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ELECTRONIC DEVICES & CIRCUITS

For

ELECTRONICS & COMMUNICATION ENGINEERING

ELECTRONIC DEVICES & CIRCUITS

SYLLABUS

Energy bands in silicon, intrinsic and extrinsic silicon. Carrier transport in silicon: diffusion current, drift current, mobility, and resistivity. Generation and recombination of carriers.p-n junction diode, Zener diode, tunnel diode, BJT, JFET, MOS capacitor, MOSFET, LED, P-I-N and avalanche photo diode, Basics of LASERs.
Device technology: integrated circuits fabrication process, oxidation, diffusion, ion implantation, photolithography, n-tub, p-tub and twin-tub CMOS process.

ANALYSIS OF GATE PAPERS

Exam Year	1 Mark Ques.	2 Mark Ques.	Total
2003	5	5	15
2004	3	7	17
2005	3	3	9
2006	4	4	12
2007	2	6	14
2008	4	4	12
2009	2	3	8
2010	2	4	10
2011	3	3	9
2012	1	3	7
2013	3	-	3
2014 Set-1	2	5	12
2014 Set-2	3	3	9
2014 Set-3	3	4	11
2014 Set-4	3	4	11
2015 Set-1	2	2	6
2015 Set-2	2	3	8
2015 Set-3	2	2	6
2016 Set-1	3	4	11
2016 Set-2	3	4	11
2016 Set-3	3	3	9
2017 Set-1	3	4	11
2017 Set-2	3	4	44

CONTENTS

1 SEMICONDUCTORS

1.1 STRUCTURE OF AN ATOM

Matter has mass and takes up space. Atoms are basic building blocks of matter, and cannot be chemically subdivided by ordinary means. Atoms are composed of three types of particles: **proton**, **neutron**, and **electron**. Proton and neutron are responsible for most of the atomic mass. The mass of an electron is very small

$m_n = 9.108X10^{-31}$ kg

Both the protons and neutrons reside in the nucleus. Protons have a positive (+) charge, neutrons have no charge i.e. they are neutral. Electrons reside in orbitals around the nucleus. They have a negative charge (-). The electrons of an atom are bound to the nucleus by the electromagnetic force. Likewise, a group of atoms can remain bound to each other by chemical bonds based on the same force, forming a molecule.

An atom containing an equal number of protons and electrons is electrically neutral; otherwise it is positively or negatively charged and is known as an **ion**. It is the number of protons that determines the atomic number .

e.g. no. of protons in the nucleus of silicon is 14 hence atomic no. of Si=14.

All atoms would like to attain electron configurations like noble gases. That is, have completed outer shells. Atoms can form stable electron configurations like noble gases by:

1. Losing electrons
2. Sharing electrons
3. Gaining electrons.

For a stable configuration each atom must fill its outer energy level. In the case of noble gases that means eight electrons in the last shell (with the exception of He which has two electrons). Atoms that have 1, 2 or 3 electrons in their outer levels will tend to lose them in interactions with atoms that have 5, 6 or 7 electrons in their outer levels. Atoms that have 5, 6 or 7 electrons in their outer levels will tend to gain electrons from atoms with 1, 2 or 3 electrons in their outer levels. Atoms that have 4 electrons in the outer most energy level will tend to neither totally lose nor totally gain electrons during interactions.

1.2 ENERGY BAND THEORY

In solid-state physics, the electronic band structure (or simply band structure) of a solid describes those ranges of energy that an electron within the solid may have (called allowed or permitted bands), and ranges of energy that it may not have (called forbidden bands).

Out of all the energy bands, three bands are most important to understand the behavior of solids. These bands are,

1) Valence band
2) Conduction band
3) Forbidden band or gap

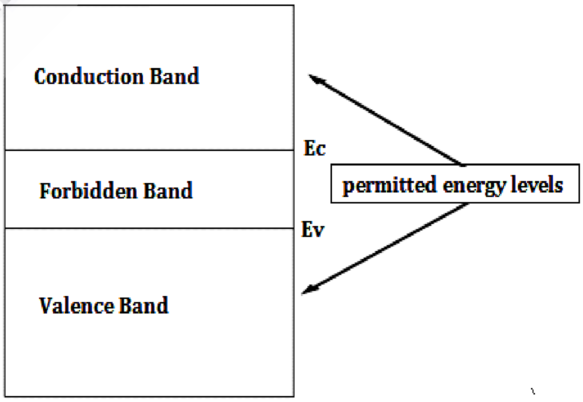


Fig. Energy Band Diagram

The energy band formed due to merging energy levels associated with the valence electrons i.e. electrons in the last shell is called **valence band.** In normal condition, valence electrons form the covalent bands and are not free. But when certain energy is imparted to them, they become free.

The energy band formed due to merging of energy levels associated with the free electrons is called **conduction band.** Under normal condition, the conduction band is empty and once energy is imparted, the valence electrons jump from valence band to conduction band and become free.
While jumping from valence band to conduction band, the electrons have to cross an energy gap. This energy gap which is present separating the conduction band and the valence band is called **forbidden band** or **forbidden gap.** The energy imparted to the electrons must be greater than the energy associated with the forbidden gap, to extract the electrons from valence band and transfer them to conduction band. The energy associated to forbidden band is denoted as E_G.
The graphical representation of the energy bands in a solid is called **energy band diagram**
Note:-The electrons cannot exist in the forbidden gap.

1.2.1 UNIT OF ENERGY eV

The unit joule is very large for the energies associated with electrons. Hence such energies are measured in electron volts denoted as eV. 1 eV is defined as the kinetic energy gained by an electron when it falls through a potential of one volt.

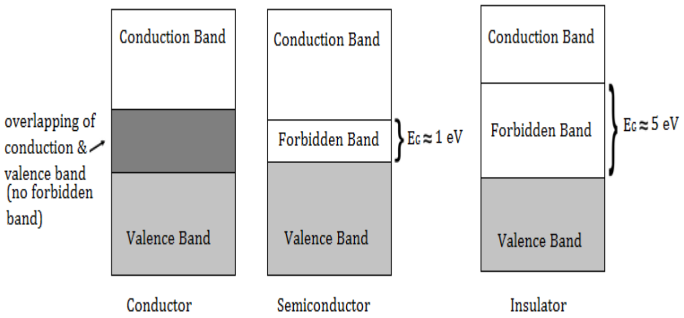
$1\text{eV} = 1.6\times10^{-19}\text{J}$

1.3 CLASSIFICATION OF MATERIALS

Based on the properties shown at different surrounding conditions, materials are classified as

1.3.1 CONDUCTORS

In the metals there is no forbidden gap between valence band and conduction band i.eE_G = 0 eV. The conduction band & valence band are overlapped in conductors**.** Hence even at room temperature, a large number of electrons are available for conduction. So without any additional energy, such metals contain a large number of free electrons and hence called good conductors.



