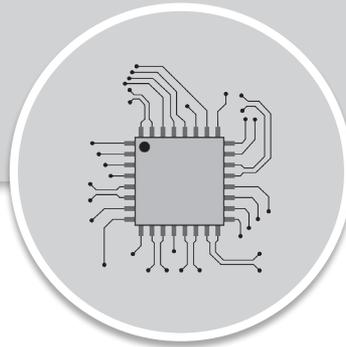# ELECTRONICS ENGINEERING

Electronic Devices and Circuits

Comprehensive Theory
with Solved Examples *and* Practice Questions
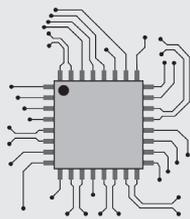
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Electronic Devices and Circuits

CONTENTS

Electronic Devices and Circuits

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Semicondcutor Physics

1.1   INTRODUCTION

In studying solid state electronic devices we are interested primarily in the electrical behavior of solids. We will also come to know the transportation of charge through a metal or semiconductor depends not only on the properties of the electron but also on the arrangement of atoms in the solid. In this chapter we shall investigate some of the important properties of electrons, with special emphasis on two points. (1) the electronic structure of atoms and (2) the interaction of atoms and electrons with excitation, such as the absorption and emission of light.

In this chapter we will discus the basic atomic properties of matter leading to discrete electronic energy levels in atoms, atomic energy levels are spread into energy bands in a crystal. This band structure allows us to distinguish between an insulator, a semiconductor and a metal.

1.2   THE NATURE OF THE ATOM

In order to explain many phenomena associated with conduction in gases, metals and semiconductors and the emission of electrons from the surface of a metal, it is necessary to assume that the atom has loosely bound electrons which can be torn away from it.

Rutherford found that the atom consists of a nucleus of positive charge that contains nearly all the mass of the atom and hence it will remain substantially immobile. Surrounding this central positive core are negatively charged electrons. As a specific illustration of this atomic model, consider the hydrogen atom. This atom consists of a positively charged nucleus (a proton) and a single electron. The force of attraction between the electron and the proton follows Coulomb's law. It can be shown from classical mechanics that the resultant closed path will be a circle or an ellipse under the action of such a force. This motion is exactly analogous to that of the planets about the sun, because in both cases the force varies inversely as the square of the distance between the particles.

Assume, therefore, that the orbit of the electron in this planetary model of the atom is a circle, the nucleus being supposed fixed in space. It is a simple matter to calculate its radius in terms of the total energy W of the electron. The force of attraction between the nucleus and the electron is $e^2/4\pi \epsilon_0 r^2$, where the electronic charge e is in Coulombs, the separation r between the two particles is in meters, the force is in Newton, and ϵ_0 is the permittivity of free space. By Newtons's second law of motion, this must be set equal to the product of the electronic mass m in kilograms and the acceleration v^2/r toward the nucleus, where v is the speed of the electron in its circular path, in meters per second.

Then
$$\frac{e^2}{4\pi \in_0 r^2} = \frac{mv^2}{r}$$

Furthermore, the potential energy of the electron at a distance r from the nucleus is $-e^2/4\pi \in_0 r$, and its kinetic energy is $\frac{1}{2} mv^2$. Then, according to the conservation of energy,

$$W = \frac{1}{2} mv^2 - \frac{e^2}{4\pi \in_o r}$$

where the energy is in Joules. Combining above equations, we get

$$W = -\frac{e^2}{8\pi \in_0 r}$$

which gives the desired relationship between the radius and the energy of the electron. This equation shows that the **total energy of the electron is always negative**. The negative sign arises because the potential energy has been chosen to be zero when r is infinite. This expression also shows that the energy of the electron becomes smaller (i.e., more negative) as it approaches closer to the nucleus.

However, an accelerated charge must radiate energy, in accordance with the classical laws of electromagnetism. If the charge is performing oscillations of a frequency f, the radiated energy will also be of this frequency. Hence, classically, it must be concluded that the frequency of the emitted radiation equals the frequency with which the electron is rotating in its circular orbit.

But if the electron is radiating energy, its total energy must decrease by the amount of this emitted energy. As a result the radius r of the orbit must decrease, in accordance with Equation above. Consequently, as the atom radiates energy, the electron must move in smaller and smaller orbits, eventually falling into the nucleus. Since the frequency of oscillation depends upon the size of the circular orbit, the energy radiated would be of a gradually changing frequency. Such a conclusion, however, is incompatible with the sharply defined frequencies of spectral lines.

