Chapter Fourteen

SEMICONDUCTOR ELECTRONICS: MATERIALS, DEVICES AND SIMPLE CIRCUITS

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14.1 Introduction

Devices in which a controlled flow of electrons can be obtained are the basic *building blocks* of all the electronic circuits. Before the discovery of transistor in 1948, such devices were mostly vacuum tubes (also called valves) like the vacuum diode which has two electrodes, viz., anode (often called plate) and cathode; triode which has three electrodes – cathode, plate and grid; tetrode and pentode (respectively with 4 and 5 electrodes). In a vacuum tube, the electrons are supplied by a heated cathode and the controlled flow of these electrons *in vacuum* is obtained by varying the voltage between its different electrodes. Vacuum is required in the inter-electrode space; otherwise the moving electrons may lose their energy on collision with the air molecules in their path. In these devices the electrons can flow only from the cathode to the anode (i.e., only in one direction). Therefore, such devices are generally referred to as *valves*. These vacuum tube devices are bulky, consume high power, operate generally at high voltages (~100 V) and have limited life and low reliability. The seed of the development of modern *solid-state semiconductor electronics* goes back to 1930's when it was realised that some solid-state semiconductors and their junctions offer the possibility of controlling the number and the direction of flow of charge carriers through them. Simple excitations like light, heat or small applied voltage can change the number of mobile charges in a semiconductor. Note that the supply

and flow of charge carriers in the semiconductor devices are *within the solid itself*, while in the earlier vacuum tubes/valves, the mobile electrons were obtained from a heated cathode and they were made to flow in an *evacuated* space or vacuum. No external heating or large evacuated space is required by the semiconductor devices. They are small in size, consume low power, operate at low voltages and have long life and high reliability. Even the Cathode Ray Tubes (CRT) used in television and computer monitors which work on the principle of vacuum tubes are being replaced by Liquid Crystal Display (LCD) monitors with supporting solid state electronics. Much before the full implications of the semiconductor devices was formally understood, a naturally occurring crystal of *galena* (Lead sulphide, PbS) with a metal point contact attached to it was used as *detector* of radio waves.

In the following sections, we will introduce the basic concepts of semiconductor physics and discuss some semiconductor devices like junction diodes (a 2-electrode device) and bipolar junction transistor (a 3-electrode device). A few circuits illustrating their applications will also be described.

14.2 Classification of Metals, Conductors and Semiconductors

On the basis of conductivity

On the basis of the relative values of electrical conductivity (σ) or resistivity ($\rho = 1/\sigma$), the solids are broadly classified as:

(i) ***Metals:*** They possess very low resistivity (or high conductivity).
$\rho \sim 10^{-2} - 10^{-8}\ \Omega$ m
$\sigma \sim 10^{2} - 10^{8}$ S m^{-1}

(ii) ***Semiconductors:*** They have resistivity or conductivity intermediate to metals and insulators.
$\rho \sim 10^{-5} - 10^{6}\ \Omega$ m
$\sigma \sim 10^{5} - 10^{-6}$ S m^{-1}

(iii) ***Insulators:*** They have high resistivity (or low conductivity).
$\rho \sim 10^{11} - 10^{19}\ \Omega$ m
$\sigma \sim 10^{-11} - 10^{-19}$ S m^{-1}

The values of ρ and σ given above are indicative of magnitude and could well go outside the ranges as well. Relative values of the resistivity are not the only criteria for distinguishing metals, insulators and semiconductors from each other. There are some other differences, which will become clear as we go along in this chapter.

Our interest in this chapter is in the study of semiconductors which could be:

(i) *Elemental semiconductors*: Si and Ge

(ii) *Compound semiconductors*: Examples are:
- Inorganic: CdS, GaAs, CdSe, InP, etc.
- Organic: anthracene, doped pthalocyanines, etc.
- Organic polymers: polypyrrole, polyaniline, polythiophene, etc.

Most of the currently available semiconductor devices are based on elemental semiconductors Si or Ge and compound *inorganic*

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semiconductors. However, after 1990, a few semiconductor devices using organic semiconductors and semiconducting polymers have been developed signalling the birth of a futuristic technology of polymer-electronics and molecular-electronics. In this chapter, we will restrict ourselves to the study of inorganic semiconductors, particularly elemental semiconductors Si and Ge. The general concepts introduced here for discussing the elemental semiconductors, by-and-large, apply to most of the compound semiconductors as well.

On the basis of energy bands

According to the Bohr atomic model, in an *isolated atom* the energy of any of its electrons is decided by the orbit in which it revolves. But when the atoms come together to form a solid they are close to each other. So the outer orbits of electrons from neighbouring atoms would come very close or could even overlap. This would make the nature of electron motion in a solid very different from that in an isolated atom.

Inside the crystal each electron has a unique position and no two electrons see exactly the same pattern of surrounding charges. Because of this, each electron will have a different *energy level*. These different energy levels with continuous energy variation form what are called *energy bands*. The energy band which includes the energy levels of the valence electrons is called the *valence band*. The energy band above the valence band is called the *conduction band*. With no external energy, all the valence electrons will reside in the valence band. If the lowest level in the conduction band happens to be lower than the highest level of the valence band, the electrons from the valence band can easily move into the conduction band. Normally the conduction band is empty. But when it overlaps on the valence band electrons can move freely into it. This is the case with metallic conductors.

If there is some gap between the conduction band and the valence band, electrons in the valence band all remain bound and no free electrons are available in the conduction band. This makes the material an insulator. But some of the electrons from the valence band may gain external energy to cross the gap between the conduction band and the valence band. Then these electrons will move into the conduction band. At the same time they will create vacant energy levels in the valence band where other valence electrons can move. Thus the process creates the possibility of conduction due to electrons in conduction band as well as due to vacancies in the valence band.

Let us consider what happens in the case of Si or Ge crystal containing N atoms. For Si, the outermost orbit is the third orbit ($n = 3$), while for Ge it is the fourth orbit ($n = 4$). The number of electrons in the outermost orbit is 4 ($2s$ and $2p$ electrons). Hence, the total number of outer electrons in the crystal is $4N$. The maximum possible number of electrons in the outer orbit is 8 ($2s + 6p$ electrons). So, for the $4N$ valence electrons there are $8N$ available energy states. These $8N$ discrete energy levels can either form a continuous band or they may be grouped in different bands depending upon the distance between the atoms in the crystal (see box on Band Theory of Solids).

At the distance between the atoms in the crystal lattices of Si and Ge, the energy band of these $8N$ states is split apart into two which are separated by an *energy gap* E_g (Fig. 14.1). The lower band which is

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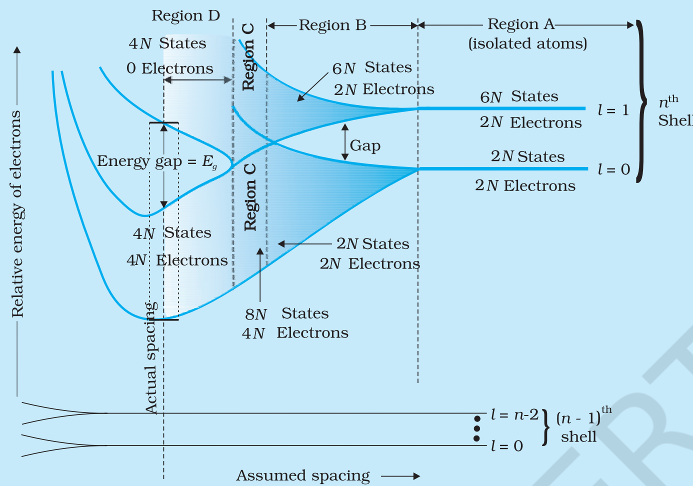
completely occupied by the $4N$ valence electrons at temperature of absolute zero is the *valence band.* The other band consisting of $4N$ energy states, called the *conduction band*, is completely empty at absolute zero.

BAND THEORY OF SOLIDS



Consider that the Si or Ge crystal contains N atoms. Electrons of each atom will have discrete energies in different orbits. The electron energy will be same if all the atoms are *isolated*, i.e., separated from each other by a large distance. However, in a crystal, the atoms are close to each other (2 to 3 Å) and therefore the electrons interact with each other and also with the neighbouring atomic cores. The overlap (or interaction) will be more felt by the electrons in the outermost orbit while the inner orbit or core electron energies may remain unaffected. Therefore, for understanding electron energies in Si or Ge crystal, we need to consider the changes in the energies of the electrons in the outermost orbit only. For Si, the outermost orbit is the third orbit (n = 3), while for Ge it is the fourth orbit (n = 4). The number of electrons in the outermost orbit is 4 (2s and 2p electrons). Hence, the total number of outer electrons in the crystal is $4N$. The maximum possible number of outer electrons in the orbit is 8 (2s + 6p electrons). So, out of the $4N$ electrons, $2N$ electrons are in the $2N$ *s-states* (orbital quantum number l = 0) and $2N$ electrons are in the available $6N$ *p-states*. Obviously, some *p*-electron states are empty as shown in the extreme right of Figure. This is the case of well separated or isolated atoms [region A of Figure].

Suppose these atoms start coming nearer to each other to form a solid. The energies of these electrons in the outermost orbit may change (both increase and decrease) due to the interaction between the electrons of different atoms. The $6N$ states for l = 1, which originally had identical energies in the isolated atoms, spread out and form an *energy band* [region B in Figure]. Similarly, the $2N$ states for l = 0, having identical energies in the isolated atoms, split into a second band (carefully see the region B of Figure) separated from the first one by an *energy gap.*

At still smaller spacing, however, there comes a region in which the bands merge with each other. The lowest energy state that is a split from the upper atomic level appears to drop below the upper state that has come from the lower atomic level. In this region (region C in Figure), *no energy gap exists where the upper and lower energy states get mixed.*

Finally, if the distance between the atoms further decreases, the energy bands again split apart and are separated by an *energy gap* E_g (region D in Figure). The total number of available energy states $8N$ has been *re-apportioned* between the two bands ($4N$ states each in the lower and upper energy bands). Here the significant point is that there are exactly as many states in the lower band ($4N$) as there are available valence electrons from the atoms ($4N$).

Therefore, this band (called the *valence band*) is completely filled while the upper band is completely empty. The upper band is called the *conduction band.*

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The lowest energy level in the conduction band is shown as E_C and highest energy level in the valence band is shown as E_V. Above E_C and below E_V there are a large number of closely spaced energy levels, as shown in Fig. 14.1.

The gap between the top of the valence band and bottom of the conduction band is called the *energy band gap* (Energy gap E_g). It may be large, small, or zero, depending upon the material. These different situations, are depicted in Fig. 14.2 and discussed below:

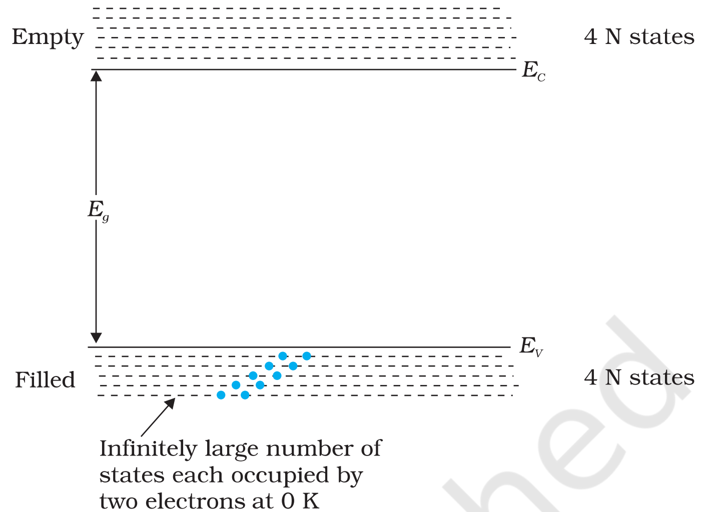

FIGURE 14.1 The energy band positions in a semiconductor at 0 K. The upper band, called the conduction band, consists of infinitely large number of closely spaced energy states. The lower band, called the valence band, consists of closely spaced completely filled energy states.

Case I: This refers to a situation, as shown in Fig. 14.2(a). One can have a metal either when the conduction band is partially filled and the balanced band is partially empty or when the conduction and valance bands overlap. When there is overlap electrons from valence band can easily move into the conduction band. This situation makes a large number of electrons available for electrical conduction. When the valence band is partially empty, electrons from its lower level can move to higher level making conduction possible. Therefore, the resistance of such materials is low or the conductivity is high.

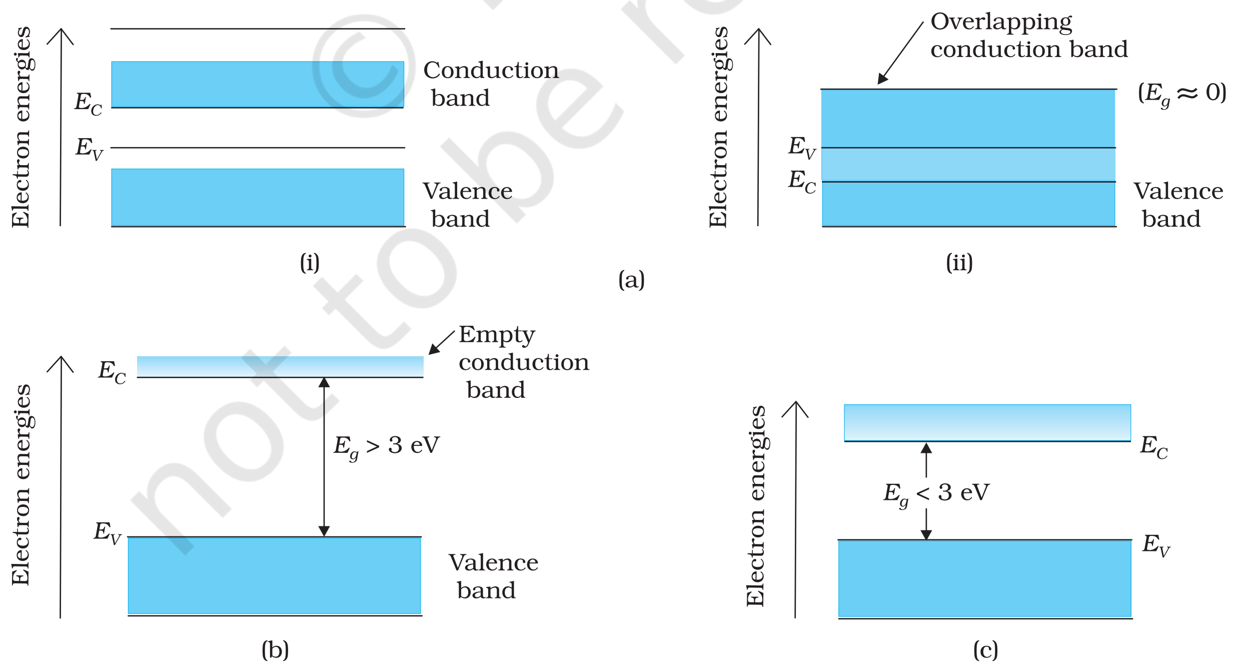

FIGURE 14.2 Difference between energy bands of (a) metals, (b) insulators and (c) semiconductors.

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Case II: In this case, as shown in Fig. 14.2(b), a large band gap E_g exists (E_g > 3 eV). There are no electrons in the conduction band, and therefore no electrical conduction is possible. Note that the energy gap is so large that electrons cannot be excited from the valence band to the conduction band by thermal excitation. This is the case of *insulators*.