1.3.2 SEMICONDUCTORS

Semiconductors are those materials whose electrical conductivity is between conductors and insulators. The forbidden gap in semiconductors is about 1 eve. In semiconductors the energy provided by heat at room temperature is sufficient to lift electrons from valence band to conduction band. But at T=0 ^{o}.k. (absolute zero or −273^{o}C), all the electrons find themselves in valence band hence S.C. behaves as perfect insulators at T = 0^{o}K. The forbidden energy band gap in semiconductors depends on temperature & it is given by

$$E_{G\,at\,T^oK} = E_{0^oK} - \beta_o T\ \text{eV}$$

where,

$\beta_o = 3.6\times10^{-4}\text{eV}/{}^oK$ for silicon

$\beta_o = 2.2\times10^{-4}\text{eV}/{}^oK$ for germanium

$E_{0^oK} = 1.21\text{eV}$ for silicon

$E_{0^oK} = 0.785\text{eV}$ for germanium

Using above equations the forbidden band gap for silicon and germanium at T = 300^{o}K i.e. at room temperature are **1.1 eV&0.72 eV** respectively.

Example:
E_G for Ge at 0°K = 0.785eV. Calculate E_G at T = 350°K.
Solution:
Given, E_{GO} = 0.785eV

$$E_G atT = 350°K = E_{GO} - 2.2\times10^{-4}\times350$$
$$= 0.785 - 2.2\times10^{-4}\times350 = 0.708eV$$

1.3.3 INSULATORS

An insulator has an energy band diagram as shown in the Fig. In case of such insulating material; there exists a large forbidden gap in between the conduction band and the valence band. Practically it is impossible for an electron to jump from the valence band to the conduction band. Hence such materials cannot conduct and called insulators. The forbidden gap is very wide, approximately of about 5 ev.

1.4 FERMI DIRAC FUNCTION

The equations for f(E) is called the Fermi – Dirac probability function, and specifies the fraction of all states at energy E (electron volts) occupied under conditions of thermal equilibrium

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

Where,
k = Boltzmann constant, eV/°K
T = Temperature in °K
E_F =Fermi level or characteristic energy in eV

Def: The Fermi level represents the energy state with 50 percent probability of being filled (i.e. 50% probability of finding an electron at this energy level) if no forbidden band exists.

Case-1

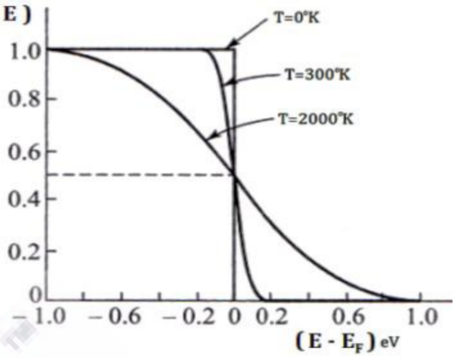
If E = E_F then $f(E) = \frac{1}{2}$ for any value of temperature

Case-2:-

When T = 0°K& if E > E_F, the exponential term becomes infinite and f(E) = 0.
It means at all energy levels above E_F the probability of finding an electron is 0 atT = 0°K.

Case-3

When T = 0°K& if E > E_F, the exponential term becomes zero andf(E) = 1.
It means at all energy levels below E_F the probability of finding an electron is 1 at T = 0°K
A plot of f(E) versus E − E_F is shown in fig

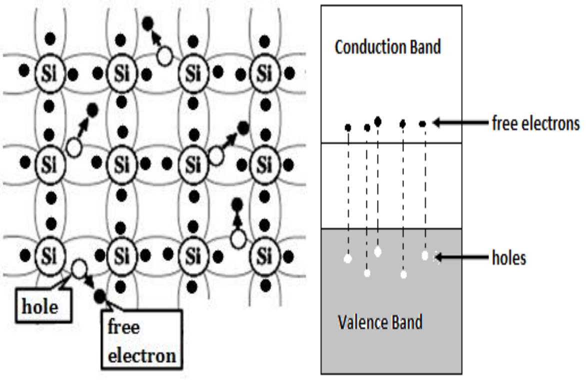


1.5 CLASSIFICATION OF SEMICONDUCTORS

Based on the composition, semiconductors are classified into two types

1.5.1 INTRINSIC SEMICONDUCTOR

In silicon each atom contains 4 valency electrons hence stability is aquired by each atom in the material through sharing of valency electrons. The bonds formed through sharing of electrons in semiconductor are called **covalent bonds.** An intrinsic semiconductor, also called an undoped semiconductor or I–type semiconductor, is a purese miconductor without any significant dopant species present. The bond structure of silicon is shown in the fig.



At a very low temperature 0°K no free electrons are available for conduction hence intrinsic semiconductor behaves as perfect insulator. With increase in temperature the covalent bonds are broken and electron hole pairs are generated. Such a generation of electron hole pairs due to thermal energy is called **thermal generation.** With the generation electron hole pairs an intrinsic semiconductor starts conducting.

Note:-In intrinsic semiconductor electron concentration is equal to hole concentration i.e.

$n = p = n_i$

$n_i$is called intrinsic carrier concentration & it is given by

$n_i^2 = A_0 T^3 e^{-E_{G0/kT}}$

At room temperature,

$n_i = 2.5 \times 10^{13}$atoms/cm³ for Germanium

$n_i = 1.5 \times 10^{10}$atoms/cm³ for Silicon

Where,

A_0 is material constant

E_{G0}isE_G at T = 0°K

k is Boltzmann's constant

$k = 8.6 \times 10^{-5}$eV/°K

1.5.1.1 ELECTRON & HOLE CONCENTRATION

The concentration of electrons in the conduction band can be expressed as

$n = N_C \exp\left[-\left(E_C - E_F\right)/kT\right]$

Where,

$$N_C = 2\left(\frac{2\pi m_n \bar{k} T}{h^2}\right)^{\frac{3}{2}}$$

which is called the effective density of states function in the conduction band. $m_n$is called effective mass of electron. $\bar{k}$ is called Boltzmann's constant

$\bar{k} = 1.381 \times 10^{-23}$ joules /° K

The concentration of hole in valence band can be expressed as

$p = N_V \exp\left[-\left(E_F - E_V\right)/kT\right]$

Where, $N_V = 2\left(\frac{2\pi m_p \bar{k} T}{h^2}\right)^{\frac{3}{2}}$

which is called the effective density of states function in the valence band.$m_p$is called effective mass of hole.

