10^{14}/\text{cm}^3$. Determine the resultant densities of free electrons and holes per cm^3
   (A) 2.5×10^{14}, 9×10^6 (B) 2.5×10^{13}, 0.9×10^6
   (C) 2.5×10^{14}, 0.9×10^6 (D) 0.9×10^6, 2.5×10^{14}
9. Calculate the drift velocity of electrons and holes in a 1 mm length of silicon bar at room temperature, if the applied voltage is 10 v.
   (A) 1,300 cm/s, 500 cm/s (B) 500 cm/s, 1,300 cm/s
   (C) 500 m/s, 1,300 m/s (D) 1,300 m/s, 500 m/s
10. A sample of Ge is doped with 10^{14} donors/cm^3 and 7×10^{13} acceptor/cm^3. At temperature of the sample, the resistivity of pure Ge is 60 Ω cm. Find the applied electric field, if the total current density is 52.3 mA/cm^2.
    ($\mu_n = 3{,}800$ cm^2/Vs)
    ($\mu_p = 1{,}800$ cm^2/Vs)
    (A) 2 V/cm (B) 20 V/cm
    (C) 2 V/m (D) 20 V/m
11. In a semiconductor, effective mass of electron is 0.07 m and effective mass of hole is 0.4 m, where *m* is a free electron mass. Assume average relaxation time for the holes is half that of electrons. Find the mobility of holes, if the mobility of electrons is 0.8 m^2/vs
    (A) 7 m^2/s (B) 70 m^2/s
    (C) 0.7 m^2/s (D) 0.07 m^2/s
12. A cylindrically shaped section of n-type silicon has 1 mm length and 0.1 mm^2 cross-sectional area. The ratio of resistance of pure Ge to that of Ge doped with 8×10^{13} donors/cm^3 approximately ______

(A) 300 (B) 4,000
(C) 5,000 (D) 6,000
Assume μ_n = 1,500 cm²/vs and μ_p = 500 cm²/vs

13. In an n-type Ge, the conductivity is measured to be 10^3 ℧/m for an impurity concentration of 10^{22} donors/cm³. The values of mobility and relaxation time of electron are, if $q = 10^{-19}$ and $m = 10^{-31}$ kg
(A) 1 m²/vs, 10^{-9} s (B) 10 m²/vs, 10^{-12} s
(C) 10 m²/vs, 10^{-9} s (D) 1 m²/vs, 10^{-12} s

14. Find the magnitude of the Hall voltage in an n-type silicon bar, with majority carriers' concentration of 10^{13} donors/cm³. Assume d = 5 mm, B_z = 0.2 wb/m² and E_x = 5 v/cm.
(A) 65 v (B) 6.5 v
(C) 0.65 v (D) 65 mv

15. Find the mobility of holes using Hall experiment, if the resistivity of the bar is 200,000 Ωcm, B_z = 0.1 wb/m², and $d = w$ = 2 mm. The measured values of current and Hall voltage are 5 µA and 30 mV, respectively.
(A) 600 cm²/Vs (B) 1,200 cm²/Vs
(C) 1,500 cm²/Vs (D) 6,000 cm²/Vs

16. A Ge sample is oriented normal to 0.5 T magnetic field, when a current of 1 mA is passed through it by applying a potential difference of 400 mv. Calculate Hall voltage, if concentration of majority carriers = 5.2×10^{19}/m³, l = 2 cm, and $w = d$ = 1 cm.
(A) 6 mV (B) 60 mV
(C) 30 mV (D) 150 mV

17. A P-type silicon semiconductor bar with resistivity 300,000 Ωcm is placed in a transverse magnetic field of 0.1 wb/m² and $d = w$ = 6 mm. If the measured values of current flowing through and Hall voltage are 10 µA and 60 mv, respectively, find mobility of holes.
(A) 1,200 cm²/Vs (B) 2,400 cm²/Vs
(C) 1,800 cm²/Vs (D) 1,500 cm²/Vs