Case III: This situation is shown in Fig. 14.2(c). Here a finite but small band gap (E_g < 3 eV) exists. Because of the small band gap, at room temperature some electrons from valence band can acquire enough energy to cross the energy gap and enter the *conduction band*. These electrons (though small in numbers) can move in the conduction band. Hence, the resistance of *semiconductors* is not as high as that of the insulators.

In this section we have made a broad classification of metals, conductors and semiconductors. In the section which follows you will learn the conduction process in semiconductors.

14.3 Intrinsic Semiconductor

We shall take the most common case of Ge and Si whose lattice structure is shown in Fig. 14.3. These structures are called the diamond-like structures. Each atom is surrounded by four nearest neighbours. We know that Si and Ge have four valence electrons. In its crystalline structure, every Si or Ge atom tends *to share* one of its four valence electrons with each of its four nearest neighbour atoms, and also *to take share* of one electron from each such neighbour. These shared electron pairs are referred to as forming a *covalent bond* or simply a *valence bond*. The two shared electrons can be assumed to shuttle back-and-forth between the associated atoms holding them together strongly. Figure 14.4 schematically shows the 2-dimensional representation of Si or Ge structure shown in Fig. 14.3 which overemphasises the covalent bond. It shows an idealised picture in which no bonds are broken (all bonds are intact). Such a situation arises at low temperatures. As the temperature increases, more thermal energy becomes available to these electrons and some of these electrons may break–away (becoming *free* electrons contributing to conduction). The thermal energy effectively ionises only a few atoms in the crystalline lattice and creates a *vacancy* in the bond as shown in Fig. 14.5(a). The neighbourhood, from which the free electron (with charge $-q$) has come out leaves a vacancy with an effective charge ($+q$). This *vacancy* with the effective positive electronic charge is called a *hole*. The hole behaves as an *apparent free particle* with effective positive charge.

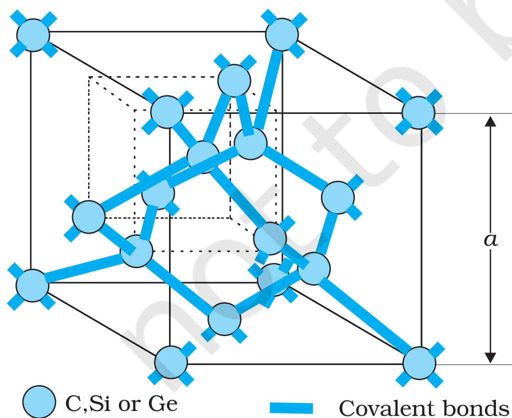

FIGURE 14.3 Three-dimensional diamond-like crystal structure for Carbon, Silicon or Germanium with respective lattice spacing a equal to 3.56, 5.43 and 5.66 Å.

In intrinsic semiconductors, the number of free electrons, n_e is equal to the number of holes, n_h. That is

$$n_e = n_h = n_i \quad (14.1)$$

where n_i is called intrinsic carrier concentration.

Semiconductors posses the unique property in which, apart from electrons, the holes also move.

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Suppose there is a hole at site 1 as shown in Fig. 14.5(a). The movement of holes can be visualised as shown in Fig. 14.5(b). An electron from the covalent bond at site 2 may jump to the vacant site 1 (hole). Thus, after such a jump, the hole is at site 2 and the site 1 has now an electron. Therefore, apparently, the hole has moved from site 1 to site 2. Note that the electron originally set free [Fig. 14.5(a)] is not involved in this process of hole motion. The free electron moves completely independently as conduction electron and gives rise to an electron current, I_e under an applied electric field. Remember that the motion of hole is only a convenient way of describing the actual motion of *bound* electrons, whenever there is an empty bond anywhere in the crystal. Under the action of an electric field, these holes move towards negative potential giving the hole current, I_h. The total current, I is thus the sum of the electron current I_e and the hole current I_h:

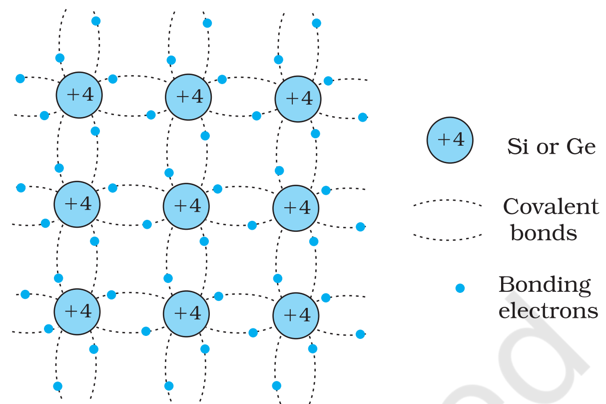

FIGURE 14.4 Schematic two-dimensional representation of Si or Ge structure showing covalent bonds at low temperature (all bonds intact). +4 symbol indicates inner cores of Si or Ge.

$$I = I_e + I_h \tag{14.2}$$

It may be noted that apart from the *process of generation* of conduction electrons and holes, a simultaneous *process of recombination* occurs in which the electrons *recombine* with the holes. At equilibrium, the rate of generation is equal to the rate of recombination of charge carriers. The recombination occurs due to an electron colliding with a hole.

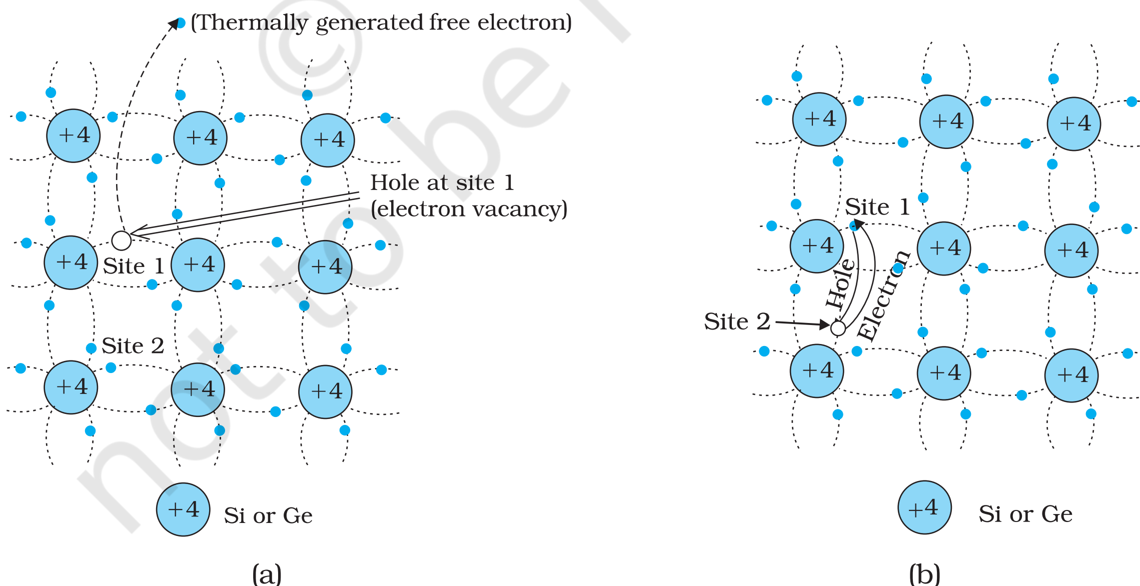

FIGURE 14.5 (a) Schematic model of generation of hole at site 1 and conduction electron due to thermal energy at moderate temperatures. (b) Simplified representation of possible thermal motion of a hole. The electron from the lower left hand covalent bond (site 2) goes to the earlier hole site1, leaving a hole at its site indicating an apparent movement of the hole from site 1 to site 2.

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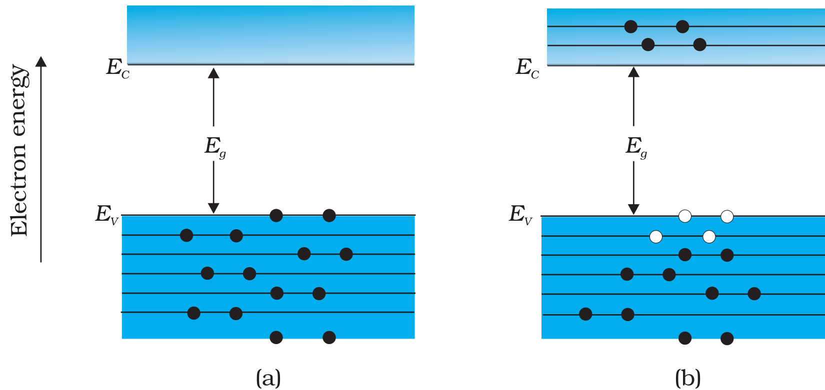

FIGURE 14.6 (a) An intrinsic semiconductor at $T = 0$ K behaves like insulator. (b) At $T > 0$ K, four thermally generated electron-hole pairs. The filled circles (•) represent electrons and empty circles (○) represent holes.

An intrinsic semiconductor will behave like an insulator at $T = 0$ K as shown in Fig. 14.6(a). It is the thermal energy at higher temperatures ($T > 0$K), which excites some electrons from the valence band to the conduction band. These thermally excited electrons at $T > 0$ K, partially occupy the conduction band. Therefore, the energy-band diagram of an intrinsic semiconductor will be as shown in Fig. 14.6(b). Here, some electrons are shown in the conduction band. These have come from the valence band leaving equal number of holes there.

EXAMPLE 14.1

Example 14.1 C, Si and Ge have same lattice structure. Why is C insulator while Si and Ge intrinsic semiconductors?

Solution The 4 bonding electrons of C, Si or Ge lie, respectively, in the second, third and fourth orbit. Hence, energy required to take out an electron from these atoms (i.e., ionisation energy E_g) will be least for Ge, followed by Si and highest for C. Hence, number of free electrons for conduction in Ge and Si are significant but negligibly small for C.

14.4 Extrinsic Semiconductor

The conductivity of an intrinsic semiconductor depends on its temperature, but at room temperature its conductivity is very low. As such, no important electronic devices can be developed using these semiconductors. Hence there is a necessity of improving their conductivity. This can be done by making use of impurities.

When a small amount, say, a few parts per million (ppm), of a suitable impurity is added to the pure semiconductor, the conductivity of the semiconductor is increased manifold. Such materials are known as *extrinsic semiconductors* or *impurity semiconductors*. The deliberate addition of a desirable impurity is called *doping* and the impurity atoms are called *dopants*. Such a material is also called a *doped semiconductor*. The dopant has to be such that it does not distort the original pure semiconductor lattice. It occupies only a very few of the original semiconductor atom sites in the crystal. A necessary condition to attain this is that the sizes of the dopant and the semiconductor atoms should be nearly the same.

There are two types of dopants used in doping the tetravalent Si or Ge:

(i) Pentavalent (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

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(ii) Trivalent (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.

We shall now discuss how the doping changes the number of charge carriers (and hence the conductivity) of semiconductors. Si or Ge belongs to the fourth group in the Periodic table and, therefore, we choose the dopant element from nearby fifth or third group, expecting and taking care that the size of the dopant atom is nearly the same as that of Si or Ge. Interestingly, the pentavalent and trivalent dopants in Si or Ge give two entirely different types of semiconductors as discussed below.

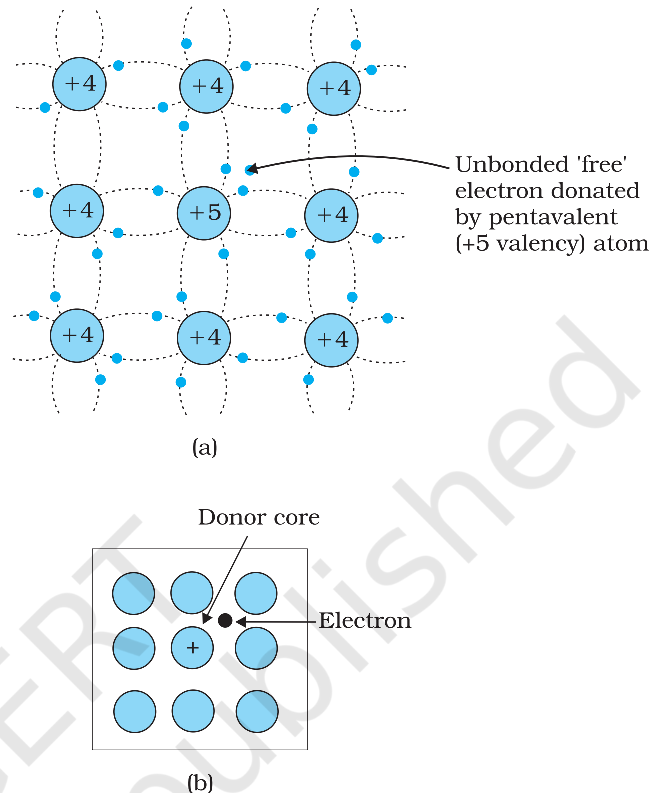

FIGURE 14.7 (a) Pentavalent donor atom (As, Sb, P, etc.) doped for tetravalent Si or Ge giving n-type semiconductor, and (b) Commonly used schematic representation of n-type material which shows only the fixed cores of the substituent donors with one additional effective positive charge and its associated extra electron.

(i) n-type semiconductor

Suppose we dope Si or Ge with a pentavalent element as shown in Fig. 14.7. When an atom of +5 valency element occupies the position of an atom in the crystal lattice of Si, four of its electrons bond with the four silicon neighbours while the fifth remains very weakly bound to its parent atom. This is because the four electrons participating in bonding are seen as part of the effective core of the atom by the fifth electron. As a result the ionisation energy required to set this electron free is very small and even at room temperature it will be free to move in the lattice of the semiconductor. For example, the energy required is ~ 0.01 eV for germanium, and 0.05 eV for silicon, to separate this electron from its atom. This is in contrast to the energy required to jump the forbidden band (about 0.72 eV for germanium and about 1.1 eV for silicon) at room temperature in the intrinsic semiconductor. Thus, the pentavalent dopant is donating one extra electron for conduction and hence is known as *donor* impurity. The number of electrons made available for conduction by dopant atoms depends strongly upon the doping level and is independent of any increase in ambient temperature. On the other hand, the number of free electrons (with an equal number of holes) generated by Si atoms, increases weakly with temperature.

In a doped semiconductor the total number of conduction electrons n_e is due to the electrons contributed by donors and those generated intrinsically, while the total number of holes n_h is only due to the holes from the intrinsic source. But the rate of recombination of holes would increase due to the increase in the number of electrons. As a result, the number of holes would get reduced further.