1.5.1.2 FERMI LEVEL

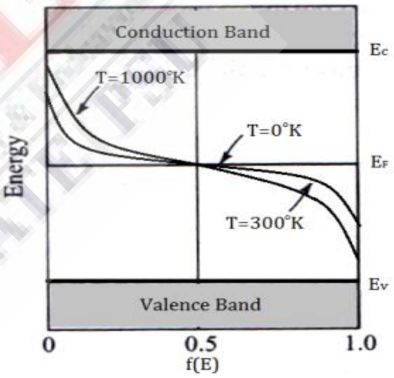
The Fermi level for an intrinsic semiconductor is given by

$$E_F = \frac{E_C + E_V}{2} - \frac{kT}{2}\ln\frac{N_C}{N_V} \qquad ...(1)$$

If the effective masses of a hole and a free electron are the same i.e. m_p=$m_n$then$N_C = N_V$,

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

Putting T = 0°K in above equation we may observe that equation (1) is also valid even for $N_C \neq N_V$. Hence the Fermi level lies in the center of the forbidden energy band.



Example

For a particular semiconductor material, $N_C = 1.5 \times 10^{18}$cm^{-3}, $N_V = 1.3 \times 10^{19}$cm^{-3}andE_G = 1.43 eV at T = 300°K Determine the position of the intrinsic Fermi level with respect to the center of the band gap.

Solution

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

$$E_{midgap} = \frac{E_C + E_V}{2}$$

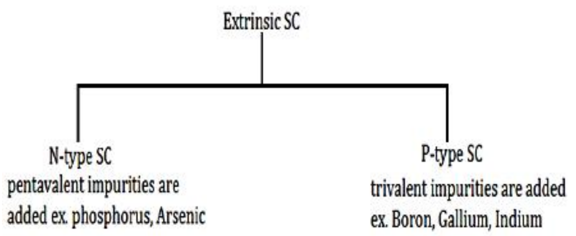
$$E_F - E_{midgap} = \frac{kT}{2}\ln\frac{N_C}{N_V}$$

$$E_F - E_{midgap} = -\frac{0.0259}{2}\text{In}\left(\frac{1.5\times10^{18}}{1.3\times10^{19}}\right)$$

$$= 0.028\text{eV}$$

Thus the Fermi level is located at 0.028 eV above the center of the band gap.

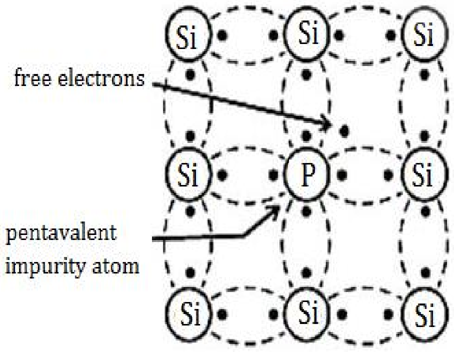
1.5.2 EXTRINSIC SEMICONDUCTOR



1.5.2.1 N-TYPE SEMICONDUCTOR

When a small amount of pentavalent impurity is added to a pure semiconductor, it is called **N-type semiconductor.** The impurity atoms will displace some of the silicon atoms in the crystal lattice. Four of the five valence electrons will occupy covalent bonds, and the fifth will be nominally unbound and will be available as a carrier of current. The energy required to detach this fifth electron from the atom is of the order of only 0.01 eV for Ge or 0.05 eV for Si.

Suitable pentavalent impurities are antimony, phosphorous, and arsenic. Such impurities donate excess (negative) electron carriers, and are therefore referred to as **donor or n-type impurities**.



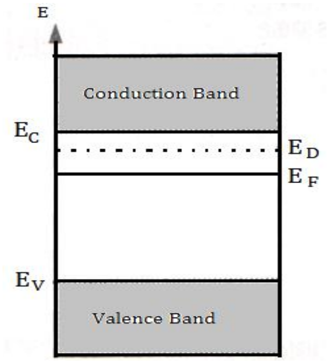
When donor impurities are added to a semiconductor, allowable energy levels are introduced just below the conduction band, as shown in fig . These new allowable levels are essentially a discrete level because the added impurity atoms are far apart in the crystal structure, and hence their interaction is small. In germanium, the distance of the new discrete allowable energy level is only 0.01 eV (0.05 eV in silicon) below the conduction band, and therefore at room temperature almost all of the "fifth" electrons of the donor material are raised into the conduction band.

If intrinsic semiconductor material is "doped" with n-type impurities, not only does the number of electrons increase, but the number of holes decrease below that which would be available in the intrinsic semiconductor. The reason for the decrease in the number of holes is that the larger number of electrons present increases the rate of recombination of electrons with holes.

Note:

1) Donor impurity concentration in an N-type semiconductor is given by
   N_D = Atomic density in semiconductor × Impurity ratio
   Where,
   Atomic density = 4.422 X 10^{22} atmos/ cm^3
   For Germanium
   Atomic density = 5 X 10^{22} atmos/ cm^3
   For Silicon
2) The electrons in N-type SC are called majority charge carriers & holes are called as minority charge carriers.

1.5.2.11 FERMI LEVEL



The Fermi level for N-type semiconductor lies near the conduction band. The position of Fermi level is given by the equation

$$E_F = E_C - kT \ln\frac{N_C}{N_D} eV$$

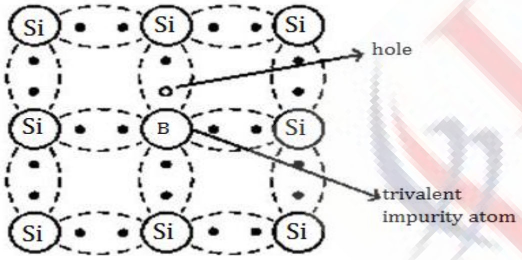
With increase in doping the Fermi level shifts towards conduction band i.e. shift upward with respect to the Fermi level of intrinsic semiconductor. This upward shift is given by

$$E_F - E_{Fi} = kT \ln \frac{N_D}{n_i} eV$$

With increase in temperature the Fermi level of N-type semiconductor shifts towards Fermi level of intrinsic semiconductor & at a very high temperature it coincides with E_{Fi} i.e. at this temperature N-type semiconductor behaves as an intrinsic semiconductor.