1.2.1 The Bohr Atom

Above difficulty was resolved by Bohr. He postulated the following three fundamental laws:

(*i*) Not all energies as given by classical mechanics are possible, but the atom can possess only certain discrete energies. While in states corresponding to these discrete energies, the electron does not emit radiation, and the electron is said to be in stationary or non-radiating, state.

(*ii*) In a transition from one stationary state corresponding to a definite energy W_2 to another stationary state, with an associated energy W_1, radiation will be emitted. The frequency of this radiant energy is given by

$$f = \frac{W_2 - W_1}{h}$$

where h is Planck's constant in Joule-seconds, the W's are expressed in Joules, and f is in cycles per second, or Hertz.

(*iii*) A stationary state is determined by the condition that the angular momentum of the electron in this state is quantized and must be an integral multiple of $h/2\pi$. Thus

$$mvr = \frac{nh}{2\pi}$$

where n is an integer.

Combining above equation, we obtain the radii of the stationary states, the energy level in Joules of each state is found to be

$$W_n = -\frac{me^4}{8h^2 \in_0^2} \cdot \frac{1}{n^2}$$

EXAMPLE : 1.1

As the Fermi energy of silver is 8.8×10^{-19} Joule, the velocity of the fastest electron in silver at 0°K (Given: Rest mass of electron = 9.1×10^{-31} kg) is

(a) 3.33×10^5 m/s
(b) 1.39×10^6 m/s
(c) 4.40×10^7 m/s
(d) 3×10^8 m/s

Solution : (b)

$$\frac{1}{2} mv^2 = E \quad \text{or} \quad v^2 = \frac{2E}{m} \quad \text{or} \quad v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2 \times 8.8 \times 10^{-19}}{9.1 \times 10^{-31}}} = 1.39 \times 10^6 \text{ m/s}$$

1.3 ATOMIC ENERGY LEVELS

For each integral value of n in above equation a horizontal line is drawn. These lines are vertically in accordance with the numerical values calculated from above equation. Such a convenient pictorial representation is called an ***energy level diagram*** and is indicated in figure for hydrogen. The number to the left of each line gives the energy of this level in electron volts. The number immediately to the right of a line is the value of n. Theoretically, an infinite number of levels exist for each atom, but only the first five and the level for $n = \infty$ are indicated in figure.

It is customary to express the energy value of the stationary states in electron volts E rather than in Joules W. Also, it is more common to specify the emitted radiation by its wavelength λ in angstroms rather than by its frequency f in Hertz. In these units, above equation may be rewritten in the form

$$\lambda = \frac{12,400}{E_2 - E_1}$$
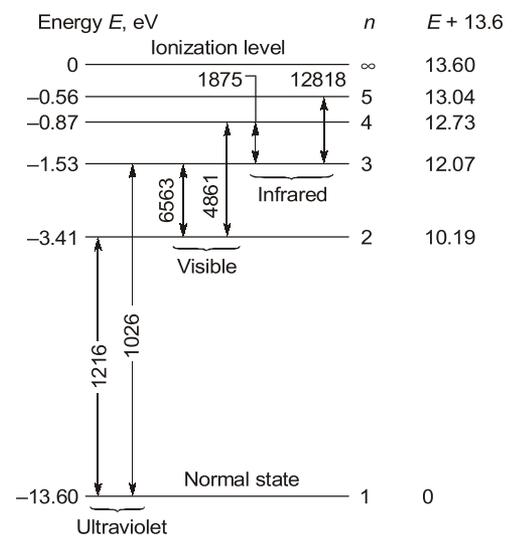
Figure : *The lowest five energy levels and the ionization level of hydrogen. The spectrum lines are in angstrom units*

NOTE

The eV unit of Energy: The joule (J) is the unit of energy in the MKS system. However, in electronics engineering problems, the joule is too large a unit. So practical unit for the energy in electronics engineering is **electron volt (eV)** and is defined as the energy gained by the electron in moving through a potential difference of 1V i.e.

1 eV = $|q| \times$ potential difference = 1.6×10^{-19} (C) $\times$ 1 (volt) = 1.6×10^{-19} (C · volt)

$$\boxed{1\,\text{eV} = 1.6 \times 10^{-19} \text{ (Joule)}}$$

EXAMPLE : 1.2

The longest wavelength that can be absorbed by silicon, which has the bandgap of 1.12 eV, is 1.1 μm. If the longest wavelength that can be absorbed by another material is 0.87 mm, then the bandgap of this material is

(a) 1.425 eV
(b) 0.886 eV
(c) 0.854 eV
(d) 0.706 eV

Solution : (a)

$$E_G = \frac{1.24}{\lambda(\mu m)} eV = \frac{1.24}{0.87 \mu m} eV = 1.425\, eV$$

1.3.1 The Photon Nature of Light

Assume that an atom has been raised from the ground state to an excited level by electron bombardment. The mean life of an excited state ranges from 10^{-7} to 10^{-10} s, the excited electron returning to its previous state after the lapse of this time. In this transition, the atom must lose an amount of energy equal to the difference in energy between the two states that it has successively occupied, this energy appearing in the form of radiation. According to the postulates of Bohr, this energy is emitted in the form of a photon of light, the frequency of this radiation is given by above equation, or the wavelength by above equation. The term photon denotes an amount of radiate energy equal to the constant h times of the frequency.