Thus, with proper level of doping the number of conduction electrons can be made much larger than the number of holes. Hence in an extrinsic

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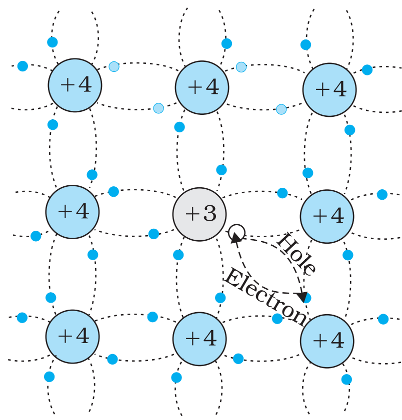
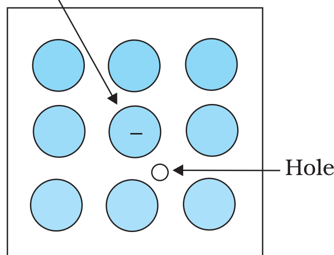


(a)



(b)

FIGURE 14.8 (a) Trivalent acceptor atom (In, Al, B etc.) doped in tetravalent Si or Ge lattice giving p-type semiconductor. (b) Commonly used schematic representation of p-type material which shows only the fixed core of the substituent acceptor with one effective additional negative charge and its associated hole.

semiconductor doped with pentavalent impurity, electrons become the *majority carriers* and holes the *minority carriers*. These semiconductors are, therefore, known as n-*type semiconductors*. For n-type semiconductors, we have,

$$n_e >> n_h \qquad (14.3)$$

(ii) p-type semiconductor

This is obtained when Si or Ge is doped with a trivalent impurity like Al, B, In, etc. The dopant has one valence electron less than Si or Ge and, therefore, this atom can form covalent bonds with neighbouring three Si atoms but does not have any electron to offer to the fourth Si atom. So the bond between the fourth neighbour and the trivalent atom has a vacancy or hole as shown in Fig. 14.8. Since the neighbouring Si atom in the lattice wants an electron in place of a hole, an electron in the outer orbit of an atom in the neighbourhood may jump to fill this vacancy, leaving a vacancy or hole at its own site. Thus the *hole* is available for conduction. Note that the trivalent foreign atom becomes effectively negatively charged when it shares fourth electron with neighbouring Si atom. Therefore, the dopant atom of p-type material can be treated as *core of one negative charge* along with its associated hole as shown in Fig. 14.8(b). It is obvious that one *acceptor* atom gives one *hole*. These holes are in addition to the intrinsically generated holes while the source of conduction electrons is only intrinsic generation. Thus, for such a material, the holes are the majority carriers and electrons are minority carriers. Therefore, extrinsic semiconductors doped with trivalent impurity are called p-*type semiconductors*. For p-type semiconductors, the recombination process will reduce the number $(n_i)$of intrinsically generated electrons to n_e. We have, for p-type semiconductors

$$n_h >> n_e \qquad (14.4)$$

Note that *the crystal maintains an overall charge neutrality as the charge of additional charge carriers is just equal and opposite to that of the ionised cores in the lattice.*

In extrinsic semiconductors, because of the abundance of majority current carriers, the minority carriers produced thermally have more chance of meeting majority carriers and thus getting destroyed. Hence, the dopant, by adding a large number of current carriers of one type, which become the majority carriers, indirectly helps to reduce the intrinsic concentration of minority carriers.

The semiconductor's energy band structure is affected by doping. In the case of extrinsic semiconductors, additional energy states due to donor impurities (E_D) and acceptor impurities (E_A) also exist. In the energy band diagram of n-type Si semiconductor, the donor energy level E_D is slightly below the bottom E_C of the conduction band and electrons from this level move into the conduction band with very small supply of energy. At room temperature, most of the donor atoms get ionised but very few (~10^{12}) atoms of Si get ionised. So the conduction band will have most electrons coming from the donor impurities, as shown in Fig. 14.9(a). Similarly,

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for p-type semiconductor, the acceptor energy level E_A is slightly above the top E_V of the valence band as shown in Fig. 14.9(b). With very small supply of energy an electron from the valence band can jump to the level E_A and ionise the acceptor negatively. (Alternately, we can also say that with very small supply of energy the hole from level E_A sinks down into the valence band. Electrons rise up and holes fall down when they gain external energy.) At room temperature, most of the acceptor atoms get ionised leaving holes in the valence band. Thus at room temperature the density of holes in the valence band is predominantly due to impurity in the extrinsic semiconductor. The electron and hole concentration in a semiconductor *in thermal equilibrium* is given by

$$n_e n_h = n_i^2 \tag{14.5}$$

Though the above description is grossly approximate and hypothetical, it helps in understanding the difference between metals, insulators and semiconductors (extrinsic and intrinsic) in a simple manner. The difference in the resistivity of C, Si and Ge depends upon the energy gap between their conduction and valence bands. For C (diamond), Si and Ge, the energy gaps are 5.4 eV, 1.1 eV and 0.7 eV, respectively. Sn also is a group IV element but it is a metal because the energy gap in its case is 0 eV.

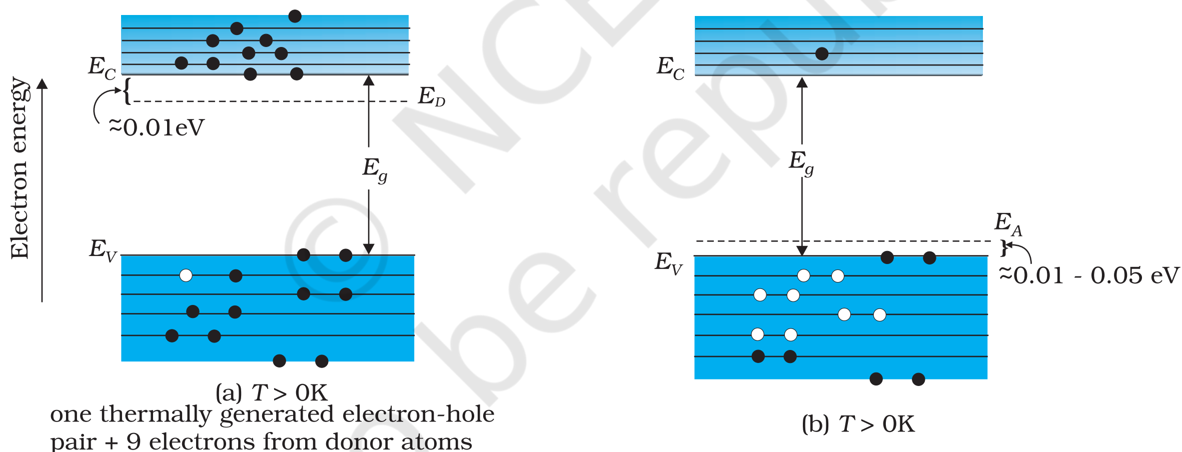

FIGURE 14.9 Energy bands of (a) n-type semiconductor at T > 0K, (b) p-type semiconductor at T > 0K.

Example 14.2 Suppose a pure Si crystal has 5×10^{28} atoms m^{-3}. It is doped by 1 ppm concentration of pentavalent As. Calculate the number of electrons and holes. Given that $n_i = 1.5 \times 10^{16}$ m^{-3}.

Solution Note that thermally generated electrons ($n_i \sim 10^{16}$ m^{-3}) are negligibly small as compared to those produced by doping.

Therefore, $n_e \approx N_D$.

Since $n_e n_h = n_i^2$, The number of holes

$n_h = (2.25 \times 10^{32})/(5 \times 10^{22})$

$\sim 4.5 \times 10^9$ m^{-3}

EXAMPLE 14.2

14.5 p-n JUNCTION

A p-n junction is the basic building block of many semiconductor devices like diodes, transistor, etc. A clear understanding of the junction behaviour is important to analyse the working of other semiconductor devices. We will now try to understand how a junction is formed and how the junction behaves under the influence of external applied voltage (also called *bias*).

14.5.1 p-n junction formation

Consider a thin p-type silicon (p-Si) semiconductor wafer. By adding precisely a small quantity of pentavelent impurity, part of the p-Si wafer can be converted into n-Si. There are several processes by which a semiconductor can be formed. The wafer now contains p-region and n-region and a metallurgical junction between p-, and n- region.

Two important processes occur during the formation of a p-n junction: *diffusion* and *drift*. We know that in an n-type semiconductor, the concentration of electrons (number of electrons per unit volume) is more compared to the concentration of holes. Similarly, in a p-type semiconductor, the concentration of holes is more than the concentration of electrons. During the formation of p-n junction, and due to the concentration gradient across p-, and n- sides, holes diffuse from p-side to n-side ($p \rightarrow n$) and electrons diffuse from n-side to p-side ($n \rightarrow p$). This motion of charge carriers gives rise to diffusion current across the junction.

When an electron diffuses from $n \rightarrow p$, it leaves behind an ionised donor on n-side. This ionised donor (positive charge) is immobile as it is bonded to the surrounding atoms. As the electrons continue to diffuse from $n \rightarrow p$, a layer of positive charge (or positive space-charge region) on n-side of the junction is developed.

Similarly, when a hole diffuses from $p \rightarrow n$ due to the concentration gradient, it leaves behind an ionised acceptor (negative charge) which is immobile. As the holes continue to diffuse, a layer of negative charge (or negative space-charge region) on the p-side of the junction is developed. This space-charge region on either side of the junction together is known as *depletion region* as the electrons and holes taking part in the initial movement across the junction *depleted* the region of its free charges (Fig. 14.10). The thickness of depletion region is of the order of one-tenth of a micrometre. Due to the positive space-charge region on n-side of the junction and negative space charge region on p-side of the junction, an electric field directed from positive charge towards negative charge develops. Due to this field, an electron on p-side of the junction moves to n-side and a hole on n-side of the junction moves to p-side. The motion of charge carriers due to the electric field is called drift. Thus a drift current, which is opposite in direction to the diffusion current (Fig. 14.10) starts.

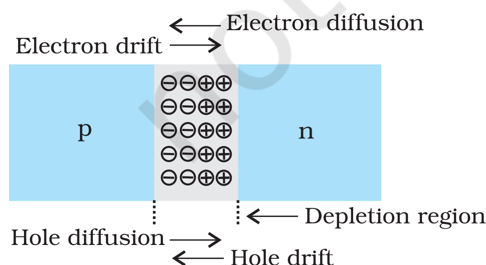

FIGURE 14.10 p-n junction formation process.

PHYSICS
Formation and working of p-n junction diode
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/pnjun.html

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Initially, diffusion current is large and drift current is small. As the diffusion process continues, the space-charge regions on either side of the junction extend, thus increasing the electric field strength and hence drift current. This process continues until the diffusion current equals the drift current. Thus a p-n junction is formed. In a p-n junction under equilibrium there is *no net* current.

The loss of electrons from the n-region and the gain of electron by the p-region causes a difference of potential across the junction of the two regions. The polarity of this potential is such as to oppose further flow of carriers so that a condition of equilibrium exists. Figure 14.11 shows the p-n junction at equilibrium and the potential across the junction. The n-material has lost electrons, and p material has acquired electrons. The n material is thus positive relative to the p material. Since this potential tends to prevent the movement of electron from the n region into the p region, it is often called a *barrier potential*.

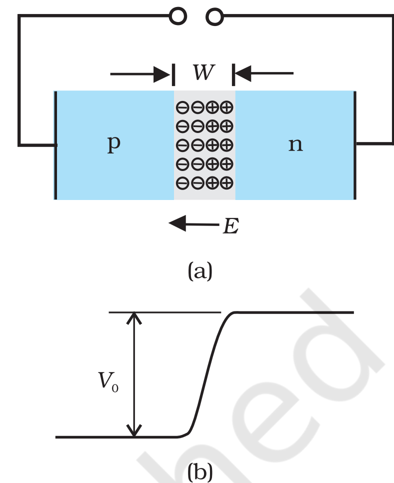

FIGURE 14.11 (a) Diode under equilibrium (V = 0), (b) Barrier potential under no bias.

Example 14.3 Can we take one slab of p-type semiconductor and physically join it to another n-type semiconductor to get p-n junction?

Solution No! Any slab, howsoever flat, will have roughness much larger than the inter-atomic crystal spacing (~2 to 3 Å) and hence *continuous contact* at the atomic level will not be possible. The junction will behave as a *discontinuity* for the flowing charge carriers.

EXAMPLE 14.3

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14.6 Semiconductor Diode

A semiconductor diode [Fig. 14.12(a)] is basically a p-n junction with metallic contacts provided at the ends for the application of an external voltage. It is a two terminal device. A p-n junction diode is symbolically represented as shown in Fig. 14.12(b).

The direction of arrow indicates the conventional direction of current (when the diode is under forward bias). The equilibrium barrier potential can be altered by applying an external voltage V across the diode. The situation of p-n junction diode under equilibrium (without bias) is shown in Fig. 14.11(a) and (b).

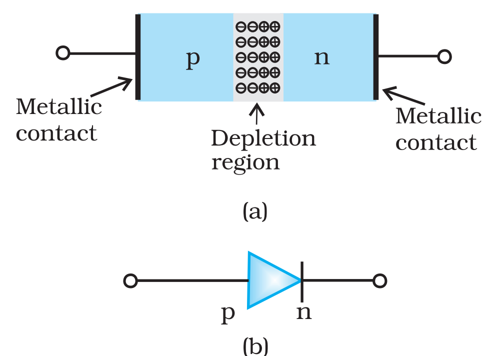

FIGURE 14.12 (a) Semiconductor diode, (b) Symbol for p-n junction diode.

14.6.1 p-n junction diode under forward bias

When an external voltage V is applied across a semiconductor diode such that p-side is connected to the positive terminal of the battery and n-side to the negative terminal [Fig. 14.13(a)], it is said to be *forward biased*.

The applied voltage mostly drops across the depletion region and the voltage drop across the p-side and n-side of the junction is negligible. (This is because the resistance of the depletion region – a region where there are no charges – is very high compared to the resistance of n-side and p-side.) The direction of the applied voltage (V) is opposite to the

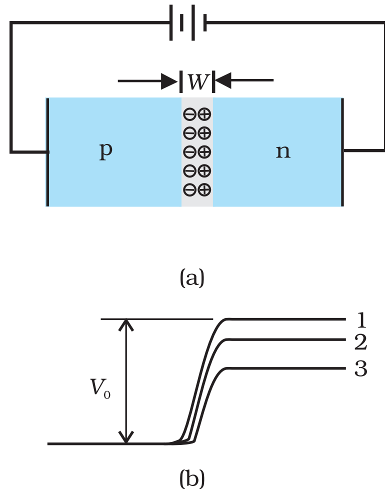

FIGURE 14.13 (a) p-n junction diode under forward bias, (b) Barrier potential (1) without battery, (2) Low battery voltage, and (3) High voltage battery.

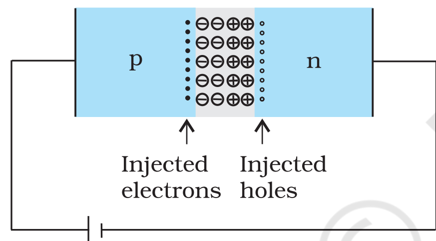

FIGURE 14.14 Forward bias minority carrier injection.

built-in potential V_0. As a result, the depletion layer width decreases and the barrier height is reduced [Fig. 14.13(b)]. The effective barrier height under forward bias is $(V_0 - V)$.

If the applied voltage is small, the barrier potential will be reduced only slightly below the equilibrium value, and only a small number of carriers in the material—those that happen to be in the uppermost energy levels—will possess enough energy to cross the junction. So the current will be small. If we increase the applied voltage significantly, the barrier height will be reduced and more number of carriers will have the required energy. Thus the current increases.

Due to the applied voltage, electrons from n-side cross the depletion region and reach p-side (where they are minority carries). Similarly, holes from p-side cross the junction and reach the n-side (where they are minority carries). This process under forward bias is known as minority carrier injection. At the junction boundary, on each side, the minority carrier concentration increases significantly compared to the locations far from the junction.

Due to this concentration gradient, the injected electrons on p-side diffuse from the junction edge of p-side to the other end of p-side. Likewise, the injected holes on n-side diffuse from the junction edge of n-side to the other end of n-side (Fig. 14.14). This motion of charged carriers on either side gives rise to current. The total diode forward current is sum of hole diffusion current and conventional current due to electron diffusion. The magnitude of this current is usually in mA.