18. Calculate the position of Fermi level relative to intrinsic Fermi level in silicon at 300 K, if the doping concentration is 10^{16} donors/cm³.
(A) E_{Fn} is 0.347 eV above E_{Fi}
(B) E_{Fn} is 0.347 eV below E_{Fi}
(C) E_{Fn} is 0.203 eV above E_{Fi}
(D) E_{Fn} is 0.203 eV below E_{Fi}

19. A Si sample is doped with 6×10^{15} donors/cm³ and 2×10^{15} acceptors/cm³. Find the position of Fermi level with respect to intrinsic Fermi level at 300 K.
(A) $E_{Fn} - E_{Fi} = 0.324$ eV (B) $E_{Fn} - E_{Fi} = -0.324$ eV
(C) $E_{Fn} - E_{Fi} = 0.226$ eV (D) $E_{Fn} - E_{Fi} = -0.226$ eV

20. Find the temperature at which there is 1% probability that a state with an energy 0.2 ev above the Fermi level will be occupied by the electron.
(A) 450 K (B) 505 K
(C) 450°C (D) 505°C

21. A Ge sample is doped with 1 phosphorous atom per 10^8 Ge atoms. Assume effective mass of electron is half of its true mass. At what doping level (N_D), Fermi level coincides with conduction band edge?
(A) 4.42×10^{18} per cm³ (B) 4.42×10^{22} per cm³
(C) 8.87×10^{22} per cm³ (D) 8.87×10^{18} per cm³

22. For Ge, if the forbidden gap width is 0.67 eV, then the position of Fermi level at 300°K if effective mass of hole is 5 times the effective mass of electron.
(A) 0.335 eV (B) 0.367 eV
(C) 0.303 eV (D) 0.67 eV

Practice Problems 2

Direction for questions 1 to 21: Select the correct alternative from the given choices.

1. The conductivity of Ge at room temperature is ______, if the mobility of electrons and holes are 3,800 and 1,800 cm²/vs, respectively
(A) 22.4 ℧/cm (B) 2.24 ℧/cm
(C) 0.224 ℧/cm (D) 0.0224 ℧/cm

2. The change in resistivity of n-type Ge with 1 donor per 10^9 Ge atoms to that of intrinsic Ge is______
(A) 10 Ωcm (B) 12.6 Ωcm
(C) 16.2 Ωcm (D) 1.26 Ωcm

3. A block of Ge is doped with 8×10^{13} donors/cm³ and 5×10^{13} acceptors/cm³. Determine free electron and hole concentrations per cm³______
(A) 6×10^{13}, 2×10^{13}
(B) 4.45×10^{13}, 1.4×10^{13}
(C) 1.4×10^{13}, 4.45×10^{13}
(D) 2×10^{13}, 6×10^{13}

4. Determine the concentration of free electrons and holes in a sample of Ge at 300°K, which has a concentration of 2×10^{14} donors/cm³ and 3×10^{14} acceptors/cm³.
(A) 6×10^{12} electrons/cm³, 5×10^{15} holes/cm³
(B) 5×10^{12} electrons/cm³, 6×10^{15} holes/cm³
(C) 6×10^{12} electrons/cm³, 1.06×10^{14} holes/cm³
(D) 1.06×10^{14} electrons/cm³, 6×10^{12} holes/cm³

5. If silicon was a monovalent metal, find the ratio of its conductivity to that of intrinsic silicon at 300 K.
(A) 2.39×10^{-12} (B) $2.39 \times 10^{+12}$
(C) 2.39×10^{-6} (D) $2.39 \times 10^{+6}$

6. Find the electric field required to give an electron in silicon with an average energy of 1 eV
(A) 4.56 kV/cm (B) 45.6 kV/cm
(C) 456 V/cm (D) 4.56 MV/cm

7. For an intrinsic silicon of cross-sectional area of 5 cm² and length of 0.5 cm, find the electron and hole component of current density, if the applied electric field is 20 v/cm

(A) 67.2 μA/cm^2, 21.6 μA/cm^2
(B) 67.2 μA/m^2, 21.6 μA/m^2
(C) 134.4 μA/cm^2, 43.2 μA/cm^2
(D) 134.4 μA/m^2, 43.2 μA/m^2