1.4 ELECTRONIC STRUCTURE OF THE ELEMENTS

The inner-shell electrons are very strongly bound to an atom, and cannot be easily removed. That is, the electrons closest to the nucleus are the most tightly bound, and so have the lowest energy. Also, atoms for which the electrons exists in closed shells form very stable configurations. For example, the inert gases He, Ne, Ar, Kr and Xe all have either completely filled shells or, at least, completely filled subshells.

Carbon, silicon, germanium, and tin have the electronic configurations indicated in Table below. Note that each of these elements has completely filled subshells except for the outermost p shell, which contains only two of the six possible electrons. Despite this similarity, carbon in crystalline form (diamond) is an insulator, silicon and germanium solids are semiconductors, and tin is a metal.

Element	Atomic Number	Configuration
C	6	$1s^2\,2s^2\,2p^2$
Si	14	$1s^2\,2s^2\,2p^6\,3s^2\,3p^2$
Ge	32	$1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}\,4s^2\,4p^2$
Sn	50	$1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}\,4s^2\,4p^6\,4d^{10}\,5s^2\,5p^2$

Table : *Electronic configuration in Group IVA*

EXAMPLE : 1.3

Atomic number of silicon is
(a) 12   (b) 13   (c) 14   (d) 15

Solution : (*c*)
From Table shown above atomic number of Silicon is 14.

1.5 THE ENERGY-BAND THEORY OF CRYSTALS

X-ray and other studies reveal that most metals and semiconductors are crystalline in structure. A crystal consists of a space array of atoms or molecules (strictly speaking, ions) built up by regular repetition in three dimensions of some fundamental structural unit. The electronic energy levels discussed for a single free atom (as in a gas, where the atoms are sufficiently far apart not to exert any influence on one another) do not apply to the same atom in a crystal. When atoms form crystals it is found that the energy levels of the inner-shell electrons are not affected appreciably by the presence of the neighbouring atoms. However, the levels of the outer-shell electrons are changed considerably, since these electrons are shared by more than one atom in the crystal. The new energy levels of the outer electrons can be determined by means of quantum mechanics, and it is found that

coupling between the outer-shell electrons of the atoms results in a band of closely spaced energy states instead of the widely separated energy levels of the isolated atom as shown in figure. A qualitative discussion of this energy-band structure follows.
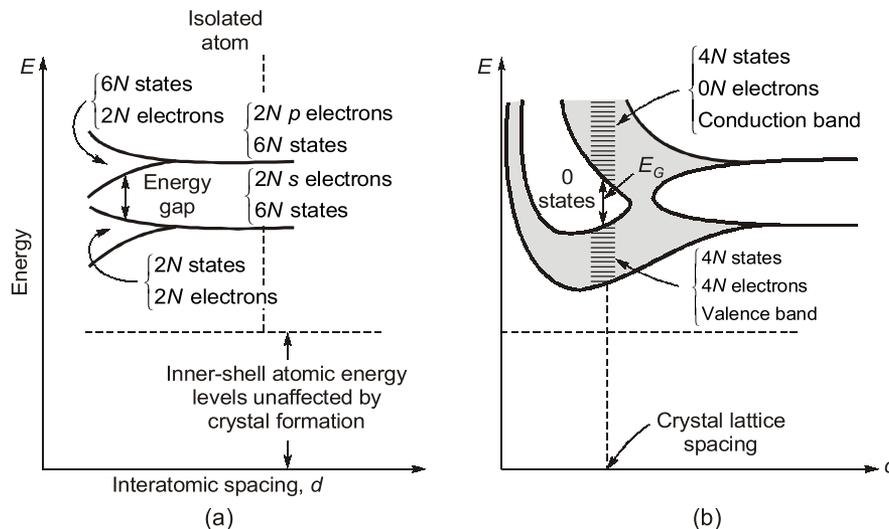

Figure : *Illustrating how the energy levels of isolated atoms are split into energy bands when these atoms are brought into close proximity to form a crystal*

Consider a crystal consisting of N atoms of one of the elements in Table above. Imagine that it is possible to vary the spacing between atoms without altering the type of fundamental crystal structure. If the atoms are so far apart that the integration between them is negligible, the energy levels will coincide with those of the isolated atom. The outer two subshells for each element in Table above contain two s electrons and two p electrons. Hence, if we ignore the inner-shell levels, then, as indicated to the extreme right in Fig. (a), there are $2N$ electrons completely filling the $2N$ possible s levels, all at the same energy. Since the p atomic subshell has six possible states, our imaginary crystal of widely spaced atoms has $2N$ electrons, which fill only one-third of the $6N$ possible p states, all at the same level.