14.6.2 p-n junction diode under reverse bias

When an external voltage (V) is applied across the diode such that n-side is positive and p-side is negative, it is said to be *reverse biased* [Fig.14.15(a)]. The applied voltage mostly drops across the depletion region. The direction of applied voltage is same as the direction of barrier potential. As a result, the barrier height increases and the depletion region widens due to the change in the electric field. The effective barrier height under reverse bias is $(V_0 + V)$, [Fig. 14.15(b)]. This suppresses the flow of electrons from n → p and holes from p → n. Thus, diffusion current, decreases enormously compared to the diode under forward bias.

The electric field direction of the junction is such that if electrons on p-side or holes on n-side in their random motion come close to the junction, they will be swept to its majority zone. This drift of carriers gives rise to current. The drift current is of the order of a few μA. This is quite low because it is due to the motion of carriers from their minority side to their majority side across the junction. The drift current is also there under forward bias but it is negligible (μA) when compared with current due to injected carriers which is usually in mA.

The diode reverse current is not very much dependent on the applied voltage. Even a small voltage is sufficient to sweep the minority carriers from one side of the junction to the other side of the junction. The current

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is not limited by the magnitude of the applied voltage but is limited due to the concentration of the minority carrier on either side of the junction.

The current under reverse bias is essentially voltage independent upto a critical reverse bias voltage, known as breakdown voltage (V_{br}). When $V = V_{br}$, the diode reverse current increases sharply. Even a slight increase in the bias voltage causes large change in the current. If the reverse current is not limited by an external circuit below the rated value (specified by the manufacturer) the p-n junction will get destroyed. Once it exceeds the rated value, the diode gets destroyed due to overheating. This can happen even for the diode under forward bias, if the forward current exceeds the rated value.

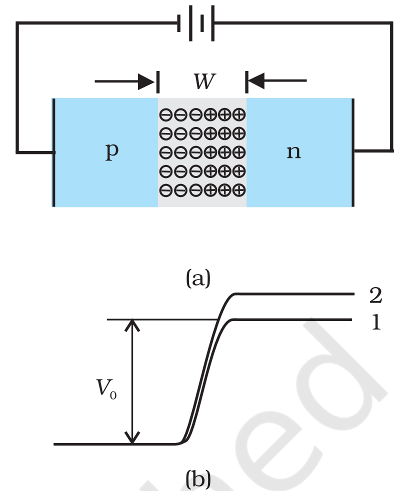

FIGURE 14.15 (a) Diode under reverse bias, (b) Barrier potential under reverse bias.

The circuit arrangement for studying the *V-I* characteristics of a diode, (i.e., the variation of current as a function of applied voltage) are shown in Fig. 14.16(a) and (b). The battery is connected to the diode through a potentiometer (or reheostat) so that the applied voltage to the diode can be changed. For different values of voltages, the value of the current is noted. A graph between *V* and *I* is obtained as in Fig. 14.16(c). Note that in forward bias measurement, we use a milliammeter since the expected current is large (as explained in the earlier section) while a micrometer is used in reverse bias to measure the current. You can see in Fig. 14.16(c) that in forward

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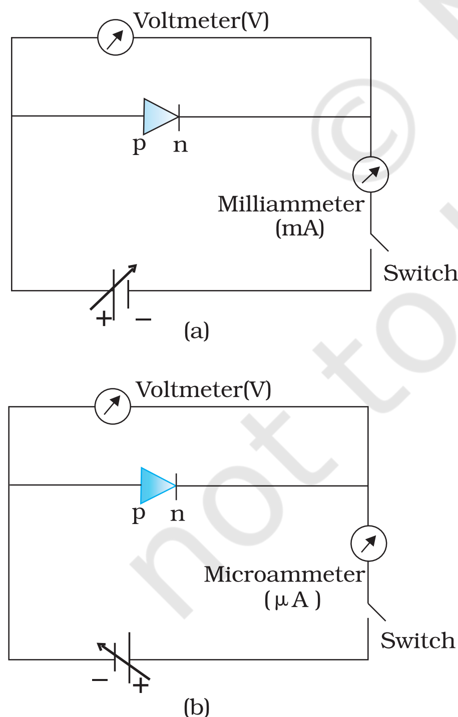

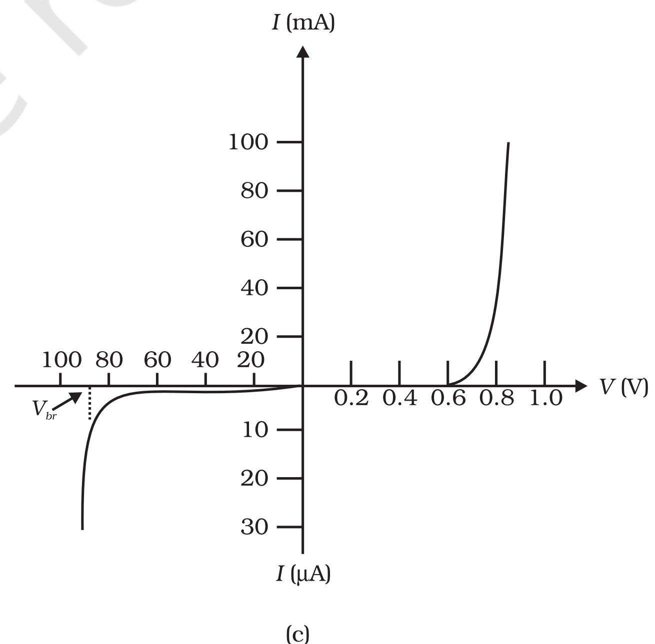

FIGURE 14.16 Experimental circuit arrangement for studying *V-I* characteristics of a p-n junction diode (a) in forward bias, (b) in reverse bias. (c) Typical *V-I* characteristics of a silicon diode.

bias, the current first increases very slowly, almost negligibly, till the voltage across the diode crosses a certain value. After the characteristic voltage, the diode current increases significantly (exponentially), even for a very small increase in the diode bias voltage. This voltage is called the *threshold voltage* or cut-in voltage (~0.2V for germanium diode and ~0.7 V for silicon diode).

For the diode in reverse bias, the current is very small (~μA) and almost remains constant with change in bias. It is called *reverse saturation current*. However, for special cases, at very high reverse bias (break down voltage), the current suddenly increases. This special action of the diode is discussed later in Section 14.8. The general purpose diode are not used beyond the reverse saturation current region.

The above discussion shows that the p-n junction diode primerly allows the flow of current only in one direction (forward bias). The forward bias resistance is low as compared to the reverse bias resistance. This property is used for rectification of ac voltages as discussed in the next section. For diodes, we define a quantity called *dynamic resistance* as the ratio of small change in voltage ΔV to a small change in current ΔI:

$$r_d = \frac{\Delta V}{\Delta I} \qquad (14.6)$$

Example 14.4 The *V-I* characteristic of a silicon diode is shown in the Fig. 14.17. Calculate the resistance of the diode at (a) I_D = 15 mA and (b) V_D = –10 V.

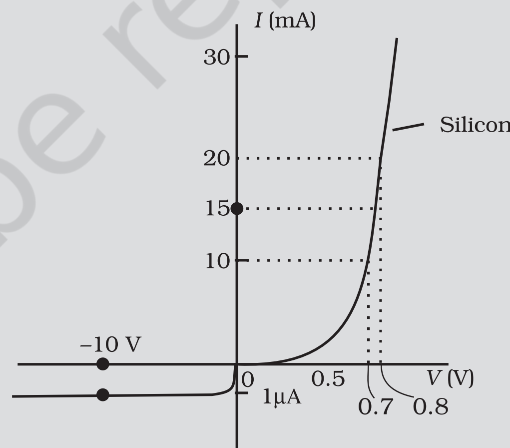

FIGURE 14.17

Solution Considering the diode characteristics as a straight line between I = 10 mA to I = 20 mA passing through the origin, we can calculate the resistance using Ohm's law.

(a) From the curve, at I = 20 mA, V = 0.8 V; I = 10 mA, V = 0.7 V

$r_{fb} = \Delta V/\Delta I$ = 0.1V/10 mA = 10 Ω

(b) From the curve at V = –10 V, I = –1 μA,

Therefore,

r_{rb} = 10 V/1μA= 1.0×10^7 Ω

EXAMPLE 14.4

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14.7 Application of Junction Diode as a Rectifier

From the *V-I* characteristic of a junction diode we see that it allows current to pass only when it is forward biased. So if an alternating voltage is applied across a diode the current flows only in that part of the cycle when the diode is forward biased. This property is used *to rectify* alternating voltages and the circuit used for this purpose is called a *rectifier*.

If an alternating voltage is applied across a diode in series with a load, a pulsating voltage will appear across the load only during the half cycles of the ac input during which the diode is forward biased. Such rectifier circuit, as shown in Fig. 14.18, is called a *half-wave rectifier*. The secondary of a transformer supplies the desired ac voltage across terminals A and B. When the voltage at A is positive, the diode is forward biased and it conducts. When A is negative, the diode is reverse-biased and it does not conduct. The reverse saturation current of a diode is negligible and can be considered equal to zero for practical purposes. (The reverse breakdown voltage of the diode must be sufficiently higher than the peak ac voltage at the secondary of the transformer to protect the diode from reverse breakdown.)

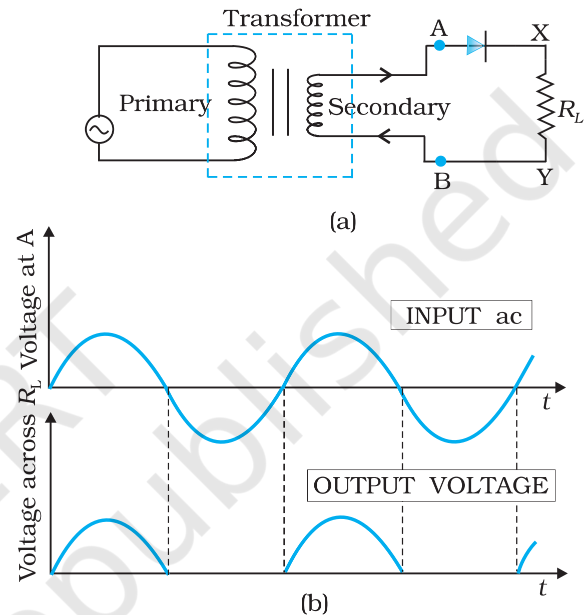

FIGURE 14.18 (a) Half-wave rectifier circuit, (b) Input ac voltage and output voltage waveforms from the rectifier circuit.

Therefore, in the positive *half-cycle* of ac there is a current through the load resistor R_L and we get an output voltage, as shown in Fig. 14.18(b), whereas there is no current in the negative half-cycle. In the next positive half-cycle, again we get the output voltage. Thus, the output voltage, though still varying, is restricted to *only one direction* and is said to be *rectified*. Since the rectified output of this circuit is only for half of the input ac wave it is called as *half-wave rectifier*.

The circuit using two diodes, shown in Fig. 14.19(a), gives output rectified voltage corresponding to both the positive as well as negative half of the ac cycle. Hence, it is known as *full-wave rectifier*. Here the p-side of the two diodes are connected to the ends of the secondary of the transformer. The n-side of the diodes are connected together and the output is taken between this common point of diodes and the midpoint of the secondary of the transformer. So for a full-wave rectifier the secondary of the transformer is provided with a centre tapping and so it is called *centre-tap transformer*. As can be seen from Fig.14.19(c) the voltage rectified by each diode is only half the total secondary voltage. Each diode rectifies only for half the cycle, but the two do so for alternate cycles. Thus, the output between their common terminals and the centre-tap of the transformer becomes a full-wave rectifier output. (Note that there is another circuit of full wave rectifier which does not need a centre-tap transformer but needs four diodes.) Suppose the input voltage to A

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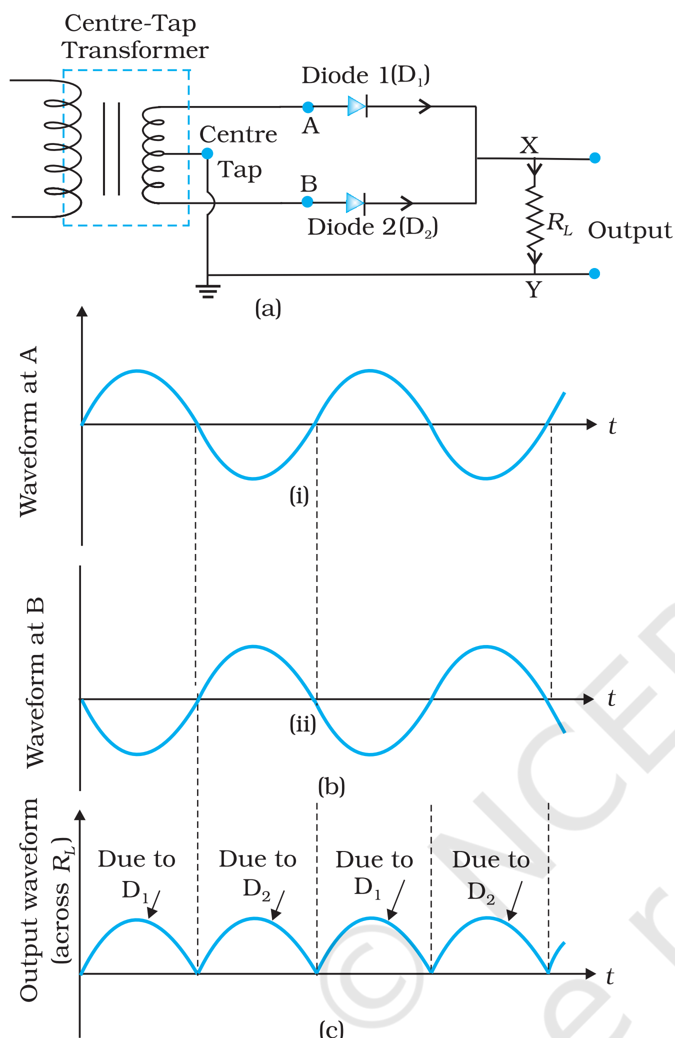

FIGURE 14.19 (a) A Full-wave rectifier circuit; (b) Input wave forms given to the diode D_1 at A and to the diode D_2 at B; (c) Output waveform across the load R_L connected in the full-wave rectifier circuit.

with respect to the centre tap at any instant is positive. It is clear that, at that instant, voltage at B being out of phase will be negative as shown in Fig.14.19(b). So, diode D_1 gets forward biased and conducts (while D_2 being reverse biased is not conducting). Hence, during this positive half cycle we get an output current (and a output voltage across the load resistor R_L) as shown in Fig.14.19(c). In the course of the ac cycle when the voltage at A becomes negative with respect to centre tap, the voltage at B would be positive. In this part of the cycle diode D_1 would not conduct but diode D_2 would, giving an output current and output voltage (across R_L) during the negative half cycle of the input ac. Thus, we get output voltage during both the positive as well as the negative half of the cycle. Obviously, this is a more efficient circuit for getting rectified voltage or current than the half-wave rectifier.

The rectified voltage is in the form of pulses of the shape of half sinusoids. Though it is unidirectional it does not have a steady value. To get steady dc output from the pulsating voltage normally a capacitor is connected across the output terminals (parallel to the load R_L). One can also use an inductor in series with R_L for the same purpose. Since these additional circuits appear to *filter* out the *ac ripple* and give a *pure dc* voltage, so they are called filters.