8. An n-type silicon bar has resistivity of 1,000 Ωcm. If the current is 10 μA and Hall voltage is 40 mv, calculate intensity of magnetic field. Assume $w = 1$ cm.
(A) 30.8 wb/m^2 (B) 0.308 wb/m^2
(C) 61.6 wb/m^2 (D) 0.616 wb/m^2

9. Let the Hall effect could not be observed in a Ge sample, whose conduction electron mobility is 2.1 times that of holes. Find the ratio of conduction electron and hole concentrations.
(A) 1:2.21 (B) 1:4.41
(C) 2.21:1 (D) 4.41:1

Direction for questions 10 and 11: In the Hall effect experiment, a p-type semiconductor bar of width 1 cm and length of 5 cm is placed in the magnetic field of 0.5 T. A potential difference of 10 v is applied across the edges given V_H = 0.05 v and $\sigma = 2.5 \times 10^{-2}$ Ωcm.

10. Determine Hall coefficient, R_H in m^3/G
(A) 1.25 (B) 1.25×10^{-3}
(C) $1.25 \times 10^{+3}$ (D) 4×10^{-3}

11. Concentration of holes and their mobility
(A) 5×10^{15} per m^3, 0.05 m^2/vs
(B) 5×10^{15} per cm^3, 0.05 m^2/vs
(C) 5×10^{21} per m^3, 5 m^2/vs
(D) 5×10^{21} per m^3, 50 m^2/vs

12. A sample of silicon is doped with 10^{17} phosphorous atoms/cm^3. Find the Hall voltage, if the sample has 100 μm thick, $I_x = 1$ mA and $B_z = 10^{-5}$ wb/m^2?
(A) 62.5 μv (B) 62.5 mv
(C) –62.5 μv (D) –62.5 mv

13. Find the displacement of E_{Fi} (intrinsic Fermi level) to the centre of band gap, $\frac{E_G}{2}$ for silicon at 300°K. Assume effective mass values of electrons and holes are 1.1 m and 0.56 m, respectively.
(A) E_{Fi} is 26 MeV below $E_{G/2}$
(B) E_{Fi} is 26 MeV below $E_{G/2}$
(C) E_{Fi} is 13 MeV above $E_{G/2}$
(D) E_{Fi} is 13 MeV below $E_{G/2}$

14. A silicon sample is doped with 10^{17} arsenic atoms/cm^3. Find equilibrium hole concentration p_o at 300 K
(A) 1.5×10^3 per cm^3
(B) 2.25×10^3 per cm^3
(C) 1.5×10^7 per cm^3
(D) 2.25×10^7 per cm^3

15. The relative position of Fermi level with respect to intrinsic Fermi level ($E_{Fn} - E_{Fi}$) is ________
(A) –0.407 eV (B) –0.143 eV
(C) 0.407 eV (D) +0.143 eV

16. In an n-type semiconductor, if the Fermi level lies 0.6 eV below the conduction band at 300 K. Find the new position of Fermi level at 330 K
(A) 0.33 eV below conduction band edge
(B) 0.33 eV above conduction band edge
(C) 0.66 eV above conduction band edge
(D) 0.66 eV below conduction band edge

17. In an n-type semiconductor, Fermi level lies 0.02 eV below the conduction band edge. If the donor concentration is increased by 4 times, find the new position of Fermi level.
(A) 0.165 eV above conduction band edge
(B) 0.165 eV below conduction band edge
(C) 0.165 eV above $E_G/2$
(D) 0.165 eV below $E_G/2$

18. If the effective mass electron is 3 times the effective mass of hole, then the distance of Fermi level in an intrinsic semiconductor from the centre of forbidden band at room temperature.
(A) E_{Fi} is 21 MeV above $E_G/2$
(B) E_{Fi} is 21 MeV below $E_G/2$
(C) E_{Fi} is 42 MeV above $E_G/2$
(D) E_{Fi} is 42 MeV below $E_G/2$

19. An Si sample is doped with 1 donor atom per 2×10^8 silicon atoms. Assume effective mass of electron is same as its true mass. Find the temperature at which Fermi level coincides with conduction band edge.
(A) 14° K (B) 14°C
(C) 0.14° K (D) 0.14°C