If we now decrease the interatomic spacing of our imaginary crystal (moving from right to left in Fig. (a), an atom will exert an electric force on its neighbours. Because of this coupling between atoms, the atomic-wave functions overlap, and the crystal becomes an electronic system which must obey the Pauli exclusion principle. Hence the $2N$ degenerate s states must spread out in energy. The separation between levels is small, but since N is very large ($\sim 10^{23}$ cm^{-3}), the total spread between the minimum and maximum energy may be several electron volts if the interatomic distance is decreased sufficiently. This large number of discrete but closely spaced energy levels is called an **energy band**, and is indicated schematically by the lower shaded region in Fig. (a). The $2N$ states in this band are completely filed with $2N$ electrons. Similarly, the upper shaded region in Fig. (a) is a band of $6N$ states which has only $2N$ of its levels occupied by electrons.

Note that there is an energy gap (a forbidden band) between the two bands discussed above and this gap decreases as the atomic spacing decreases. For small enough distance (not indicated in Fig. (a) but shown in Fig. (b) these bands will overlap. Under such circumstances the $6N$ upper states merge with the $2N$ lower states, giving a total of $8N$ levels, half of which are occupied by the $2N + 2N = 4N$ available electrons. At this spacing each atom has given up four electrons to the band; these electrons can no longer be said to orbit in s or p subshells of an isolated atom, but rather they belong to the crystal as a whole. In this sense the elements in Table are tetravalent, since they contribute four electrons each to the crystal. The band these electrons occupy is called the **valence band**.

If the spacing between atoms is decreased below the distance at which the bands overlap, the interaction between atoms is indeed large. the energy-band structure then depends upon the orientation of the atoms

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relative to one another in space (the crystal structure) and upon the atomic number, which determines the electrical constitution of each atom. Solutions of Schrodinger's equation are complicated, and have been obtained approximately for only relatively few crystals. These solutions lead us to expect an energy-band diagram somewhat as pictured[4] in Fig. (b). At the crystal-lattice spacing (the dashed vertical line), we find the valence band *filled* with 4*N* electrons separated by a forbidden band (no allowed energy states) of extent E_G from an *empty* band consisting of 4*N* additional states. This upper vacant band is called the *conduction band*.

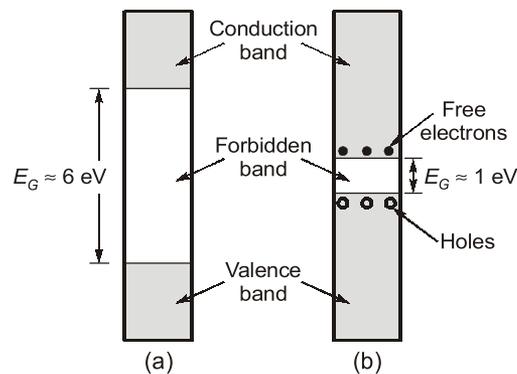## 1.6 INSULATORS, SEMICONDUCTORS AND METALS

Figure : *Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor*

1.6.1 Insulators

- An insulating material has an energy band diagram as shown in Fig.(a).
- It has a very wide forbidden-energy gap ($\simeq 6$ eV) separating the filled valence band from the vacant conduction band. Because of this, it is practically impossible for an electron in the valence band to jump the gap, and reach the conduction band.
- At room temperature, an insulator does not conduct. However it may conduct if its temperature is very high or if a high voltage is applied across it. This is termed as the **breakdown of the insulator.**
- **Example:** diamond.

1.6.2 Semiconductors

- A semiconductor has an energy-band gap as shown in Fig. (b).
- At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G, which is much smaller in semiconductors ($E_G \simeq 1$ eV) than in insulators.
- The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy.
- The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy.
- **Example:** Ge and Si.

1.6.3 Metals

- There is no forbidden energy gap between the valence and conduction bands. The two bands actually overlap as shown in Fig. (c).
- Without supplying any additional energy such as heat or light, a metal already contains a large number of free electrons and that is why it works as a good conductor.
- **Example:** Al, Cu etc.