1.5.2.2 P-TYPE SEMICONDUCTOR

When a small amount of trivalent impurity is added to a pure semiconductor, it is called **P-type semiconductor.** The trivalent impurity has three valence electrons. The examples of such elements are gallium, boron or indium, such an impurity is called **acceptor impurity.**



Consider the formation of p-type material by adding boron into silicon (Si). The Boron atom has three valence electrons. So Boron atom fits in the silicon crystal in such a way that it's three valence electros from covalent bonds with the three adjacent silicon atoms. Being short of one electron, the fourth covalent bond in the valence shell is incomplete. The resulting vacancy is called a hole. Such p-type material formation is represented in the Fig .This means that each gallium atom added into silicon atom gives one hole. The number of such holes can be controlled by the amount of impurity added to the silicon. As the holes are treated as positively charged, the material is known as p-type material.

At room temperature, the thermal energy is sufficient to extract an electron from the neighboring atom which fills the vacancy in the incomplete bond around impurity atom. But this creates a vacancy in the adjacent bond from where the electron had jumped, which is nothing but a hole. This indicates that a hole created due to added impurity is ready to accept an electron and hence is called acceptor impurity.

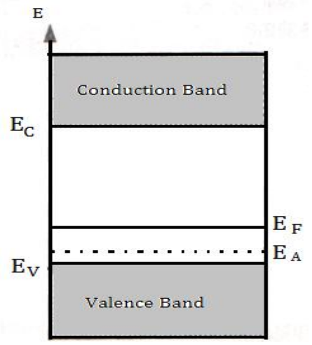
Note:

1) Acceptor impurity concentration in an P-type semiconductor is given by
   N_A =Atomic density in semiconductor × Impurity ratio
   Where,
   Atomic density = 4.422×10^{22}atmos/cm^3 for Germanium
   Atomic density = 5 X 10^{22}atmos/cm^3 for Silicon
2) The holes in P-type SC are called majority charge carriers & electrons are called as minority charge carriers.

1.5.2.2.1 FERMI LEVEL

The Fermi level for P-type semiconductor lies near the valence band. The position of Fermi level is given by the equation

$$E_F = E_V + kT \ln \frac{N_V}{N_A} eV$$



With increase in doping the Fermi level shifts towards valence band i.e. shift downward with respect to the Fermi level of intrinsic semiconductor. This downward shift is given by

$$E_{Fi} - E_F = kT \ln \frac{N_A}{n_i} eV$$

With increase in temperature the Fermi level of P-type semiconductor shifts towards Fermi level of intrinsic semiconductor & at a very high temperature it coincides with E_{Fi} i.e. at this temperature p-type semiconductor behaves as an intrinsic semiconductor.

1.6 MOBILITY OF CHARGE CARRIERS

Consider a material is subjected to an external electric field E Volts/m. As a result of electrostatic force, the charge carriers start moving in a definite direction. The velocity of these charge carriers is called drift velocity. This velocity of charge carriers is directly proportional to the applied electric field

$v_d \propto E \Rightarrow v_d = \mu E$

Where μ is constant of proportionality and is called mobility of the electrons. This is applicable to the free electrons as well as the holes.

So in general,

Mobility of a charged particle

$$\mu = \frac{v_d}{E} \frac{m^2}{V-sec}$$

At room temperature the mobility of electrons and holes are

mobility	germanium	silicon
μ_n	$3800 \frac{cm^2}{V-sec}$	$1300 \frac{cm^2}{V-sec}$
μ_p	$1800 \frac{cm^2}{V-sec}$	$500 \frac{cm^2}{V-sec}$

1.6.1 EFFECT OF TEMPERATURE

At any temperature above absolute zero, the vibrating atoms create pressure (acoustic) waves in the crystal, which are termed phonons. Like electrons, phonons can be considered to be particles. A phonon can interact (collide) with an electron (or hole) and scatter it. At higher temperature, there are more phonons, therefore increased phonon scattering which tends to reduce mobility i.e. with increase in temperature mobility of charge carriers decreases.

1.6.2 EFFECT OF DOPING

Semiconductors are doped with donors and/or acceptors, which are typically ionized, and are thus charged. The Columbic forces will deflect an electron or hole approaching the ionized impurity. This is known as ionized impurity scattering. The amount of deflection depends on the speed of the carrier and its proximity to the ion. The more heavily a material is doped, the higher the probability that a carrier will collide with an ion in a given time, and the smaller the mean free time between collisions, and the smaller the mobility i.e. with increase in doping the mobility of charge carries decreases.

Example

A bar of silicon 1 cm long is subjected to a potential difference of 20 v. If the velocity of electrons in bar is 250m/s. Determine the mobility of electrons.

Solution

Given,

$\ell = 1cm = 1\times10^{-2} m$

$V = 20 volts$

$V = 250 m/sec$

We know,

$$\text{Mobility } \mu = \frac{v}{E}$$

$$\text{electric field}(E) = \frac{V}{\ell} = \frac{20}{1\times10^{-2}}$$

$$= 2000 \, V/m$$

$$\therefore \mu = \frac{250}{2000} = 0.125 \, m^2/v-sec$$

$$= 1250 \, cm^2/v-sec$$

1.7 LAW OF ELECTRICAL NEUTRALITY

Statement: It states that a semiconductor is always electrically neutral i.e. total positive charge in semiconductor is equal to total negative charge.

Let N_D be the concentration of donor atoms which donate electrons and become positively charged ions. Hence we can say

that N_D is concentration of positively charged immobile ions contributed by donor atoms.
Total positive charge density = N_D + p
where p is concentration of holes i.e. positive charges
Similarly, N_A is the concentration of acceptor atoms which accept electrons and becomes negatively charged ions. Hence we can say that N_A is the concentration of negative ions contributed by the acceptor atoms.
Total negative charge density = N_A + n
where n is concentration of electrons i.e. negative charges.
Since the semiconductor is electrically neutral, the magnitude of positive charge density must equal to that of negative charge density.

$$\therefore \; N_D + p = N_A + n$$

Case-1
In n-type material, N_A = 0 and the number of holes is much smaller than number of electrons i.e. p<<n. Hence neglecting p, the equation reduce to,

$$N_D \cong n$$

Case-2
In p-type material, N_D = 0 and the number of electrons is much less than number of holes i.e. n<<p. Hence neglecting n, the equation reduces to,

$$N_A \cong p$$

1.8 MASS ACTION LAW

Statement: If n is the concentration of free electrons and p is the concentration of holes then the law of mass action states thats thermal equilibrium the product of concentrations of electrons and holes is always constant & it is square of intrinsic carrier concentration. Mathematically,

$$np = n_i^2$$

Where n_i is intrinsic concentration.
The law can be applied to both intrinsic and extrinsic semiconductors.