20. How much donor impurity should be added to pure Ge, so that its resistivity drops to 10% of its original value?
(A) $N_D = 3.68 \times 10^{14}$ per m^3
(B) $N_D = 3.68 \times 10^{14}$ per cm^3
(C) $N_D = 3.68 \times 10^{16}$ per cm^3
(D) $N_D = 3.68 \times 10^{16}$ per m^3

21. Find the intrinsic carrier concentration of Ge at 400°K.
(A) 1.732×10^{15} per cm^3
(B) 1.732×10^{13} per cm^3
(C) 2.5×10^{13} per cm^3
(D) 2.5×10^{15} per cm^3

Previous Years' Questions

1. The impurity commonly used for realizing the base region of a silicon n-p-n transistor is **[2004]**
(A) gallium (B) indium
(C) boron (D) phosphorus

2. The resistivity of a uniformly doped n-type silicon sample is 0.5 Ωcm. If the electron mobility (μ_n) is 1,250 cm^2/Vs and the charge of an electron is 1.6×10^{-19} C, the donor impurity concentration (N_D) in the sample is **[2004]**
(A) $2 \times 10^{16}/cm^3$ (B) $1 \times 10^{16}/cm^3$
(C) $2.5 \times 10^{15}/cm^3$ (D) $2 \times 10^{15}/cm^3$

3. The neutral base width of a bipolar transistor biased in the active region is 0.5 µm. The maximum electron concentration and the diffusion constant in the base are $10^{14}/cm^3$ and $D_n = 25$ cm^2/s, respectively. Assuming negligible recombination in the base, the collector current density is (the electron charge is 1.6×10^{-19} Coulomb) **[2004]**
(A) 800 A/cm^2 (B) 8 A/cm^2
(C) 200 A/cm^2 (D) 2 A/cm^2

4. The band gap of silicon at room temperature is **[2005]**
(A) 1.3 eV (B) 0.7 eV
(C) 1.1 eV (D) 1.4 eV

5. The primary reason for the widespread use of silicon in semiconductor device technology is **[2005]**
(A) abundance of silicon on the surface of the earth
(B) larger band gap of silicon in comparison to germanium.
(C) favourable properties of silicon dioxide (SiO_2)
(D) low melting point

6. A silicon sample A is doped with 10^{18} atoms/cm^3 of boron. Another sample B of identical dimensions is doped with 10^{18} atoms/cm^3 of phosphorus. The ratio of electron to hole mobility is 3. The ratio of conductivity of the sample A to B is **[2005]**
(A) 3 (B) $\frac{1}{3}$
(C) $\frac{2}{3}$ (D) $\frac{3}{2}$

7. The concentration of minority carriers in an extrinsic semiconductor under equilibrium is **[2006]**
(A) directly proportional to the doping concentration
(B) inversely proportional to the doping concentration
(C) directly proportional to the intrinsic concentration
(D) inversely proportional to the intrinsic concentration

8. Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the **[2006]**
(A) diffusion current
(B) drift current
(C) recombination current
(D) induced current

9. The majority carries in an n-type semiconductor have an average drift velocity V in a direction perpendicular to a uniform magnetic field B. The electric field E induced to Hall effect acts in the direction **[2006]**
(A) $V \times B$ (B) $B \times V$
(C) along V (D) opposite to V

10. A heavily doped n-type semiconductor has the following data:
Hole–electron mobility ratio: 0.4
Doping concentration: 4.2×10^8 atoms/m^3
Intrinsic concentration: 1.5×10^4 atoms/m^3
The ratio of conductance of the n-type semiconductor to that of the intrinsic semiconductor of same material and at the same temperature is given by **[2006]**
(A) 0.00005 (B) 2,000
(C) 10,000 (D) 20,000

11. The electron and hole concentrations in an intrinsic semiconductor are n_i per cm^3 at 300°K. Now, if acceptor impurities are introduced with a concentration of N_A per cm^3 (where $N_A >> n_i$), the electron concentration per cm^3 at 300 K will be **[2007]**
(A) n_i (B) $n_i + N_A$
(C) $N_A - n_i$ (D) $\frac{n_i^2}{N_A}$