> **REMEMBER**
>
> Conduction band electrons can move along sea of atoms present in the specimen under consideration while the valence band electrons (restrained electrons) are bound to parent atom. These conduction band electrons are known as *free electrons*.

> **NOTE**
>
> Since the band-gap energy of a crystal is a function of interatomic spacing, it is not surprising that E_G depends somewhat on temperature. It has been determined experimentally that E_G for silicon decrease with temperature at the rate of 3.60×10^{-4} eV/°K. Hence, for silicon,
> $$E_G(T) = 1.21 - 3.60 \times 10^{-4} T$$
> and at room temperature (300°K), $\quad E_G = 1.1$ eV
> Similarly, for germanium, $\qquad E_G(T) = 0.785 - 2.23 \times 10^{-4} T$
> and at room temperature, $\qquad\qquad E_G = 0.72$ eV

| **EXAMPLE : 1.4** | The bandgap of Silicon at room temperature is |

(a) 1.3 eV   (b) 0.7 eV   (c) 1.1 eV   (d) 1.4 eV

Solution : (c)

$$E_G(T) = 1.21 - 3.60 \times 10^{-4} T$$
At $T = 300$ °K, $\qquad E_G = 1.1$ eV

| **EXAMPLE : 1.5** | Which one of the following statements is correct in respect of the use of Direct Gap (DG) and Indirect Gap (IG) semiconductors in fabrication of Light Emitting diode? |

(a) Both DG and IG semiconductors are suitable
(b) Only DG semiconductor is suitable
(c) DG semiconductor is suitable and some IG materials having proper dopants are also used
(d) only IG semiconductors are suitable

Solution : (b)
Since the direct gap semiconductor gives the energy difference as a photon of light, it is suitable in the fabrication of LED.

1.7   ELECTRONS AND HOLES IN AN INTRINSIC SEMICONDUCTOR

Germanium and silicon are the two most important semiconductors used in electronic devices. The crystal structure of these materials consists of a regular repetition in three dimensions of a unit cell having the form of a tetrahedron with an atom at each vertex. This structure is illustrated symbolically in two dimensions in Fig. (a). Germanium has a total of 32 electrons in its atomic structure, arranged in shells as indicated in Table. Each atom in a germanium crystal contributes four valence electrons, so that the atom is tetravalent.

The inert ionic core of the germanium atom carries a positive charge of +4 measured in units of the electronic charge. The binding forces between neighbouring atoms result from the fact that each of the valence electrons of a germanium atom is shared by one of its four nearest neighbors. The electron pair or covalent bond is represented in below Fig. (a) by two dashed lines which join each atom to each of its neighbours. The fact that

the valence electrons serve to bind one atom to the next also results in the valence electron being tightly bound to the nucleus. Hence, in spite of the availability of four valence electrons, the crystal has a low conductivity.

At a very low temperature (say 0°K) the ideal structure of Fig. is approached, and the crystal behaves as an insulator, since no free carriers of electricity are available. However, at room temperature, some of the covalent bonds will be broken because of the thermal energy supplied to the crystal, and conduction is made possible. This situation is illustrated in Fig. (b). Here an electron, which for the far greater period of time forms part of a covalent bond, is pictured as being dislodged and therefore free to wander in a random fashion throughout the crystal. The energy E_G required to break such a covalent bond is about 0.72 eV for germanium and 1.1 eV for silicon at room temperature. The absence of the electron in the covalent bond is represented by the small circle in Fig. (b), and such an incomplete covalent bond is called a *hole*. The importance of the hole is that it may serve as as a carrier of electricity comparable in effectiveness to the free electron.
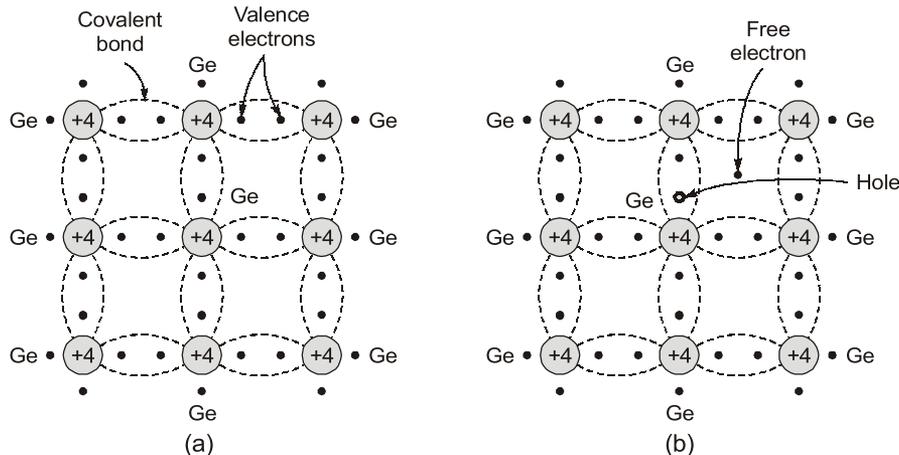