Case-1
In N-type SC

$$n_n \times p_n = n_i^2$$

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

Using above equation we can calculate the value of p_n i.e. concentration of holes in N-type material (minority carriers concentration in N-type)

Case-2
In P-type SC

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

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

Using above equation we can calculate the value of n_p i.e. concentration of electrons in P-type material (minority carrier concentration in P-type)

Note: Mass action law can be used to calculate concentration of minority carriers in extrinsic semiconductors.

1.9 CONDUCTIVITY

Conductivity of a material is defined as the product of carrier concentration, charge of carriers & their motilities.
conductivity(σ)= charge carrier concentration × charge of carriers × mobilty

$$\sigma = nq\mu_n + pq\mu_p \text{siemens} / m$$

1.9.1 CONDUCTIVITY OF INTRINSIC SEMICONDUCTOR

We know that,

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

But in intrinsic semiconductor, the electron hole pairs are generated and at any instant number of free electrons is same as number of holes.

$$\text{i.e.}\; n = p = n_i$$

Substituting in above equation,

$\sigma_i = n_i q(\mu_n + \mu_p)$ …… (1.17)

Where σ_i is conductivity of intrinsic semiconductor.

Note: With increase in temperature, mobility of electrons & holes decreases but at the same time there is large increase in electron &hole concentration hence the conductivity of intrinsic semiconductor increases with temperature i.e. conductivity of intrinsic semiconductor has positive coefficient of temperature.

1.9.2 CONDUCTIVITY OF N-TYPE SEMICONDUCTOR

In n-type of material, the free electrons are majority carriers and the holes are minority carriers. When donor impurity is added to the intrinsic semiconductor, donor atom donates electron to the conduction band and becomes positively charged ion.

Let

N_D = Concentration of donor atoms

n = Concentration of free electrons in n-type material

P = Concentration of holes in n type material.

We know, $\sigma = (n\mu_n + p\mu_p)q$

But the concentration of holes in a n-type semiconductor is very less as compared to the concentration of free electrons i.e. $P_n \ll n_n$. Hence neglecting P_n we can write

$\sigma_n = n\mu_n q$

Now practically all the donor atoms added release their fifth electron as a free electron at room temperature. Hence concentration of donor atoms (N_D) added is approximately equal to the concentration of free electrons in n-type material (n_n) i.e.

$n_n \cong N_D$

Hence conductivity of n-type material is,

$\sigma_n = N_D \mu_n q$

Note: With increase in temperature the mobility of charge carriers decreases by large value in a doped semiconductor, hence conductivity of N-type semiconductor decrease with temperature i.e. conductivity in N-type semiconductor has negative coefficient of temperature.

1.9.3 CONDUCTIVITY OF P-TYPE SEMICONDUCTOR

In p-type of material, the holes are majority carriers and the free electrons are minority carriers. When acceptor impurity is added to the intrinsic semiconductor, acceptor atom accepts an electron to become negatively charged ion.

Let

N_A = Concentration of acceptor atoms

n_p = Concentration of free electrons in p-type material

P_P = Concentration of holes in p- type material

We know, $\sigma = (n\mu_n + p\mu_p)q$

But the concentration of electrons in p-type materials is very much less as compared to the concentration of holes i.e. $n_p \ll P_P$.

Hence neglecting n_p we can write,

$\sigma_p = P_P \mu_p q$

Now practically all the acceptor atoms added accept the electron and produce hole. Hence concentration of acceptor atoms (N_A) is approximately equal to the concentration of holes in P-type material (P_P) i.e. $P_P \cong N_A$

Hence conductivity of p-type material is,

$\sigma_p = N_A \mu_p q$

Note: With increase in temperature the mobility of charge carriers decreases by large value in a doped semiconductor, hence conductivity of P-type semiconductor decrease with temperature i.e. conductivity in P-type semiconductor has negative coefficient of temperature.

Example

Find conductivity of N-type Semiconductor with Donor impurity concentration 10^{18} atoms/ cm^3 & mobility of electrons $3800 cm^2/v-sec$

Solution:
Given ,

$N_D = 10^{18}$ atoms / cm^3

$\mu_n = 3800 cm^2 / v - sec$

$\sigma = N_D q \mu_n$

$= 10^{18} \times 1.6 \times 10^{-19} \times 3800$

$= 608 s / m$

1.10 RESISTIVITY

Resistivity is the reciprocal of conductivity i.e.

$$\rho = \frac{1}{\sigma} \Omega - m$$

1.10.1 RESISTIVITY OF INTRINSIC SEMICONDUCTOR

For intrinsic semiconductor conductivity is given by

$$\sigma_i = n_i q(\mu_n + \mu_p) 3$$

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

Note: Resistivity of intrinsic semiconductor has negative coefficient of temperature.

1.10.2 RESISTIVITY OF N-TYPE SEMICONDUCTOR

For N-type semiconductor conductivity is given by

$$\sigma_n = N_D \mu_n q$$

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

Note: Resistivity of N-type semiconductor has positive coefficient of temperature.

1.10.3 RESISTIVITY OF P-TYPE SEMICONDUCTOR

For N-type semiconductor conductivity is given by

$$\sigma_p = N_A \mu_p q$$

$$\therefore \rho = \frac{1}{N_A \mu_p q}$$

Note: Resistivity of P-type semiconductor has positive coefficient of temperature.

1.11 RESISTANCE

Resistance of a material is defined as

$R = \rho l / A \Omega$

where,
ρ is the resistivity of material
l is the length of material
A is crossectional area of the material

Example
A bar of intrinsic silicon has a crossectional area of $2.5 \times 10^{-4} m^2$. The electron density is $1.4 \times 10^{16} /m^3$. How long the bar be if I=1.2mA when 9 volts is applied across it. The mobility of electros & holes are $0.14 m^2 / vsec \,\&\, 0.05 m^2 / vsec$ resp.