12. Which of the following is true? **[2008]**
(A) A silicon wafer heavily doped with boron is a p^+ substrate
(B) A silicon wafer lightly doped with boron is a p^+ substrate
(C) A silicon wafer heavily doped with arsenic is a p^+ substrate
(D) A silicon wafer lightly doped with arsenic is a p^+ substrate

13. Silicon is doped with boron to a concentration of 4×10^{17} atoms/cm^3. Assuming the intrinsic carrier concentration of silicon to be $1.5 \times 10^{10}/cm^3$ and the value of $\frac{kT}{q}$ to be 25 mV at 300 K.
When compared to undoped silicon, the Fermi level of doped silicon **[2008]**
(A) goes down by 0.13 eV
(B) goes up by 0.13 eV
(C) goes down by 0.427 eV
(D) goes up by 0.427 eV

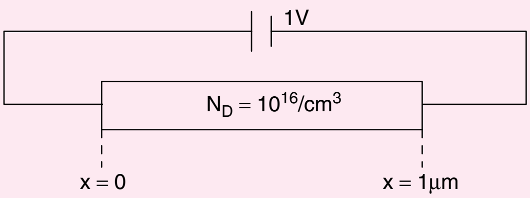
14. In an n-type silicon crystal at room temperature, which of the following can have a concentration of 4×10^{19} cm^{-3}? **[2009]**

(A) Silicon atoms (B) Holes
(C) Dopant atoms (D) Valence electrons

15. At room temperature, a possible value for the mobility of electrons in the inversion layer of a silicon n-channel MOSFET is **[2010]**

(A) 450 cm^2/Vs (B) 1,350 cm^2/Vs
(C) 1,800 cm^2/Vs (D) 3,600 cm^2/Vs

Direction for questions 16 and 17: The silicon sample with unit cross-sectional area shown in the following figure is in thermal equilibrium. The following information is given: T = 300 K, electronic charge = 1.6×10^{-19} C, thermal voltage = 26 mV and electron mobility = 1,350 cm^2/Vs **[2010]**



16. The magnitude of the electric field at x = 0.5 μm is **[2010]**

(A) 1 kV/cm (B) 5 kV/cm
(C) 10 kV/cm (D) 26 kV/cm

17. The magnitude of the electron drift current density at x = 0.5 μm is **[2010]**

(A) 2.16×10^4 A/cm^2 (B) 1.08×10^4 A/cm^2
(C) 4.32×10^3 A/cm^2 (D) 6.48 x 10^2 A/cm^2

18. Drift current in semiconductors depends upon **[2011]**

(A) only the electric field
(B) only the carrier concentration gradient
(C) both the electric field and the carrier concentration
(D) both the electric field and the carrier concentration gradient.

19. The source of a silicon ($n_i = 10^{10}$ per cm^3) n-channel MOS transistor has an area of 1 μm^2 and a depth of 1 μm. If the dopant density in the source is 10^{19}/cm^3, the number of holes in the source region with the abovementioned volume is approximately **[2012]**

(A) 10^7 (B) 100
(C) 10 (D) 0

20. The doping concentrations on the p-side and n-side of a silicon diode are 1×10^{16} cm^{-3} and 1×10^{17} cm^{-3}, respectively. A forward bias of 0.3 V is applied to the diode. At T = 300 K, the intrinsic carrier concentration of silicon $n_i = 1.5 \times 10^{10}$ cm^{-3} and $\frac{kT}{q}$ = 26 mV.