Figure : *(a) Crystal structure of germanium, illustrated symbolically in two dimensions*
(b) Germanium crystal with a broken covalent bond

The mechanism by which a hole contributes to the conductivity is qualitatively as follows: When a bond is incomplete so that a hole exists, it is relatively easy for a valence electron in a neighboring atom to leave its covalent bond to fill this hole. An electron moving from a bond to fill a hole leaves a hole in its initial position. Hence the hole effectively moves in the direction opposite to that of the electron. This hole, in its new position, may now be filled by an electron from another covalent bond, and the hole will correspondingly move one more step in the direction opposite to the motion of the electron. Here we have a mechanism for the conduction of electricity which does not involve *free electrons*. This phenomenon is illustrated schematically in Fig. below, where a circle with a dot in it represents a completed bond, and an empty circle designates a hole. Fig. below shows a row of 10 ions, with a broken bond, or hole, at ion 6. Now imagine that an electron from ion 7 moves into the hole at ion 6. This indicates that the motion of the hole in one direction actually means the transport of a negative charge an equal distance in the opposite direction. So far as the flow of electric current is concerned, the hole behaves like a positive charge equal in magnitude to the electronic charge. We can consider that the holes are physical entities whose movement constitutes a flow of current.
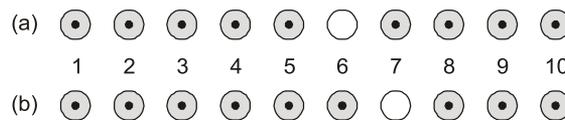

Figure : *The mechanism by which a hole contributes to the conductivity*

In a pure semiconductor the number of holes is equal to the number of free electrons. Thermal agitation continues to produce new hole-electron pairs, whereas other hole-electron pairs disappear as a result of recombination.

EXAMPLE : 1.6	A 'hole' in a semiconductor has

1. Positive charge equal to the electron charge.
2. Positive mass equal to the mass of the electron.
3. An 'effective mass' greater than the effective mass of electron.
4. Negative mass and positive charge equal to the charge in nucleus.

Which of these statements are correct?

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

Solution : (b)

A hole in a semiconductor has positive charge equal to electron charge and an effective mass greater than the effective mass of electron.

1.8 CONDUCTIVITY OF A SEMICONDUCTOR

It is well known to us that the conductivity of a material depends on the concentration of free electrons in it. Good conductors consists of large concentration of free electrons. The concentration in semiconductors is in between the values of density of free electrons in conductor and insulator.

The conductivity of semiconductors is moderate i.e. not very high and not very low with each electron-hole pair created, there are two charge carriers produced. One is negative charge carriers associated with electrons and other is positive charge carriers associated to the holes. Let the mobility of the hole in the crystal is μ_p and the mobility of electron in the same crystal in μ_n. These holes and electrons move in opposite direction but contribute the current in the same direction. The conductivity of the semiconductor can be defined as

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

but for intrinsic semiconductor, $n_i = n = p$

and hence, $\sigma_i = n_i(\mu_n + \mu_p)e$

Here, n = Magnitude of free-electron concentration ; p = Magnitude of hole concentration

   e = Charge of an electron = 1.6×10^{-19} C ; σ = Conductivity

   n_i = Intrinsic concentration

NOTE

Intrinsic concentration of pure semiconductor varies with temperature in accordance with the relationship.

$$n_i^2 = A_0 T^3 \exp\left(\frac{-E_{G0}}{kT}\right)$$

where, E_{G0} = Energy gap at 0°K in eV ; k = Boltzmann's constant in eV/°K

   T = Absolute temperature in °K ; A_o = Material constant independent of temperature

■   So with increasing temperature, n_i increases and correspondingly, the conductivity increases.