Solution:
we know that,

$$R = V/I = 9/1.2 \times 10^{-3} = 7.5 k\Omega$$

Now,

$$R = \rho\ell / A$$

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

$$= \frac{1}{1.4 \times 10^{16} \times 1.6 \times 10^{-19} (0.14 + 0.05)}$$

$$= 2349.62 \Omega - m$$

$$\ell = \frac{R \times A}{\rho} = \frac{7500 \times 2.5 \times 10^{-4}}{2349.62}$$

$$= 0.79 mm$$

1.12 CONDUCTANCE

Conductance of the material is the reciprocal of its resistance i.e.

$G = 1/R$ ℧

$\Rightarrow \quad G = A / \rho l$

$\Rightarrow \quad G = \sigma A / l$

where,
σ is the conductivity of material
l is the length of material
A is crossectional area of the material

1.13 CURRENT DENSITY

The current density J is defined as the current per unit area of the conducting medium.

$J = \frac{I}{A} Amp/m^2$

1.13.1 DRIFT CURRENT

When conductor is subjected to an external voltage, free electrons move from negative to positive terminal & holes moved from positive to negative terminal with a steady velocity constituting a current. Such a current is called drift current which is due to drifting under the effect of external voltage.

1.13.2 DIFFUSION CURRENT

Consider a semiconductor, along its length, in the direction of x as shown in fig; there decrease in the concentration of electrons. As we move from x_1 to x_2 there is decrease in electron concentration i.e. there exist a concentration gradient $\frac{dn}{dx}$. Due to such concentration gradient, electrons move from the higher concentration area to the lower concentration area to adjust the concentration. Such a movement of electrons, due to the concentration gradient in a semiconductor is called diffusion. Due to the movement of electrons, current is constituted in a bar which is called diffusion current. This is the characteristic of semiconductors and cannot be observed in conductors.

1.13.2.1 DIFFUSION LENGTH

Diffusion length is the average length a carrier moves between generation and recombination. Mathematically it is given by $L = \sqrt{D\tau}$

where,

D is diffusion constant

τ is minority carrier lifetime

Note:

1) Minority carrier lifetime is the average time between generation & recombination of minority charge carriers
2) Semiconductor materials that are heavily doped have greater recombination rates and consequently, have shorter diffusion lengths.
3) Higher diffusion lengths are indicative of materials with longer lifetimes, and is therefore an important quality to consider with semiconductor materials.

1.13.3 DRIFT CURRENT DENSITY

The drift current density is expressed as,

$J = \sigma E$

Where,

σ is conductivity and is measured in $(\Omega - m)^{-1}$

E is applied electric field expressed in V/m

1) Electron drift current density is given by $J_n = nq\mu_n E$
2) Hole drift current density is given by $J_p = pq\mu_p E$

1.13.4 DIFFUSION CURRENT DENSITY

The diffusion current density is proportional to the concentration gradient

i.e. $J_p \propto \frac{dp}{dx}$ & $J_n \propto \frac{dn}{dx}$

where,

J_p is diffusion current density due to holes

J_n is diffusion current density due to electrons

1) The hole diffusion current density is given by,

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

   where, D_p is diffusion constant for holes expressed in m^2/sec

2) The electron diffusion current density is given by,

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

where, D_n is diffusion constant for electrons expressed in m^2/sec

1.13.5 TOTAL CURRENT DENSITY

The drift current is due to the applied voltage while the diffusion current is due to the concentration gradient & in semiconductor it is very much possible that both the types of currents may exist simultaneously.

Total current density due to the electrons is

$$J_n = nq\mu_n E + qDn\frac{dn}{dx}$$

And total current density due to the hoes is,

$$J_p = pq\mu_p E - qDp\frac{dp}{dx}$$

Example

Calculate the diffusion current in a piece of germanium having concentration gradient of 1.5×10^{22} electrons/ m^4 & $D_n = 0.0012 m^2/s$

Solution

$$J = qD_n\left(\frac{d_n}{d_x}\right) amp/m^2$$

$$= 1.6\times10^{-19}\times0.0012\times1.5\times10^{22}$$

$$= 2.88 A/m^2$$

1.14 EINSTEIN'S RELATION

It states that, at thermal equilibrium, the ratio of diffusion constant to the mobility is constant. This is **Einstein's relation.** Mathematically it is expressed as,

$$\frac{Dp}{\mu_p} = \frac{Dn}{\mu_n} = kT = V_T$$

where, T is the temperature in °K

k is Boltzmann's constant

$= 8.62\times10^{-5} eV/°K$

V_T is called thermal voltage

$$V_T = \frac{T}{11600}$$

At T=300°K,

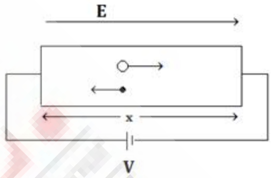
$$V_T = \frac{300}{11600} = 0.0256V \approx 26mV$$

1.15 ELECTRIC FIELD

When a potential difference is applied across a material, a force acts on the charge carriers due to which electrons & holes move in the material i.e. a current flows through the material, this force on charge carriers is called electric field intensity.

Mathematically it is given by

$$E = -\frac{dV}{dx}\ V/m$$

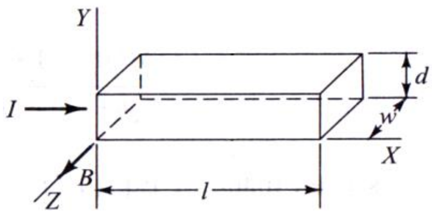


Note: In a material with uniform doping & uniform crossectional area the electric field is same at any point on the material and the magnitude this electric field can be calculated using equation

$$E = \frac{voltage applied}{length of material}$$

1.16 HALL EFFECT

If specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, an electric field *E* is induced in the direction perpendicular to both I and B. This phenomenon is known as the Hall Effect.



When a current carrying material is placed in transverse magnetic field, a force acts on the charge carriers called Lorentz's force given by

$$\vec{F} = q(v\times B)$$

where, q is charge of carriers(1.6×10^{-19}C)

v is velocity of charge carriers(m/s)
B is magnetic flux density (Tesla or weber/m^2)

The force acting on holes is $\overline{F_p} = +q(v_p \times B)$

For the given direction of current and magnetic field the direction of $(v_p \times B)$ is downward (direction of v_p is same as the direction of current) using right hand rule. Hence the direction of force on hole is also downward.