The electron concentration at the edge of the depletion region on the p-side is **[2014]**

(A) 2.3×10^9 cm^{-3} (B) 1×10^{16} cm^{-3}
(C) 1×10^{17} cm^{-3} (D) 2.25×10^6 cm^{-3}

21. A silicon bar is doped with donor impurities $N_D = 2.25 \times 10^{15}$ atoms/cm^{-3}. Given the intrinsic carrier concentration of silicon at T = 300 K is $n_i = 1.5 \times 10^{10}$ cm^{-3}. Assuming complete impurity ionization, the equilibrium electron and hole concentrations are **[2014]**

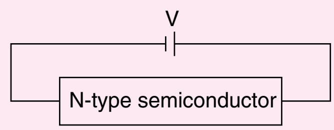
(A) $n_0 = 1.5 \times 10^{16}$ cm^{-3}, $p_0 = 1.5 \times 10^5$ cm^{-3}
(B) $n_0 = 1.5 \times 10^{10}$ cm^{-3}, $p_0 = 1.5 \times 10^{15}$ cm^{-3}
(C) $n_0 = 2.25 \times 10^{15}$ cm^{-3}, $p_0 = 1.5 \times 10^{10}$ cm^{-3}
(D) $n_0 = 2.25 \times 10^{15}$ cm^{-3}, $p_0 = 1 \times 10^5$ cm^{-3}

22. Assume electronic charge $q = 1.6 \times 10^{-19}$ C, kT/q = 25 mV and electron mobility μ_n = 1,000 cm^2/Vs. If the concentration gradient of electrons injected into a P-type silicon sample is 1×10^{21}/cm^3, the magnitude of electron diffusion current density (in A/cm^2) is ______. **[2014]**

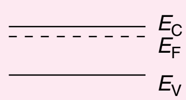
23. At T = 300 K, the hole mobility of a semiconductor μ_p = 500 cm^2/Vs and $\frac{kT}{q}$ = 26 mV. The hole diffusion constant D_p in cm^2/s is ______. **[2014]**

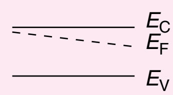
24. Consider a silicon sample doped with $N_D = 1 \times 10^{15}$/cm^3 donor atoms. Assume that the intrinsic carrier concentration $n_i = 1.5 \times 10^{10}$/cm^3. If the sample is additionally doped with $N_A = 1 \times 10^{18}$/cm^3 acceptor atoms, the approximate number of electrons/cm^3 in the sample at T = 300 K will be ______. **[2014]**

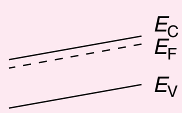
25. An N-type semiconductor having uniform doping is biased as shown in the figure

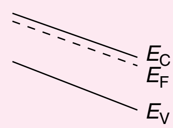


If E_C is the lowest energy level of the conduction band, E_V is the highest energy level of the valence band, and E_F is the Fermi level, which one of the following represents the energy band diagram for the biased N-type semiconductor? **[2014]**

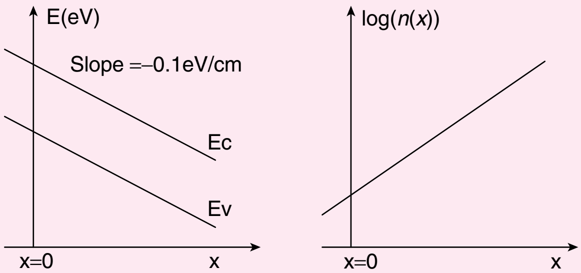
(a) 

(b) 

(c) 

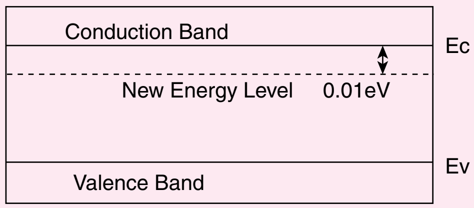
(d) 

26. The energy band diagram and the electron density profile $n(x)$ in a semiconductor are shown in the figures. Assume that $n(x)$ = 1015 $e^{(q\alpha x/kT)}$ cm–3, with α = 0.1 V/cm and x expressed in cm. Given $\frac{kT}{q}$ = 0.026 V, D_n = 36 cm^2 s^{-1}, and $\frac{D}{\mu} = \frac{kT}{q}$. The electron current density (in A/cm^2) at x = 0 is **[2015]**



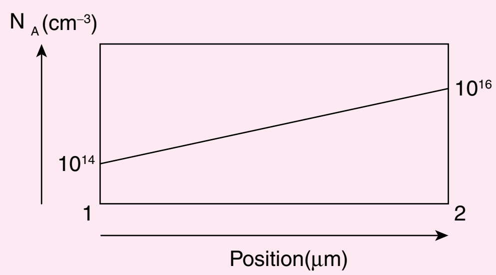
(A) -4.4×10^{-2}
(B) -2.2×10^{-2}
(C) 0
(D) 2.2×10^{-2}