■   Conductivity is the reciprocal of resistivity i.e.

$$\sigma = \frac{1}{\rho} \quad \text{where, } \rho = \frac{RA}{l}$$

Here, ρ = Resistivity of the material ; A = Cross-sectional area of the material

   l = Length of the material

If the conductivity is measured together with the Hall coefficient, the mobility can be determined from

$$\mu = \sigma R_H$$

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

> **NOTE**
>
> We have assumed that all particles travel with mean drift speed. Actually the current carriers have a random thermal distribution in speed. If this distribution is taken into account then
>
> $$R_H = \frac{3\pi}{8\rho} \quad \text{and} \quad \mu = \left(\frac{8\sigma}{3\pi}\right)R_H$$
>
> • For n-type semiconductor Hall voltage (V_H) and Hall coefficient (R_H) is negative.
> • For p-type semiconductor Hall voltage (V_H) and Hall coefficient (R_H) is positive.
>
> • Hall voltage is large for semiconductor than metal, since $V_H \propto R_H$ i.e., $V_H \propto \frac{1}{\sigma}$.
> • For intrinsic semiconductor $V_H = 0$.

1.16.1 Usefulness of Hall Effect
- Hall effect is used to determine whether a semiconductor is *n*-type or p-type.
- It is used to measure majority carrier concentration.
- It is used to measure majority carrier mobility.

1.16.2 Applications
- Magnetofield meter is an instrument operating on the principal of Hall effect and it is used for the measurement of magnetic flux density *B*.
- Hall effect is also used in Hall effect multiplier. It gives an output proportional to the product of two signals. If *I* is made proportional to one of the inputs and if *B* is linearly related to the second signal, then, V_H is proportional to the product of two signals.

> **NOTE**
>
> The minority carrier mobility, lifetime and diffusion coefficient can be determined from Haynes-Shockley experiment.

OBJECTIVE BRAIN TEASERS

Q.1 Silicon is doped with 10^{17} As atoms/cm^3 then the shift between the energy level of extrinsic and intrinsic silicon is
(a) 0.21 eV   (b) 0.41 eV
(c) 0.61 eV   (d) 0.81 eV

Q.2 The Spectral response of certain elements at 300°K is shown below, then
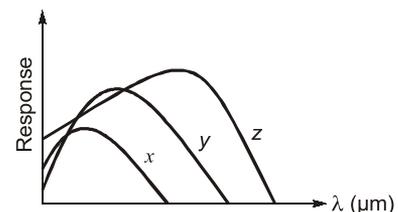
(a) $x = Ge, y = Si, z = GaAs$
(b) $x = GaAs, y = Si, z = Ge$
(c) $x = Si, y = GaAs, z = Ge$
(d) $x = GaAs, y = Ge, z = Si$

Q.3 The magnitude of diffusion constant for a n type Germanium bar of 1 mm thickness and 3 mm width with $B_z = 0.1$ Wb/m^2, $I_x = 10$ mA, $V_H = 50$ mV and $\rho = 20,0000$ Ω-cm is approximately
(a) 1.94×10^{-6} /m^2/sec
(b) 7.5×10^{-6} /m^2/sec
(c) 2.5×10^{-6} /m^2/sec
(d) 5×10^{-6} /m^2/sec

Q.4 Consider a Silicon p-n junction with $N_A << N_D$. The resistivity of p-side is 3.5 Ω-cm, the internal contact potential is 0.35 V and applied reverse bias is 5 V. If the junction has circular cross-section with diameter 500 µm, then the junction capacitance is
(Assume $\mu_p = 500$ cm^2/V-sec, $\mu_n = 1300$ cm^2/V-sec, $n_i = 1.5 \times 10^{10}$/cm^3, $\varepsilon_r = 11.7$ for *Si*)
(a) 14 pF
(b) 2 pF
(c) 16 pF
(d) 32 pF

Q.5 A sample of Germanium is doped to the extent of 10^{14} donor atoms/cm^3 and 5×10^{13} acceptor atoms/cm^3. At 300° K the resistivity of the intrinsic Germanium is 60 Ω-cm. The applied electric field is 2 V/cm, $\mu_p/\mu_n = 1/2$ and $n_i = 2.5 \times 10^{13}$/cm^3. The concentration of electron is
(a) 6.03×10^{13}/cm^3
(b) 4.05×10^{13}/cm^3
(c) 3×10^{13}/cm^3
(d) 1.05×10^{13}/cm^3

Q.6 For Silicon semiconductor, $\mu_n = 1500$ cm^2/V-sec, $\mu_p = 750$ cm^2/ V-sec and $n_i = 1.8 \times 10^{11}$/cm^3. The maximum resistivity will be
(a) 8.18 kΩ-cm
(b) 16.36 kΩ-cm
(c) 12.26 kΩ-cm
(d) None of these

Q.7 In a certain copper conductor, if the current density is 2.4 A/mm^2 and the electron density is 5×10^{28} electrons/m^3, then the drift velocity of copper is
(a) 0.3 mm/sec
(b) 0.6 mm/sec
(c) 0.9 mm/sec
(d) 0.4 mm/sec