Now we shall discuss the role of capacitor in filtering. When the voltage across the capacitor is rising, it gets charged. If there is no external load, it remains charged to the peak voltage of the rectified output. When there is a load, it gets discharged through the load and the voltage across it begins to fall. In the next half-cycle of rectified output it again gets charged to the peak value (Fig. 14.20). The rate of fall of the voltage across the capacitor depends inversely upon the product of capacitance *C* and the effective resistance R_L used in the circuit and is called the *time constant*. To make the time constant large value of *C* should be large. So capacitor input filters use large capacitors. The *output voltage* obtained by using capacitor input filter is nearer to the *peak voltage* of the rectified voltage. This type of filter is most widely used in power supplies.

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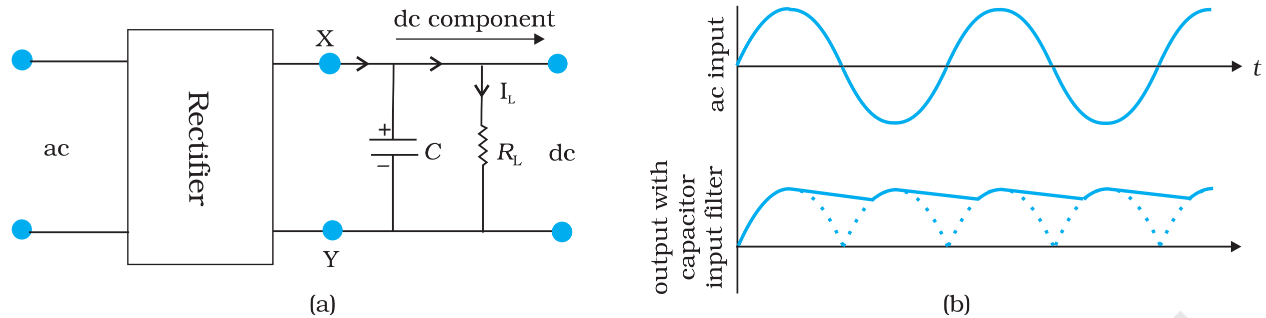

FIGURE 14.20 (a) A full-wave rectifier with capacitor filter, (b) Input and output voltage of rectifier in (a).

14.8 Special Purpose p-n Junction Diodes

In the section, we shall discuss some devices which are basically junction diodes but are developed for different applications.

14.8.1 Zener diode

It is a special purpose semiconductor diode, named after its inventor C. Zener. It is designed to operate under reverse bias in the breakdown region and used as a voltage regulator. The symbol for Zener diode is shown in Fig. 14.21(a).

Zener diode is fabricated by heavily doping both p-, and n- sides of the junction. Due to this, depletion region formed is very thin ($<10^{-6}$ m) and the electric field of the junction is extremely high ($\sim 5\times10^{6}$ V/m) even for a small reverse bias voltage of about 5V. The I-V characteristics of a Zener diode is shown in Fig. 14.21(b). It is seen that when the applied reverse bias voltage(V) reaches the breakdown voltage (V_z) of the Zener diode, there is a large change in the current. Note that after the breakdown voltage V_z, a large change in the current can be produced by almost insignificant change in the reverse bias voltage. In other words, Zener voltage remains constant, even though current through the Zener diode varies over a wide range. This property of the Zener diode is used for regulating supply voltages so that they are constant.

Let us understand how reverse current suddenly increases at the breakdown voltage. We know that reverse current is due to the flow of electrons (minority carriers) from p $\rightarrow$ n and holes from n $\rightarrow$ p. As the reverse bias voltage is increased, the electric field at the junction becomes significant. When the reverse bias voltage V = V_z, then the electric field strength is high enough to pull valence electrons from the host atoms on the p-side which are accelerated to n-side. These electrons account for high current observed at the breakdown. The emission of electrons from the host atoms due to the high electric field is known as internal field emission or field ionisation. The electric field required for field ionisation is of the order of 10^6 V/m.

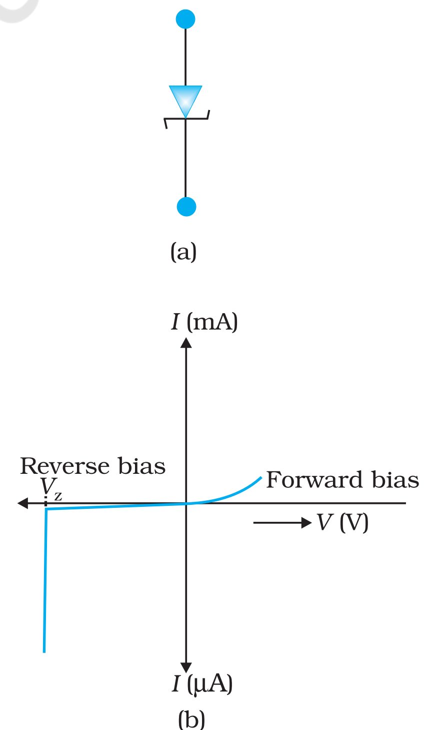

FIGURE 14.21 Zener diode, (a) symbol, (b) I-V characteristics.

Zener diode as a voltage regulator

We know that when the ac input voltage of a rectifier fluctuates, its rectified output also fluctuates. To get a constant dc voltage from the dc unregulated output of a rectifier, we use a Zener diode. The circuit diagram of a voltage regulator using a Zener diode is shown in Fig. 14.22.

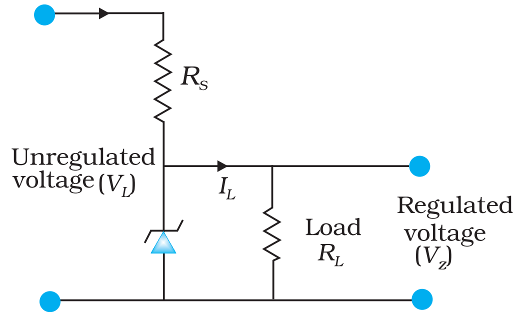

FIGURE 14.22 Zener diode as DC voltage regulator

The unregulated dc voltage (filtered output of a rectifier) is connected to the Zener diode through a series resistance R_s such that the Zener diode is reverse biased. If the input voltage increases, the current through R_s and Zener diode also increases. This increases the voltage drop across R_s without any change in the voltage across the Zener diode. This is because in the breakdown region, Zener voltage remains constant even though the current through the Zener diode changes. Similarly, if the input voltage decreases, the current through R_s and Zener diode also decreases. The voltage drop across R_s decreases without any change in the voltage across the Zener diode. Thus any increase/ decrease in the input voltage results in, increase/ decrease of the voltage drop across R_s without any change in voltage across the Zener diode. Thus the Zener diode acts as a voltage regulator. We have to select the Zener diode according to the required output voltage and accordingly the series resistance R_s.

Example 14.5 In a Zener regulated power supply a Zener diode with V_Z = 6.0 V is used for regulation. The load current is to be 4.0 mA and the unregulated input is 10.0 V. What should be the value of series resistor R_S?

Solution

The value of R_S should be such that the current through the Zener diode is much larger than the load current. This is to have good load regulation. Choose Zener current as five times the load current, i.e., I_Z = 20 mA. The total current through R_S is, therefore, 24 mA. The voltage drop across R_S is 10.0 – 6.0 = 4.0 V. This gives $R_S = 4.0\text{V}/(24 \times 10^{-3})$ A = 167 Ω. The nearest value of carbon resistor is 150 Ω. So, a series resistor of 150 Ω is appropriate. Note that slight variation in the value of the resistor does not matter, what is important is that the current I_Z should be sufficiently larger than I_L.

EXAMPLE 14.5

14.8.2 Optoelectronic junction devices

We have seen so far, how a semiconductor diode behaves under applied electrical inputs. In this section, we learn about semiconductor diodes in which carriers are generated by photons (photo-excitation). All these devices are called *optoelectronic devices*. We shall study the functioning of the following optoelectronic devices:

(i) *Photodiodes* used for detecting optical signal (photodetectors).
(ii) *Light emitting diodes* (LED) which convert electrical energy into light.
(iii) *Photovoltaic devices* which convert optical radiation into electricity (*solar cells*).

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(i) *Photodiode*

A Photodiode is again a special purpose p-n junction diode fabricated with a transparent window to allow light to fall on the diode. It is operated under reverse bias. When the photodiode is illuminated with light (photons) with energy ($h\nu$) greater than the energy gap (E_g) of the semiconductor, then electron-hole pairs are generated due to the absorption of photons. The diode is fabricated such that the generation of *e-h* pairs takes place in or near the depletion region of the diode. Due to electric field of the junction, electrons and holes are separated before they recombine. The direction of the electric field is such that electrons reach n-side and holes reach p-side. Electrons are collected on n-side and holes are collected on p-side giving rise to an emf. When an external load is connected, current flows. The magnitude of the photocurrent depends on the intensity of incident light (photocurrent is proportional to incident light intensity).

It is easier to observe the change in the current with change in the light intensity, if a reverse bias is applied. Thus photodiode can be used as a photodetector to detect optical signals. The circuit diagram used for the measurement of *I-V* characteristics of a photodiode is shown in Fig. 14.23(a) and a typical *I-V* characteristics in Fig. 14.23(b).

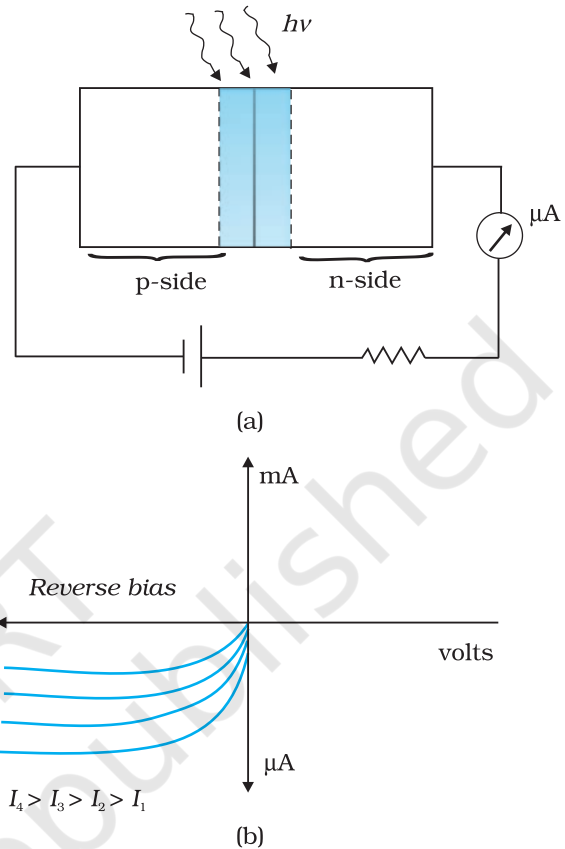

FIGURE 14.23 (a) An illuminated photodiode under reverse bias , (b) *I-V* characteristics of a photodiode for different illumination intensity $I_4 > I_3 > I_2 > I_1$.

Example 14.6 The current in the forward bias is known to be more (~mA) than the current in the reverse bias (~μA). What is the reason then to operate the photodiodes in reverse bias?

Solution Consider the case of an n-type semiconductor. Obviously, the majority carrier density (n) is considerably larger than the minority hole density p (i.e., $n >> p$). On illumination, let the excess electrons and holes generated be Δn and Δp, respectively:

$$n' = n + \Delta n$$

$$p' = p + \Delta p$$

Here n' and p' are the electron and hole concentrations* at any particular illumination and n and p are carriers concentration when there is no illumination. Remember $\Delta n = \Delta p$ and $n >> p$. Hence, the

EXAMPLE 14.6

* Note that, to create an e-h pair, we spend some energy (photoexcitation, thermal excitation, etc.). Therefore when an electron and hole recombine the energy is released in the form of light (radiative recombination) or heat (non-radiative recombination). It depends on semiconductor and the method of fabrication of the p-n junction. For the fabrication of LEDs, semiconductors like GaAs, GaAs-GaP are used in which radiative recombination dominates.

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EXAMPLE 14.6

fractional change in the majority carriers (i.e., $\Delta n/n$) would be much less than that in the minority carriers (i.e., $\Delta p/p$). In general, we can state that the fractional change due to the photo-effects on the *minority carrier dominated reverse bias current* is more easily measurable than the fractional change in the forward bias current. Hence, photodiodes are preferably used in the reverse bias condition for measuring light intensity.

(ii) *Light emitting diode*

It is a heavily doped p-n junction which under forward bias emits spontaneous radiation. The diode is encapsulated with a transparent cover so that emitted light can come out.

When the diode is forward biased, electrons are sent from n $\rightarrow$ p (where they are minority carriers) and holes are sent from p $\rightarrow$ n (where they are minority carriers). At the junction boundary the concentration of minority carriers increases compared to the equilibrium concentration (i.e., when there is no bias). Thus at the junction boundary on either side of the junction, excess minority carriers are there which recombine with majority carriers near the junction. On recombination, the energy is released in the form of photons. Photons with energy equal to or slightly less than the band gap are emitted. When the forward current of the diode is small, the intensity of light emitted is small. As the forward current increases, intensity of light increases and reaches a maximum. Further increase in the forward current results in decrease of light intensity. LEDs are biased such that the light emitting efficiency is maximum.

The *V-I* characteristics of a LED is similar to that of a Si junction diode. But the threshold voltages are much higher and slightly different for each colour. The reverse breakdown voltages of LEDs are very low, typically around 5V. So care should be taken that high reverse voltages do not appear across them.

LEDs that can emit red, yellow, orange, green and blue light are commercially available. The semiconductor used for fabrication of visible LEDs must at least have a band gap of 1.8 eV (spectral range of visible light is from about 0.4 μm to 0.7 μm, i.e., from about 3 eV to 1.8 eV). The compound semiconductor Gallium Arsenide – Phosphide ($GaAs_{1-x}P_x$) is used for making LEDs of different colours. $GaAs_{0.6}\,P_{0.4}$ (E_g ~ 1.9 eV) is used for red LED. GaAs (E_g ~ 1.4 eV) is used for making infrared LED. These LEDs find extensive use in remote controls, burglar alarm systems, optical communication, etc. Extensive research is being done for developing white LEDs which can replace incandescent lamps.

LEDs have the following advantages over conventional incandescent low power lamps:

(i) Low operational voltage and less power.
(ii) Fast action and no warm-up time required.
(iii) The bandwidth of emitted light is 100 Å to 500 Å or in other words it is nearly (but not exactly) monochromatic.
(iv) Long life and ruggedness.
(v) Fast on-off switching capability.

2022-23

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(iii) *Solar cell*

A solar cell is basically a p-n junction which generates emf when solar radiation falls on the p-n junction. It works on the same principle (photovoltaic effect) as the photodiode, except that no external bias is applied and the junction area is kept much larger for solar radiation to be incident because we are interested in more power.

A simple p-n junction solar cell is shown in Fig. 14.24.

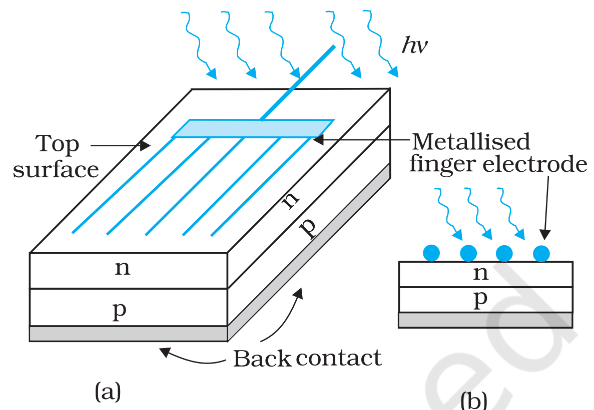

FIGURE 14.24 (a) Typical p-n junction solar cell; (b) Cross-sectional view.