The force acting on electrons is

$\overline{F_n} = -q(v_n \times B)$

For the given direction of current and magnetic field the direction of $(v_n \times B)$ is upward (direction of v_n is opposite to that of current) using right hand rule. But as electrons are negatively charged carriers, the direction of force on electrons is also downward.

Due to displacement of charge carriers in the downward direction, a potential difference is developed across the top & bottom surfaces of the material called Hall voltage & mathematically its is given by

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

where, ρ is called charge density

$$\rho = \frac{1}{\text{charge}(q) \times \text{carrierconcentration(norp)}}$$

The reciprocal of charge density is called hall coefficient.

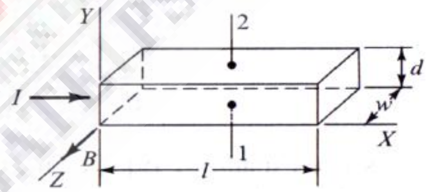
$$R_H = \frac{I}{\rho}$$

Applications:

1) It is used to determine whether a semiconductor is n-or p–type.
(Type of material is determine by observing the polarity of hall voltage)
2) It is used to find the carrier concentration.
(Carrier concentration (n or p) $= 1/(R_H \times q)$)
3) It is used to determine the mobility of charge carriers using equation $\mu = \sigma \times R_H$.
4) It is used to calculate magnetic flux density.

Example

Consider a rectangular cross –sectional semiconductor bar with length $l = 12$mm, width $w = 5$mm and thickness $d = 4$mm which is placed in the coordinate system as shown in fig. The positive and negative terminals of a battery of voltage $V_d = 5$V are connected between the two cross–sectional surface of the bar at $x = 0$ and $x = l$ respectively. A magnetic field $B = 6 \times 10^3$ Gauss is applied perpendicular to the bar along the +z-direction. If the bar is of n-type semiconductor with electron concentration $n_n = 2.5 \times 10^{15}\, cm^{-3}$ and the current flowing through the bar is $I = 10$mA, determine the magnitude and polarity of the Hall voltage between the terminal 1 and 2. Also find the value of the Hall coefficient.



Solution

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

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

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

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

Substituting the values of

$I = 10 \times 10^{-3}$ A,

$$B = 6 \times 10^3 \text{Gauss} = \left(\frac{10^{-8} Wb}{cm^2}\right) = 6 \times 10^{-5} \frac{wb}{cm^2}$$

$\rho = 4.0 \times 10^{-4} C / cm^2$ and $w = 5 \times 10^{-1}$ cm in Eq; the magnitude of the Hall voltage is given by $V_H = \frac{BI}{\rho w} = 3.0 \times 10^{-3} V = 3.0 mV$

Since the direction of applied electric field is in the $+X$ direction, the velocity of the electron v must be in the $-X$ direction. Thus, the direction of deflection of the electrons can be determined as follows.
Let the magnetic field and velocity of electrons in the bar be expressed as

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

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

$$F_e = e\left(B \times v_e\right) = eBv\left(-\hat{z} \times \hat{x}\right) = eBv\left(-\hat{y}\right)$$

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

$$R_H = \frac{1}{\rho} = \frac{1}{4.0 \times 10^{-4} C / cm^{-3}} = -2.5 \times 10^3 cm^3 / C$$

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

1.17 PROPERTIES OF GERMANIUM & SILICON

Property	Ge	Si
Atomic number	32	14
Atoms per cm^3	4.42×10^{22}	5×10^{22}
E_{GO} at 0°K	0.785eV	1.21 eV
n_i at 300°K per cm^3	2.5×10^{13}	1.5×10^{10}
Intrinsic resistivity at 300°K in $\Omega - cm$	45	2.3×10^5
μ_n $cm^2/V - sec$	3800	1300
μ_p $cm^2/V - sec$	1800	500
D_n cm^2/sec	99	34
D_p cm^2/sec	47	13

GATE QUESTIONS

Topics **Page No**

1 BASIC SEMICONDUCTOR PHYSICS

Q.1 n-type silicon is obtained by doping silicon with
a) Germanium b)Aluminum
c)Boron d)Phosphorous
[GATE-2003]

Q.2 The band gap of silicon at 300K is
a)1.36eV b)1.10 eV
c)0.80 eV d)0.67 eV
[GATE-2003]

Q.3 The intrinsic carrier concentration of silicon sample of 300K is 1.5 x $10^{16}/m^3$. If after doping, the number of majority carriers is $5x10^{20}/m^3$, the minority carrier density is
a) $4.50\times10^{11}/m^3$ b) $3.33\times10^{4}/m^3$
c) $5.00\times10^{20}/m^3$ d) $3.00\times\frac{10^{-5}}{m^3}$
[GATE-2003]

Q.4 The impurity commonly used for realizing the base region of a silicon n-p-n transistor is
a)Gallium b)Indium
c)Boron d)Phosphorus
[GATE-2004]

Q.5 The concentration of minority carriers in an extrinsic semiconductor under equilibrium is
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
[GATE-2006]

Q.6 Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the
a) Diffusion current
b) Drift current
c) Recombination current
d) Induced current
[GATE-2006]

Q.7 The majority carriers 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 due to Hall effect acts in the direction
a) $V\times B$ b) $B\times V$
c) along V d)opposite to V
[GATE-2006]

Q.8 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
a) 0.00005 b) 2,000
c) 10,000 d) 20,000
[GATE-2006]

Q.9 The electron and hole concentration 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 $N_A \gg n_i$),the electron concentration per cm^3 at 300 K will be
a) n_i b) $n_i + N_A$
c) $N_A - n_i$ d) $\frac{n_i^2}{N_a}$
[GATE-2007]

EXPLANATIONS

Q.1 (d)
N-type silicon is obtained by doping silicon with a pentavalent impurity i.e. phosphorus.

Q.2 (b)

Q.3 (a)
$n_i^2 = np$
$n_i =$ intrinsic concentration
$$p = \frac{n_i^2}{n} = \frac{1.5\times10^{16}\times1..5\times10^{16}}{5\times10^{20}}$$
$$= 45\times10^{10} = 4.5\times10^{11}$$

Q.4 (c)
For an n-p-n transistor, the base region is a p type semiconductor. In the options there are 3 trivalent impurities but for silicon boron is preferred.

Q.5 (b)
Minority concentration
$$= \frac{n_i^2}{\text{majority carrier concentration}}$$
$$\text{I, e, } p \propto \frac{1}{h}$$

Q.6 (a)
The injected minority carrier current is diffusion current and it is because of concentration gradient.