27. A small percentage of impurity is added to an intrinsic semiconductor at 300K. Which one of the following statements is true for the energy band diagram shown in the following figure? **[2016]**



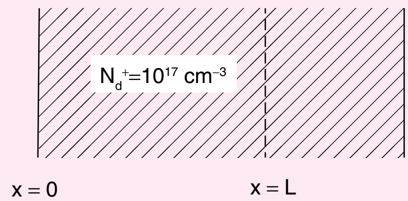
(A) Intrinsic semiconductor doped with pentavalent atoms to form n-type semiconductor.
(B) Intrinsic semiconductor doped with trivalent atoms to form n-type semiconductor.
(C) Intrinsic semiconductor doped with pentavalent atoms to form p-type semiconductor.
(D) Intrinsic semiconductor doped with trivalent atoms to form p-type semiconductor.

28. The figure shows the doping distribution in a *p*-type semiconductor in log scale.



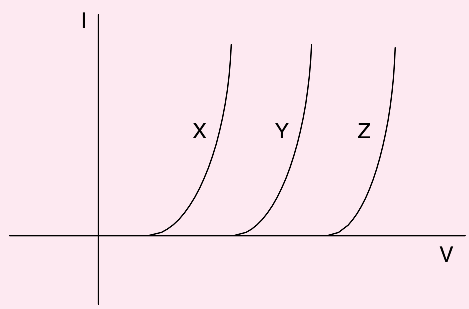
The magnitude of the electric field (in kV/cm) in the semiconductor due to non uniform doping is ________ . **[2016]**

29. Consider a region of silicon devoid of electrons and holes, with an ionized donor density of $N_a^+ = 10^{17}$ cm^{-3}. The electric field at $x = 0$ is 0 V/cm and the electric field at $x = L$ is 50 kV/cm in the positive x direction. Assume that the electric field is zero in the y and z directions



Given $q = 1.6 \times 10^{-19}$ coulomb, $\in_0 = 8.85 \times 10^{-14}$ F/cm, $\in_r = 11.7$ for silicon, the value of L in nm is ________. **[2016]**

30. The I – V characteristics of three types of dioes at the room temperature, made of semiconductors X, Y and Z are shown in the figure. Assume that the diodes are uniformly doped and identical in all respects except their materials. If E_{gx}, E_{gy} and E_{gz} are the band gaps of X, Y and Z respectively, then **[2016]**



(A) $E_{gx} > E_{gy} > E_{gz}$
(B) $E_{gx} = E_{gy} = E_{gz}$
(C) $E_{gx} < E_{gy} < E_{gz}$
(D) No relationship among these band gaps exists.

Answer Keys

Exercises

Practice Problems 1

1. B	**2.** B	**3.** A	**4.** B	**5.** C	**6.** A	**7.** C	**8.** C	**9.** D	**10.** A
11. D	**12.** B	**13.** D	**14.** D	**15.** A	**16.** A	**17.** A	**18.** A	**19.** A	**20.** B
21. D	**22.** B								

Practice Problems 2

1. D	**2.** B	**3.** B	**4.** C	**5.** B	**6.** B	**7.** A	**8.** B	**9.** B	**10.** B
11. A	**12.** C	**13.** D	**14.** B	**15.** C	**16.** D	**17.** A	**18.** B	**19.** C	**20.** D
21. A									

Previous Years' Questions

1. C	**2.** C	**3.** B	**4.** C	**5.** A	**6.** B	**7.** B	**8.** A	**9.** B	**10.** D
11. D	**12.** A	**13.** C	**14.** C	**15.** B	**16.** C	**17.** A	**18.** C	**19.** D	**20.** A
21. D	**22.** 3,990 to 4,010		**23.** 13 cm^2/s		**24.** 225	**25.** D	**26.** C	**27.** A	
28. 1010 to 1.25			**29.** 32.35nm		**30.** C				