A p-Si wafer of about 300 μm is taken over which a thin layer (~0.3 μm) of n-Si is grown on one-side by diffusion process. The other side of p-Si is coated with a metal (back contact). On the top of n-Si layer, metal finger electrode (or metallic grid) is deposited. This acts as a front contact. The metallic grid occupies only a very small fraction of the cell area (<15%) so that light can be incident on the cell from the top.

The generation of emf by a solar cell, when light falls on, it is due to the following three basic processes: generation, separation and collection— (i) generation of e-h pairs due to light (with $h\nu > E_g$) close to the junction; (ii) separation of electrons and holes due to electric field of the depletion region. Electrons are swept to n-side and holes to p-side; (iii) the electrons reaching the n-side are collected by the front contact and holes reaching p-side are collected by the back contact. Thus p-side becomes positive and n-side becomes negative giving rise to *photovoltage*.

When an external load is connected as shown in the Fig. 14.25(a) a photocurrent I_L flows through the load. A typical *I-V* characteristics of a solar cell is shown in the Fig. 14.25(b).

Note that the $I - V$ characteristics of solar cell is drawn in the fourth quadrant of the coordinate axes. This is because a solar cell does not draw current but supplies the same to the load.

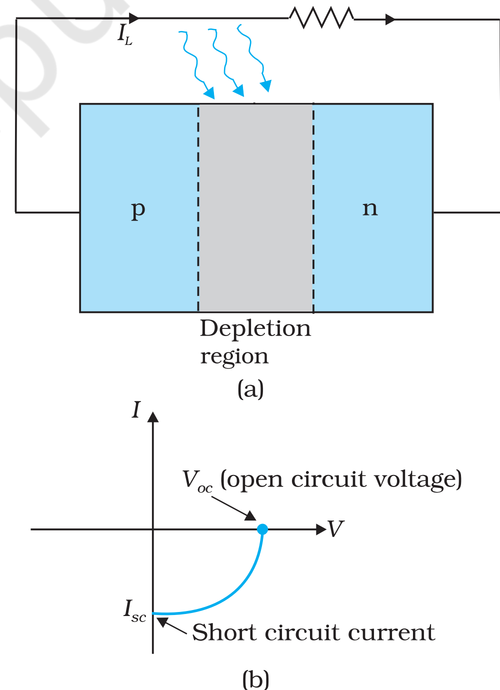

FIGURE 14.25 (a) A typical illuminated p-n junction solar cell; (b) *I-V* characteristics of a solar cell.

Semiconductors with band gap close to 1.5 eV are ideal materials for solar cell fabrication. Solar cells are made with semiconductors like Si (E_g = 1.1 eV), GaAs (E_g = 1.43 eV), CdTe (E_g = 1.45 eV), $CuInSe_2$ (E_g = 1.04 eV), etc. The important criteria for the selection of a material for solar cell fabrication are (i) band gap (~1.0 to 1.8 eV), (ii) high optical absorption (~10^4 cm^{-1}), (iii) electrical conductivity, (iv) availability of the raw material, and (v) cost. Note that sunlight is not always required for a solar cell. *Any* light with photon energies greater than the bandgap will do. Solar cells are used to power electronic devices in satellites and space vehicles and also as power supply to some calculators. Production of low-cost photovoltaic cells for large-scale solar energy is a topic for research.

2022-23

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Example 14.7 Why are Si and GaAs are preferred materials for solar cells?

Solution The solar radiation spectrum received by us is shown in Fig. 14.26.

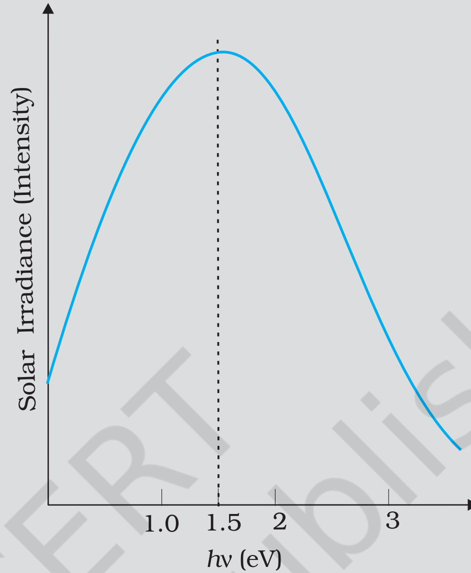

FIGURE 14.26

The maxima is near 1.5 eV. For photo-excitation, $h\nu > E_g$. Hence, semiconductor with band gap ~1.5 eV or lower is likely to give better solar conversion efficiency. Silicon has E_g ~ 1.1 eV while for GaAs it is ~1.53 eV. In fact, GaAs is better (in spite of its higher band gap) than Si because of its relatively higher absorption coefficient. If we choose materials like CdS or CdSe (E_g ~ 2.4 eV), we can use only the high energy component of the solar energy for photo-conversion and a significant part of energy will be of no use.

The question arises: why we do not use material like PbS (E_g ~ 0.4 eV) which satisfy the condition $h\nu > E_g$ for ν maxima corresponding to the solar radiation spectra? If we do so, most of the solar radiation will be absorbed on the *top-layer* of solar cell and will not reach in or near the depletion region. For effective electron-hole separation, due to the junction field, we want the photo-generation to occur in the junction region only.

Example 14.7

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14.9 Digital Electronics and Logic Gates

In electronics circuits like amplifiers, oscillators, introduced to you in earlier sections, the signal (current or voltage) has been in the form of continuous, time-varying voltage or current. Such signals are called continuous or *analog signals*. A typical analog signal is shown in Figure. 14.27(a). Fig. 14.27(b) shows a *pulse waveform* in which only discrete values of voltages are possible. It is convenient to use binary numbers to represent such signals. A binary number has only two digits '0' (say, 0V) and '1' (say, 5V). In digital electronics we use only these two levels of voltage as shown in Fig. 14.27(b). Such signals are called *Digital Signals*.

In digital circuits only two values (represented by 0 or 1) of the input and output voltage are permissible.

This section is intended to provide the first step in our understanding of digital electronics. We shall restrict our study to some basic building blocks of digital electronics (called *Logic Gates*) which process the digital signals in a specific manner. Logic gates are used in calculators, digital watches, computers, robots, industrial control systems, and in telecommunications.

A light switch in your house can be used as an example of a digital circuit. The light is either ON or OFF depending on the switch position. When the light is ON, the output value is '1'. When the light is OFF the output value is '0'. The inputs are the position of the light switch. The switch is placed either in the ON or OFF position to activate the light.

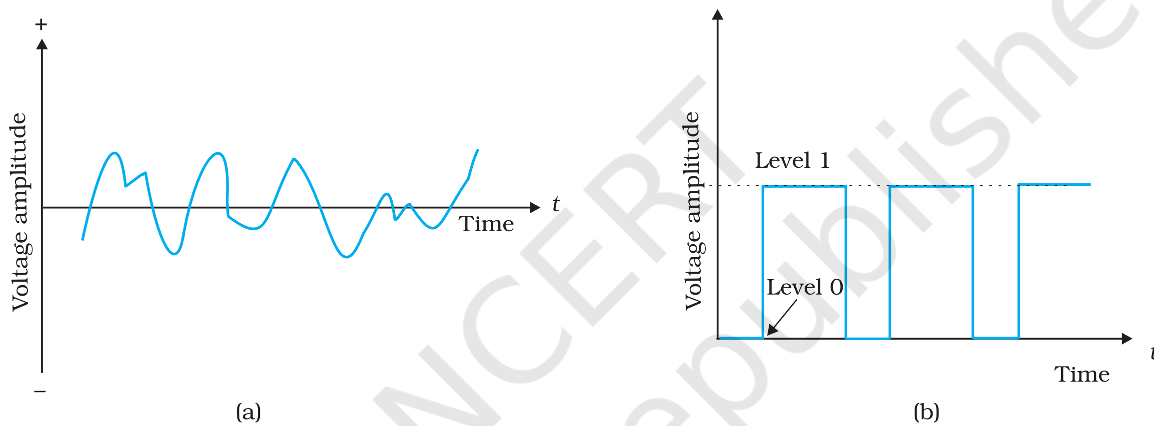
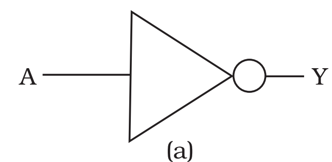


FIGURE 14.27 (a) Analog signal, (b) Digital signal.

14.9.1 Logic gates

A gate is a digital circuit that follows curtain *logical* relationship between the input and output voltages. Therefore, they are generally known as *logic gates* — gates because they control the flow of information. The five common logic gates used are NOT, AND, OR, NAND, NOR. Each logic gate is indicated by a symbol and its function is defined by a *truth table* that shows all the possible input logic level combinations with their respective output logic levels. Truth tables help understand the behaviour of logic gates. These logic gates can be realised using semiconductor devices.



(a)

Input	Output
A	Y
0	1
1	0

(b)

FIGURE 14.28 (a) Logic symbol, (b) Truth table of NOT gate.

(i) NOT gate

This is the most basic gate, with one input and one output. It produces a '1' output if the input is '0' and vice-versa. That is, it produces an inverted version of the input at its output. This is why it is also known as an *inverter*. The commonly used symbol together with the truth table for this gate is given in Fig. 14.28.

(ii) OR Gate

An *OR* gate has two or more inputs with one output. The logic symbol and truth table are shown in Fig. 14.29. The output Y is 1 when either input A *or* input B *or* both are 1s, that is, if any of the input is high, the output is high.

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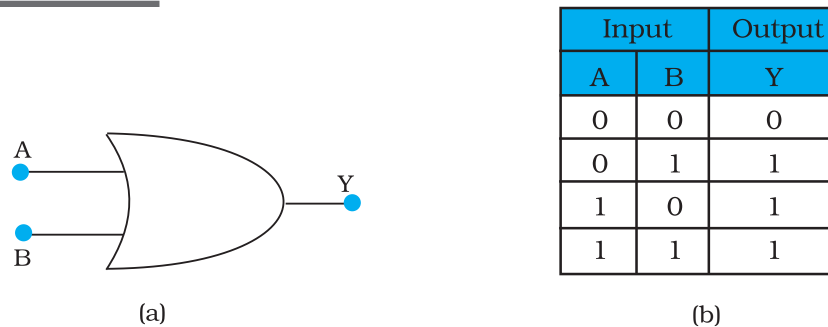


Input		Output
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

(b)

FIGURE 14.29 (a) Logic symbol (b) Truth table of OR gate.

Apart from carrying out the above mathematical logic operation, this *gate* can be used for modifying the pulse waveform as explained in the following example.

EXAMPLE 14.8

Example 14.8 Justify the output waveform (Y) of the OR gate for the following inputs A and B given in Fig. 14.30.

Solution Note the following:

- At $t < t_1$; A = 0, B = 0; Hence Y = 0
- For t_1 to t_2; A = 1, B = 0; Hence Y = 1
- For t_2 to t_3; A = 1, B = 1; Hence Y = 1
- For t_3 to t_4; A = 0, B = 1; Hence Y = 1
- For t_4 to t_5; A = 0, B = 0; Hence Y = 0
- For t_5 to t_6; A = 1, B = 0; Hence Y = 1
- For $t > t_6$; A = 0, B = 1; Hence Y = 1

Therefore the waveform Y will be as shown in the Fig. 14.30.

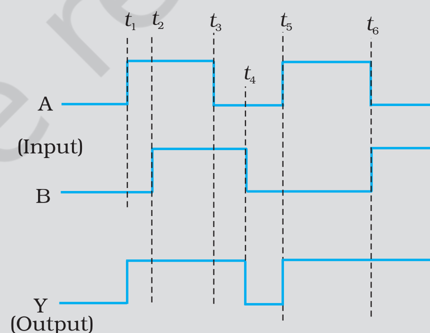
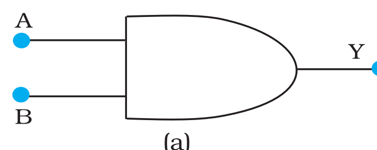


FIGURE 14.30

(iii) AND Gate

An *AND* gate has two or more inputs and one output. The output Y of AND gate is 1 only when input A *and* input B are both 1. The logic symbol and truth table for this gate are given in Fig. 14.31



(a)

Input		Output
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

(b)

FIGURE 14.31 (a) Logic symbol, (b) Truth table of AND gate.

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Example 14.9 Take A and B input waveforms similar to that in Example 14.8. Sketch the output waveform obtained from AND gate.

Solution

- For $t \leq t_1$; A = 0, B = 0; Hence Y = 0
- For t_1 to t_2; A = 1, B = 0; Hence Y = 0
- For t_2 to t_3; A = 1, B = 1; Hence Y = 1
- For t_3 to t_4; A = 0, B = 1; Hence Y = 0
- For t_4 to t_5; A = 0, B = 0; Hence Y = 0
- For t_5 to t_6; A = 1, B = 0; Hence Y = 0
- For $t > t_6$; A = 0, B = 1; Hence Y = 0

Based on the above, the output waveform for AND gate can be drawn as given below.

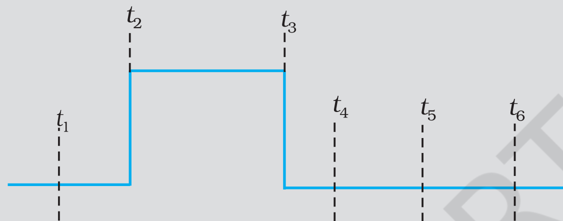


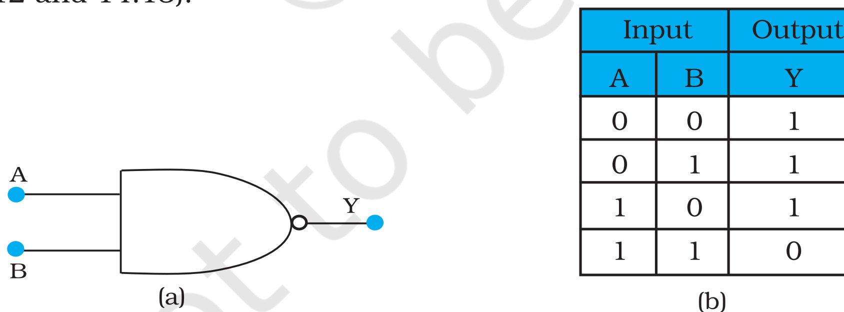
FIGURE 14.32

EXAMPLE 14.9

(iv) NAND Gate

This is an AND gate followed by a NOT gate. If inputs A *and* B are both '1', the output Y is *not* '1'. The gate gets its name from this NOT AND behaviour. Figure 14.33 shows the symbol and truth table of NAND gate.

NAND gates are also called *Universal Gates* since by using these gates you can realise other basic gates like OR, AND and NOT (Exercises 14.12 and 14.13).



Input		Output
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

(b)

FIGURE 14.33 (a) Logic symbol, (b) Truth table of NAND gate.