Q.7 (b)
The electric field will be perpendicular to both V and B, and in$B \times V$ direction.

Q.8 (d)
$$\frac{\sigma_n}{\sigma_i} = \frac{nq\mu n}{n_i q(\mu_n + \mu_p)} = \frac{n}{n_i\left(1+\frac{\mu_p}{\mu_n}\right)}$$
$$= \frac{4.2\times10^8}{1.5\times10^{4[1+0.4]}} = 20,000$$

Q.9 (d)
By the law of electrical neutrality
$p + N_D = n + N_A$
As $N_D = 0$
$N_A \gg n_i \cong 0 p = N_A$
Using mass action law $np = n_i^2$
So, $n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A}$

Q.10 (a)
Boron is acceptor impurity, so high concentration makes p^+substrate.

Q.11 (c)
For p-type material ,
$N_A = n_i e^{+(E_{Fi}-E_F)}/KT$
$\Rightarrow 4\times10^{17} = 1.5\times10^{10} e^{(E_{Fi}-E_F)}/KT$
$\Rightarrow \frac{E_{Fi}-E_F}{KT} = 17.1$
$\Rightarrow E_{Fi} - E_F = 17.1\times25mv$
$= 0.427eV$
It is p-type so Fermi level goes down by 0.427eV

Q.12 (c)

Q.13 (a)
$\frac{D}{\mu} = V_T$
$\Rightarrow \frac{\mu}{D} = \frac{1}{V_T} \Rightarrow \text{units}: V^{-1}$

Q.14 (b)
Dry oxidation is preferred because of less contamination.

Q.15 (c)
Electric field will be constant inside sample.

ASSIGNMENT QUESTIONS

Q.1 At room temperature, the current in an intrinsic semiconductor is due to

a) Holes b) Electrons
c) Ions d) Holes and electrons

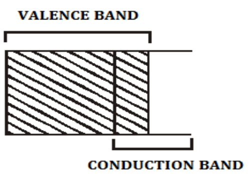
Q.2 Match List I with List II and select the correct answer using the codes given below the lists:

List I (List of materials)

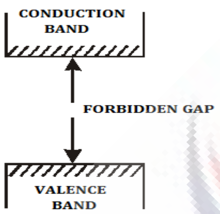
A) Conductor
B) Semiconductor
C) Insulator

List II (Energy-band diagram)

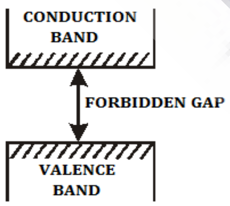
1)



2)



3)



Codes:

	A	B	C
a)	1	3	2
b)	3	1	2
c)	1	2	3
d)	2	3	1

Q.3 For a photoconductor with equal electron and hole mobilities and perfect ohmic contacts at the ends, an increase in the intensity of optical illumination results in

a) A change in open circuit voltage
b) A change in short-circuit current
c) A reduction of resistance
d) An increase of resistance

Q.4 A sample of N-type semiconductor has electron density of $6.25 \times 10^{18}/cm^3$ at 300 K. If the intrinsic concentration of carriers in this sample is $2.5 \times 10^{13}/cm^3$, at this temperature, the hole density works out to be

a) $10^6/cm^3$ b) $10^8/cm^3$
c) $10^{10}/cm^3$ d) $10^{12}/cm^3$

Q.5 If the drift velocity of holes under a field gradient of 100 V/m is 5m/s their mobility (in the same SI units) is

a) 0.05 b) 0.5
c) 50 d) 500

Q.6 Which of the following statements relate to the Hall effect?

1. A potential difference is developed across a current-carrying metal strip when the strip is placed in a transverse magnetic field.
2. The Hall effect is very weak in metals but is large in semiconductors.
3. The Hall effect is very weak in semiconductors but is large in metals.
4. It is applied in the measurement of the magnetic field intensity.

Select the correct answer using the codes given below:

a) 1, 2 and 3 b) 2 and 4
c) 1, 3 and 4 d) 1, 2 and 4

Q.7 The conductivity of a semiconductor crystal due to any current carrier is NOT proportional to

EXPLANATIONS

Q.1 (d)

In intrinsic semiconductor n=p & both take part in conduction.

Q.2 (a)

1) For conductors and conduction band and valence band overlaps at room temperature.
2) For insulators the forbidden gap is larger than for semiconductors.

Q.3 (c)

With increase in intensity more number of electrons and holes are generated and conductivity increases i.e. resistance decreases.

Q.4 (b)

According to mass action law

$$p = \frac{n_i^2}{n}$$

$$= \frac{\left(2.5\times10^{13}\right)^2}{6.25\times10^{18}}$$

$$= 10^8 / cm3$$

Q.5 (a)

$$E = 100\frac{V}{m}$$

$$V_d = 5\frac{m}{s}$$

$$\mu = \frac{V_d}{E} = \frac{5}{100} = 0.05\frac{m^2}{V-sec}$$

Q.6 (d)

$$R_H = \frac{1}{\mathbf{nq}}$$

For metals n(electron concentration) is very large as compared to semiconductor.

Therefore, R_H is small

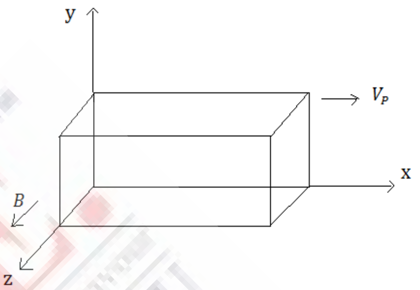
Q.7 (b)

$\sigma = nq\mu_n + pq\mu_p$

n(electron concentration) depends on N_c

(density of states in conduction band)

Q.8 (c)



Holes will experience a force in downward direction, a positive voltage in negative y direction and negative voltage in positive y direction.

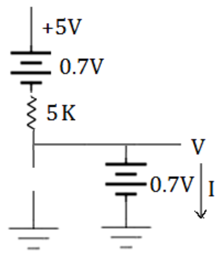
Q.9 (b)

$$R(T) = R(0℃)(1+\alpha T)$$

$$1.1 = 1(1+\alpha T)$$

$$\alpha T = 0.1 \Rightarrow T = \frac{0.1}{\alpha} = \frac{0.1}{10^{-3}} = 100℃$$

Q.10 (c)



V=0.7 V

$$I = \frac{5-0.7-0.7}{5K} = 720\mu A$$

Q.11 (d)

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