Q.8 A Hall effect transducer can be used to measure
(a) displacement, temperature and magnetic flux
(b) displacement, position and velocity
(c) position, magnetic flux and pressure
(d) displacement, position and magnetic flux

Q.9 Given:
$N(E)$: Density of states
$f(E)$: Probability that a quantum state with energy E is occupied by an electron.
E_c : Energy level of conduction band.
The expression $\int_{E_c}^{\infty} N(E)f(E)dE$ gives
(a) minimum number of electrons in conduction band
(b) concentration of electrons in conduction band
(c) energy of electron concentration in conduction band
(d) conductivity of electrons in conduction band

Q.10 Silicon is doped with boron to a concentration of 4×10^{17} atoms/cm^3. Assume the intrinsic carrier concentration of Silicon to be 1.5×10^{10}/cm^3 and the value of kT/q to be 25 mV at 300°K. Compared to undoped Silicon, the Fermi level of doped Silicon
(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

ANSWERS KEY

1. (b)	2. (b)	3. (a)	4. (a)	5. (a)
6. (b)	7. (a)	8. (a)	9. (b)	10. (c)

HINTS & EXPLANATIONS

1. (b)

Given, $N_D = 10^{17}$ cm^{-3}
$n_i = 1.5 \times 10^{-10}$ cm^{-3} and $V_T = 26$ mV

Shift $= V_T \ln\left(\dfrac{N_D}{n_i}\right) = 26 \times 10^{-3} \ln\left(\dfrac{10^{17}}{1.5 \times 10^{-10}}\right)$

Shift $= 0.41$ eV

2. (b)

The wavelength,

$$\lambda = \frac{1.2406}{E_G(\text{eV})} \; ; \lambda \propto \frac{1}{E_G}$$

But $\sigma = N_D q \mu_n$

$J = N_D q \mu_n E$

Drift velocity,

$v_d = \mu_n E = \dfrac{J}{N_D q} = \dfrac{2.4 \times 10^6}{5 \times 10^{28} \times 1.6 \times 10^{-19}}$

$v_d = 3 \times 10^{-4}$ m/sec $= 0.3$ mm/sec

8. **(a)**

Hall effect transducer can be used to measure:

(i) Magnetic flux   (ii) Displacement

(iii) Temperature   (iv) Mobility

(v) Carrier concentration

9. **(b)**

The concentration of electrons in conduction band is given by,

$$n_0 = \int_{E_c}^{\infty} N(E) f(E) dE$$

Where, $N(E)$: Density of state

$f(E)$: Probability that a quantum state with energy E is occupied by an electron.

E_C : Energy level of conduction band.

10. **(c)**

Given,

$N_A = 4 \times 10^{17}$ cm^{-3}, $n_i = 1.5 \times 10^{10}$ cm^{-3},

$\dfrac{KT}{q} = 25$ mV

Here, boron is doped. So, the type of semiconductor is p-type.

Shift $= -\dfrac{KT}{q} \ln\left(\dfrac{N_A}{n_i}\right)$

$= -25 \times 10^{-3} \ln\left(\dfrac{4 \times 10^{17}}{1.5 \times 10^{10}}\right)$

Shift $= -0.427$ eV ($-$ve sign shows the downward shift)

So, compared to undoped silicon, the fermi level of doped silicon goes down by 0.427 eV.

CONVENTIONAL BRAIN TEASERS

Q.1 The energy band gap of silicon (Si) depends on the temperature as follows:

$$E_g = 1.17 \text{ eV} - 4.73 \times 10^{-4} \dfrac{T^2}{T + 636}$$

If the intrinsic carrier concentration of Si at $T = 300$ K is 1.05×10^{10} cm^{-3}. Find the concentration of electrons in the conduction band of intrinsic (undoped) Si at temperature $T = 77$ K? (Assume, $KT = 0.026$ eV, $E_g(300 \text{ K}) = 1.12$ eV)

1. **(Sol.)**

Given that,

Energy band gap of silicon, $E_g = 1.17 \text{ eV} - 4.73 \times 10^{-4} \dfrac{T^2}{T + 636}$

The intrinsic carrier concentration, $n_i^2 \propto T^3 e^{-E_g / KT}$

$n_i \propto T^{3/2} e^{-\frac{E_g}{2KT}}$

Let at temperature, $T_1 = 300$ K,

$n_i(T_1) \propto (T_1)^{3/2} e^{-\frac{E_g}{2KT_1}}$ ...(i)

Let at temperature, $T_2 = 77$ K

$n_i(T_2) \propto (T_2)^{3/2} e^{-\frac{E_g}{2KT_2}}$ ...(ii)