Example 14.10 Sketch the output Y from a NAND gate having inputs A and B given below:

Solution

- For $t < t_1$; A = 1, B = 1; Hence Y = 0
- For t_1 to t_2; A = 0, B = 0; Hence Y = 1
- For t_2 to t_3; A = 0, B = 1; Hence Y = 1
- For t_3 to t_4; A = 1, B = 0; Hence Y = 1

EXAMPLE 14.10

2022-23

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EXAMPLE 14.10

- For t_4 to t_5; A = 1, B = 1; Hence Y = 0
- For t_5 to t_6; A = 0, B = 0; Hence Y = 1
- For $t > t_6$; A = 0, B = 1; Hence Y = 1

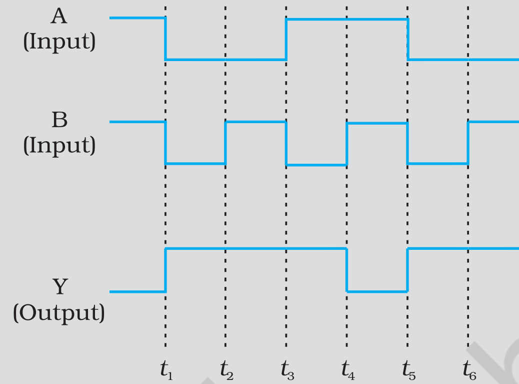
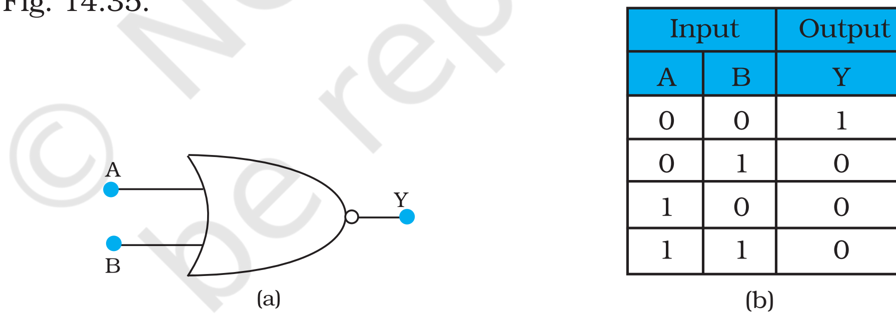


FIGURE 14.34

(v) NOR Gate

It has two or more inputs and one output. A NOT- operation applied *after* OR gate gives a NOT-OR gate (or simply NOR gate). Its output Y is '1' only when both inputs A and B are '0', i.e., neither one input *nor* the other is '1'. The symbol and truth table for NOR gate is given in Fig. 14.35.



Input		Output
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

FIGURE 14.35 (a) Logic symbol, (b) Truth table of NOR gate.

NOR gates are considered as *universal* gates because you can obtain all the gates like AND, OR, NOT by using only NOR gates (Exercises 14.14 and 14.15).

FASTER AND SMALLER: THE FUTURE OF COMPUTER TECHNOLOGY

The *Integrated Chip* (IC) is at the heart of all computer systems. In fact ICs are found in almost all electrical devices like cars, televisions, CD players, cell phones etc. The miniaturisation that made the modern personal computer possible could never have happened without the IC. ICs are electronic devices that contain many transistors, resistors, capacitors, connecting wires – all in one package. You must have heard of the

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microprocessor. The microprocessor is an IC that processes all information in a computer, like keeping track of what keys are pressed, running programmes, games etc. The IC was first invented by Jack Kilky at Texas Instruments in 1958 and he was awarded Nobel Prize for this in 2000. ICs are produced on a piece of semiconductor crystal (or chip) by a process called *photolithography*. Thus, the entire Information Technology (IT) industry hinges on semiconductors. Over the years, the complexity of ICs has increased while the size of its features continued to shrink. In the past five decades, a dramatic miniaturisation in computer technology has made modern day computers *faster and smaller*. In the 1970s, Gordon Moore, co-founder of INTEL, pointed out that the memory capacity of a chip (IC) approximately doubled every one and a half years. This is popularly known as *Moore's law*. The number of transistors per chip has risen exponentially and each year computers are becoming more powerful, yet cheaper than the year before. It is intimated from current trends that the computers available in 2020 will operate at 40 GHz (40,000 MHz) and would be much smaller, more efficient and less expensive than present day computers. The explosive growth in the semiconductor industry and computer technology is best expressed by a famous quote from Gordon Moore: "If the auto industry advanced as rapidly as the semiconductor industry, a Rolls Royce would get half a million miles per gallon, and it would be cheaper to throw it away than to park it".

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SUMMARY

1. Semiconductors are the basic materials used in the present solid state electronic devices like diode, transistor, ICs, etc.
2. Lattice structure and the atomic structure of constituent elements decide whether a particular material will be insulator, metal or semiconductor.
3. Metals have low resistivity (10^{-2} to 10^{-8} Ωm), insulators have very high resistivity (>10^8 Ω m^{-1}), while semiconductors have intermediate values of resistivity.
4. Semiconductors are elemental (Si, Ge) as well as compound (GaAs, CdS, etc.).
5. Pure semiconductors are called 'intrinsic semiconductors'. The presence of charge carriers (electrons and holes) is an 'intrinsic' property of the material and these are obtained as a result of thermal excitation. The number of electrons (n_e) is equal to the number of holes (n_h) in intrinsic conductors. Holes are essentially electron vacancies with an effective positive charge.
6. The number of charge carriers can be changed by 'doping' of a suitable impurity in pure semiconductors. Such semiconductors are known as extrinsic semiconductors. These are of two types (n-type and p-type).
7. In n-type semiconductors, $n_e >> n_h$ while in p-type semiconductors $n_h >> n_e$.
8. n-type semiconducting Si or Ge is obtained by doping with pentavalent atoms (donors) like As, Sb, P, etc., while p-type Si or Ge can be obtained by doping with trivalent atom (acceptors) like B, Al, In etc.
9. $n_e n_h = n_i^2$ in all cases. Further, the material possesses an *overall charge neutrality*.

10. There are two distinct band of energies (called valence band and conduction band) in which the electrons in a material lie. Valence band energies are low as compared to conduction band energies. All energy levels in the valence band are filled while energy levels in the conduction band may be fully empty or partially filled. The electrons in the conduction band are free to move in a solid and are responsible for the conductivity. The extent of conductivity depends upon the energy gap (E_g) between the top of valence band (E_V) and the bottom of the conduction band E_C. The electrons from valence band can be excited by heat, light or electrical energy to the conduction band and thus, produce a change in the current flowing in a semiconductor.
11. For insulators $E_g > 3$ eV, for semiconductors E_g is 0.2 eV to 3 eV, while for metals $E_g \approx 0$.
12. p-n junction is the 'key' to all semiconductor devices. When such a junction is made, a 'depletion layer' is formed consisting of immobile ion-cores devoid of their electrons or holes. This is responsible for a junction potential barrier.
13. By changing the external applied voltage, junction barriers can be changed. In forward bias (n-side is connected to negative terminal of the battery and p-side is connected to the positive), the barrier is decreased while the barrier increases in reverse bias. Hence, forward bias current is more (mA) while it is very small (μA) in a p-n junction diode.
14. Diodes can be used for rectifying an ac voltage (restricting the ac voltage to one direction). With the help of a capacitor or a suitable filter, a dc voltage can be obtained.
15. There are some special purpose diodes.
16. Zener diode is one such special purpose diode. In reverse bias, after a certain voltage, the current suddenly increases (breakdown voltage) in a Zener diode. This property has been used to obtain *voltage regulation*.
17. p-n junctions have also been used to obtain many photonic or optoelectronic devices where one of the participating entity is 'photon': (a) Photodiodes in which photon excitation results in a change of reverse saturation current which helps us to measure light intensity; (b) Solar cells which convert photon energy into electricity; (c) Light Emitting Diode and Diode Laser in which electron excitation by a bias voltage results in the generation of light.
18. There are some special circuits which handle the digital data consisting of 0 and 1 levels. This forms the subject of Digital Electronics.
19. The important digital circuits performing special logic operations are called logic gates. These are: OR, AND, NOT, NAND, and NOR gates.

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POINTS TO PONDER

1. The energy bands (E_C or E_V) in the semiconductors are space delocalised which means that these are not located in any specific place inside the solid. The energies are the overall averages. When you see a picture in which E_C or E_V are drawn as straight lines, then they should be respectively taken simply as the *bottom* of conduction band energy levels and *top* of valence band energy levels.
2. In elemental semiconductors (Si or Ge), the n-type or p-type semiconductors are obtained by introducing 'dopants' as defects. In compound semiconductors, the change in relative stoichiometric ratio can also change the type of semiconductor. For example, in ideal GaAs

the ratio of Ga:As is 1:1 but in Ga-rich or As-rich GaAs it could respectively be $Ga_{1.1}$ $As_{0.9}$ or $Ga_{0.9}$ $As_{1.1}$. In general, the presence of defects control the properties of semiconductors in many ways.

3. In modern day circuit, many logical gates or circuits are integrated in one single 'Chip'. These are known as Intgrated circuits (IC).

EXERCISES

14.1 In an n-type silicon, which of the following statement is true:
(a) Electrons are majority carriers and trivalent atoms are the dopants.
(b) Electrons are minority carriers and pentavalent atoms are the dopants.
(c) Holes are minority carriers and pentavalent atoms are the dopants.
(d) Holes are majority carriers and trivalent atoms are the dopants.

14.2 Which of the statements given in Exercise 14.1 is true for p-type semiconductos.

14.3 Carbon, silicon and germanium have four valence electrons each. These are characterised by valence and conduction bands separated by energy band gap respectively equal to $(E_g)_C$, $(E_g)_{Si}$ and $(E_g)_{Ge}$. Which of the following statements is true?
(a) $(E_g)_{Si} < (E_g)_{Ge} < (E_g)_C$
(b) $(E_g)_C < (E_g)_{Ge} > (E_g)_{Si}$
(c) $(E_g)_C > (E_g)_{Si} > (E_g)_{Ge}$
(d) $(E_g)_C = (E_g)_{Si} = (E_g)_{Ge}$

14.4 In an unbiased p-n junction, holes diffuse from the p-region to n-region because
(a) free electrons in the n-region attract them.
(b) they move across the junction by the potential difference.
(c) hole concentration in p-region is more as compared to n-region.
(d) All the above.

14.5 When a forward bias is applied to a p-n junction, it
(a) raises the potential barrier.
(b) reduces the majority carrier current to zero.
(c) lowers the potential barrier.
(d) None of the above.

14.6 In half-wave rectification, what is the output frequency if the input frequency is 50 Hz. What is the output frequency of a full-wave rectifier for the same input frequency.

14.7 A p-n photodiode is fabricated from a semiconductor with band gap of 2.8 eV. Can it detect a wavelength of 6000 nm?

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ADDITIONAL EXERCISES

14.8 The number of silicon atoms per m^3 is 5×10^{28}. This is doped simultaneously with 5×10^{22} atoms per m^3 of Arsenic and 5×10^{20} per m^3 atoms of Indium. Calculate the number of electrons and holes. Given that $n_i = 1.5 \times 10^{16}\ m^{-3}$. Is the material n-type or p-type?

14.9 In an intrinsic semiconductor the energy gap E_g is 1.2eV. Its hole mobility is much smaller than electron mobility and independent of temperature. What is the ratio between conductivity at 600K and that at 300K? Assume that the temperature dependence of intrinsic carrier concentration n_i is given by

$$n_i = n_0 \exp\left(-\frac{E_g}{2k_B T}\right)$$

where n_0 is a constant.

14.10 In a p-n junction diode, the current I can be expressed as

$$I = I_0 \exp\left(\frac{eV}{2k_B T} - 1\right)$$

where I_0 is called the reverse saturation current, V is the voltage across the diode and is positive for forward bias and negative for reverse bias, and I is the current through the diode, k_B is the Boltzmann constant (8.6×10^{-5} eV/K) and T is the absolute temperature. If for a given diode $I_0 = 5 \times 10^{-12}$ A and T = 300 K, then

(a) What will be the forward current at a forward voltage of 0.6 V?

(b) What will be the increase in the current if the voltage across the diode is increased to 0.7 V?

(c) What is the dynamic resistance?

(d) What will be the current if reverse bias voltage changes from 1 V to 2 V?

14.11 You are given the two circuits as shown in Fig. 14.36. Show that circuit (a) acts as OR gate while the circuit (b) acts as AND gate.

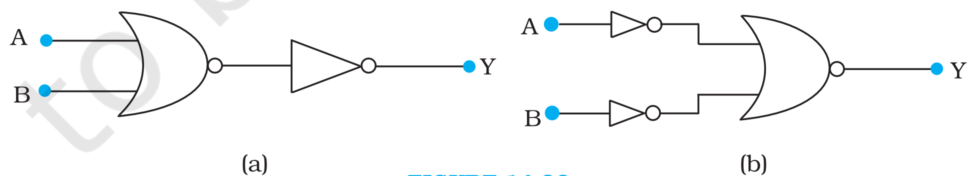

FIGURE 14.36

14.12 Write the truth table for a NAND gate connected as given in Fig. 14.37.

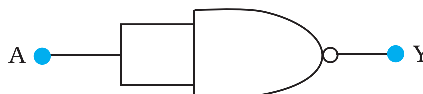

FIGURE 14.37

Hence identify the exact logic operation carried out by this circuit.

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14.13 You are given two circuits as shown in Fig. 14.38, which consist of NAND gates. Identify the logic operation carried out by the two circuits.

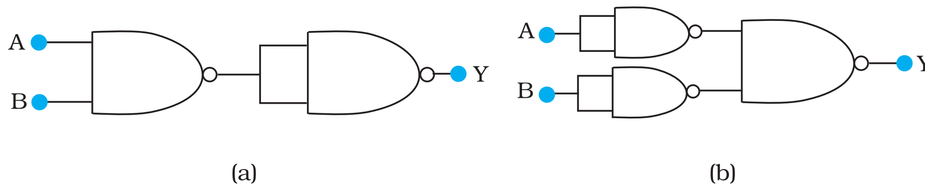

FIGURE 14.38

14.14 Write the truth table for circuit given in Fig. 14.39 below consisting of NOR gates and identify the logic operation (OR, AND, NOT) which this circuit is performing.

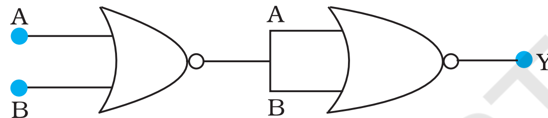

FIGURE 14.39

(Hint: A = 0, B = 1 then A and B inputs of second NOR gate will be 0 and hence Y=1. Similarly work out the values of Y for other combinations of A and B. Compare with the truth table of OR, AND, NOT gates and find the correct one.)

14.15 Write the truth table for the circuits given in Fig. 14.40 consisting of NOR gates only. Identify the logic operations (OR, AND, NOT) performed by the two circuits.

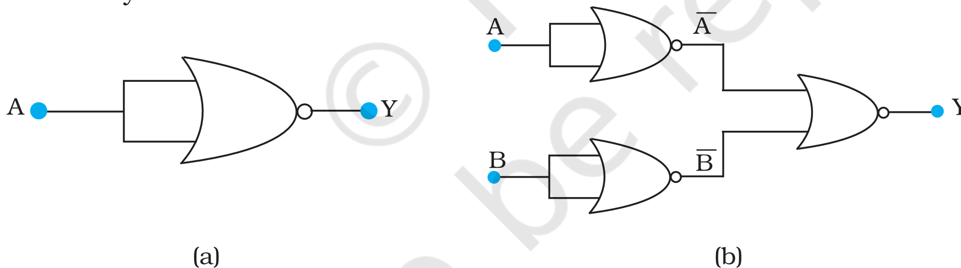

FIGURE 14.40

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ANSWERS

CHAPTER 9

9.1 $v = -54$ cm. The image is real, inverted and magnified. The size of the image is 5.0 cm. As $u \to f$, $v \to \infty$; for $u < f$, image is virtual.

9.2 $v = 6.7$ cm. Magnification = 5/9, i.e., the size of the image is 2.5 cm. As $u \to \infty$; $v \to f$ (but never beyond) while $m \to 0$.

9.3 1.33; 1.7 cm

9.4 $n_{ga} = 1.51$; $n_{wa} = 1.32$; $n_{gw} = 1.144$; which gives sin $r = 0.6181$ i.e., $r \simeq 38°$.

9.5 $r = 0.8 \times \tan i_c$ and $\sin i_c = 1/1.33 \cong 0.75$, where r is the radius (in m) of the largest circle from which light comes out and i_c is the critical angle for water-air interface, Area = 2.6 m^2

9.6 $n \cong 1.53$ and D_m for prism in water $\cong 10°$

9.7 $R = 22$ cm

9.8 Here the object is virtual and the image is real. $u = +12$ cm (object on right; virtual)

(a) $f = +20$ cm. Image is real and at 7.5 cm from the lens on its right side.

(b) $f = -16$ cm. Image is real and at 48 cm from the lens on its right side.

9.9 $v = 8.4$ cm, image is erect and virtual. It is diminished to a size 1.8 cm. As $u \to \infty$, $v \to f$ (but never beyond f while $m \to 0$).

Note that when the object is placed at the focus of the concave lens (21 cm), the image is located at 10.5 cm (not at infinity as one might wrongly think).

9.10 A diverging lens of focal length 60 cm

9.11 (a) $v_e = -25$ cm and $f_e = 6.25$ cm give $u_e = -5$ cm; $v_O = (15 - 5)$ cm = 10 cm,

$f_O = u_O = -2.5$ cm; Magnifying power = 20

(b) $u_O = -2.59$ cm.

Magnifying power = 13.5.

9.12 Angular magnification of the eye-piece for image at 25 cm

$= \frac{25}{2.5} + 1 = 11$; $|u_e| = \frac{25}{11}$ cm $= 2.27$ cm; $v_O = 7.2$ cm

Separation = 9.47 cm; Magnifying power = 88

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9.13 24; 150 cm

9.14 (a) Angular magnification = 1500

(b) Diameter of the image = 13.7 cm.

9.15 Apply mirror equation and the condition:

(a) $f < 0$ (concave mirror); $u < 0$ (object on left)

(b) $f > 0$; $u < 0$

(c) $f > 0$ (convex mirror) and $u < 0$

(d) $f < 0$ (concave mirror); $f < u < 0$

to deduce the desired result.

9.16 The pin appears raised by 5.0 cm. It can be seen with an explicit ray diagram that the answer is independent of the location of the slab (for small angles of incidence).

9.17 (a) $\sin i_c' = 1.44/1.68$ which gives $i_c' = 59°$. Total internal reflection takes place when $i > 59°$ or when $r < r_{max} = 31°$. Now, $(\sin i_{max} / \sin r_{max}) = 1.68$, which gives $i_{max} \simeq 60°$. Thus, all incident rays of angles in the range $0 < i < 60°$ will suffer total internal reflections in the pipe. (If the length of the pipe is finite, which it is in practice, there will be a lower limit on i determined by the ratio of the diameter to the length of the pipe.)

(b) If there is no outer coating, $i_c' = \sin^{-1}(1/1.68) = 36.5°$. Now, $i = 90°$ will have $r = 36.5°$ and $i' = 53.5°$ which is greater than i_c'. Thus, *all* incident rays (in the range $53.5° < i < 90°$) will suffer total internal reflections.

9.18 (a) Rays converging to a point 'behind' a plane or convex mirror are reflected to a point in front of the mirror on a screen. In other words, a plane or convex mirror can produce a real image if the object is virtual. Convince yourself by drawing an appropriate ray diagram.

(b) When the reflected or refracted rays are divergent, the image is virtual. The divergent rays can be converged on to a screen by means of an appropriate converging lens. The convex lens of the eye does just that. The virtual image here serves as an object for the lens to produce a real image. Note, the screen here is not located at the position of the virtual image. There is no contradiction.

(c) Taller

(d) The apparent depth for oblique viewing decreases from its value for near-normal viewing. Convince yourself of this fact by drawing ray diagrams for different positions of the observer.

(e) Refractive index of a diamond is about 2.42, much larger than that of ordinary glass (about 1.5). The critical angle of diamond is about 24°, much less than that of glass. A skilled diamond-cutter exploits the larger range of angles of incidence (in the diamond), 24° to 90°, to ensure that light entering the diamond is totally reflected from many faces before getting out–thus producing a sparkling effect.

9.19 For fixed distance s between object and screen, the lens equation does not give a real solution for u or v if f is greater than $s/4$.

Therefore, $f_{max} = 0.75$ m.

9.20 21.4 cm

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9.21 (a) (i) Let a parallel beam be the incident from the left on the convex lens first.

$f_1 = 30$ cm and $u_1 = -\infty$, give $v_1 = +30$ cm. This image becomes a virtual object for the second lens.

$f_2 = -20$ cm, $u_2 = +(30 - 8)$ cm $= +22$ cm which gives, $v_2 = -220$ cm. The parallel incident beam appears to diverge from a point 216 cm from the centre of the two-lens system.

(ii) Let the parallel beam be incident from the left on the concave lens first: $f_1 = -20$ cm, $u_1 = -\infty$, give $v_1 = -20$ cm. This image becomes a real object for the second lens: $f_2 = +30$ cm, $u_2 = -(20 + 8)$ cm $= -28$ cm which gives, $v_2 = -420$ cm. The parallel incident beam appears to diverge from a point 416 cm on the left of the centre of the two-lens system.

Clearly, the answer depends on which side of the lens system the parallel beam is incident. *Further we do not have a simple lens equation true for all u (and v) in terms of a definite constant of the system (the constant being determined by f_1 and f_2, and the separation between the lenses).* The notion of effective focal length, therefore, does not seem to be meaningful for this system.

(b) $u_1 = -40$ cm, $f_1 = 30$ cm, gives $v_1 = 120$ cm.

Magnitude of magnification due to the first (convex) lens is 3.

$u_2 = +(120 - 8)$ cm $= +112$ cm (object virtual);

$f_2 = -20$ cm which gives $v_2 = -\dfrac{112 \times 20}{92}$ cm

Magnitude of magnification due to the second (concave) lens = 20/92.

Net magnitude of magnification = 0.652

Size of the image = 0.98 cm

9.22 If the refracted ray in the prism is incident on the second face at the critical angle i_c, the angle of refraction r at the first face is $(60° - i_c)$.

Now, $i_c = \sin^{-1}(1/1.524) \simeq 41°$

Therefore, $r = 19°$

$\sin i = 0.4962$; $i \simeq 30°$

9.23 (a) $\dfrac{1}{v} + \dfrac{1}{9} = \dfrac{1}{10}$

i.e., $v = -90$ cm,

Magnitude of magnification = 90/9 = 10.

Each square in the virtual image has an area $10 \times 10 \times 1\ \text{mm}^2 = 100\ \text{mm}^2 = 1\ \text{cm}^2$

(b) Magnifying power = 25/9 = 2.8

(c) No, magnification of an image by a lens and angular magnification (or magnifying power) of an optical instrument are two separate things. The latter is the ratio of the angular size of the object (which is equal to the angular size of the image even if the image is magnified) to the angular size of the object if placed at the near point (25 cm). Thus, magnification magnitude is $|(v/u)|$ and magnifying power is $(25/\,|u|)$. Only when the image is located at the near point $|v| = 25$ cm, are the two quantities equal.

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9.24 (a) Maximum magnifying power is obtained when the image is at the near point (25 cm)

$u = -7.14$ cm.

(b) Magnitude of magnification = $(25/|u|) = 3.5$.

(c) Magnifying power = 3.5

Yes, the magnifying power (when the image is produced at 25 cm) is equal to the magnitude of magnification.

9.25 Magnification $= \sqrt{(6.25/1)} = 2.5$

$v = +2.5u$

$$+\frac{1}{2.5u} - \frac{1}{u} = \frac{1}{10}$$

i.e., $u = -6$ cm

$|v| = 15$ cm

The virtual image is closer than the normal near point (25 cm) and cannot be seen by the eye distinctly.

9.26 (a) Even though the absolute image size is bigger than the object size, the angular size of the image is equal to the angular size of the object. The magnifier helps in the following way: without it object would be placed no closer than 25 cm; with it the object can be placed much closer. The closer object has larger angular size than the same object at 25 cm. It is in this sense that angular magnification is achieved.

(b) Yes, it decreases a little because the angle subtended at the eye is then slightly less than the angle subtended at the lens. The effect is negligible if the image is at a very large distance away. [*Note:* When the eye is separated from the lens, the angles subtended at the eye by the first object and its image are not equal.]

(c) First, grinding lens of very small focal length is not easy. More important, if you decrease focal length, aberrations (both spherical and chromatic) become more pronounced. So, in practice, you cannot get a magnifying power of more than 3 or so with a simple convex lens. However, using an aberration corrected lens system, one can increase this limit by a factor of 10 or so.

(d) Angular magnification of eye-piece is $[(25/f_e) + 1]$ (f_e in cm) which increases if f_e is smaller. Further, magnification of the objective

is given by $$\frac{v_O}{|u_O|} = \frac{1}{(|u_O|/f_O) - 1}$$

which is large when $|u_O|$ is slightly greater than f_O. The microscope is used for viewing very close object. So $|u_O|$ is small, and so is f_O.

(e) The image of the objective in the eye-piece is known as 'eye-ring'. All the rays from the object refracted by objective go through the eye-ring. Therefore, it is an ideal position for our eyes for viewing. If we place our eyes too close to the eye-piece, we shall not collect much of the light and also reduce our field of view. If we position

our eyes on the eye-ring and the area of the pupil of our eye is greater or equal to the area of the eye-ring, our eyes will collect all the light refracted by the objective. The precise location of the eye-ring naturally depends on the separation between the objective and the eye-piece. When you view through a microscope by placing your eyes on one end,the ideal distance between the eyes and eye-piece is usually built-in the design of the instrument.

9.27 Assume microscope in normal use i.e., image at 25 cm. Angular magnification of the eye-piece

$$= \frac{25}{5} + 1 = 6$$

Magnification of the objective

$$= \frac{30}{6} = 5$$

$$\frac{1}{5u_O} - \frac{1}{u_O} = \frac{1}{1.25}$$

which gives $u_O = -1.5$ cm; $v_0 = 7.5$ cm. $|u_e| = (25/6)$ cm = 4.17 cm. The separation between the objective and the eye-piece should be (7.5 + 4.17) cm = 11.67 cm. Further the object should be placed 1.5 cm from the objective to obtain the desired magnification.

9.28 (a) $m = (f_O/f_e) = 28$

(b) $m = \frac{f_O}{f_e}\left[1 + \frac{f_O}{25}\right] = 33.6$

9.29 (a) $f_O + f_e = 145$ cm

(b) Angle subtended by the tower = (100/3000) = (1/30) rad.

Angle subtended by the image produced by the objective

$$= \frac{h}{f_O} = \frac{h}{140}$$

Equating the two, $h = 4.7$ cm.

(c) Magnification (magnitude) of the eye-piece = 6. Height of the final image (magnitude) = 28 cm.

9.30 The image formed by the larger (concave) mirror acts as virtual object for the smaller (convex) mirror. Parallel rays coming from the object at infinity will focus at a distance of 110 mm from the larger mirror. The distance of virtual object for the smaller mirror = (110 –20) = 90 mm. The focal length of smaller mirror is 70 mm. Using the mirror formula, image is formed at 315 mm from the smaller mirror.

9.31 The reflected rays get deflected by twice the angle of rotation of the mirror. Therefore, $d/1.5 = \tan 7°$. Hence $d = 18.4$ cm.

9.32 $n = 1.33$

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Chapter 10

10.1 (a) Reflected light: (wavelength, frequency, speed same as incident light)

λ = 589 nm, $\nu = 5.09 \times 10^{14}$ Hz, $c = 3.00 \times 10^{8}$ m s^{-1}

(b) Refracted light: (frequency same as the incident frequency)
$\nu = 5.09 \times 10^{14}$ Hz
$v = (c/n) = 2.26 \times 10^{8}$ m s^{-1}, $\lambda = (v/\nu)$ = 444 nm

10.2 (a) Spherical
(b) Plane
(c) Plane (a small area on the surface of a large sphere is nearly planar).

10.3 (a) 2.0×10^{8} m s^{-1}
(b) No. The refractive index, and hence the speed of light in a medium, depends on wavelength. [When no particular wavelength or colour of light is specified, we may take the given refractive index to refer to yellow colour.] Now we know violet colour deviates more than red in a glass prism, i.e. $n_v > n_r$. Therefore, the violet component of white light travels slower than the red component.

10.4 $$\lambda = \frac{1.2 \times 10^{-2} \times 0.28 \times 10^{-3}}{4 \times 1.4} \text{ m} = 600 \text{ nm}$$

10.5 K/4

10.6 (a) 1.17 mm (b) 1.56 mm

10.7 0.15°

10.8 $\tan^{-1}(1.5) \simeq 56.3°$

10.9 5000 Å, 6×10^{14} Hz; 45°

10.10 40 m

10.11 Use the formula $\lambda' - \lambda = \frac{v}{c}\lambda$

i.e., $v = \frac{c}{\lambda}(\lambda' - \lambda) = \frac{3 \times 10^{8} \times 15}{6563} = 6.86 \times 10^{5}$ m s^{-1}

10.12 In corpuscular (particle) picture of refraction, particles of light incident from a rarer to a denser medium experience a force of attraction normal to the surface. This results in an increase in the normal component of the velocity but the component along the surface is unchanged. This means

$c \sin i = v \sin r$ or $\frac{v}{c} = \frac{\sin i}{\sin r} = n$. Since $n > 1$, $v > c$.

The prediction is *opposite* to the experimental results ($v < c$). The wave picture of light is consistent with the experiment.

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10.13 With the point object at the centre, draw a circle touching the mirror. This is a plane section of the spherical wavefront from the object that has just reached the mirror. Next draw the locations of this same wavefront after a time *t* in the presence of the mirror, and in the absence of the mirror. You will get two arcs symmetrically located on either side of the mirror. Using simple geometry, the centre of the reflected wavefront (the image of the object) is seen to be at the same distance from the mirror as the object.

10.14 (a) The speed of light in vacuum is a universal constant independent of all the factors listed and anything else. In particular, note the surprising fact that it is independent of the relative motion between the source and the observer. This fact is a basic axiom of Einstein's special theory of relativity.

(b) Dependence of the speed of light in a medium:

(i) does not depend on the nature of the source (wave speed is determined by the properties of the medium of propagation. This is also true for other waves, e.g., sound waves, water waves, etc.).

(ii) independent of the direction of propagation for *isotropic* media.

(iii) independent of the motion of the source relative to the medium but depends on the motion of the observer relative to the medium.

(iv) depends on wavelength.

(v) independent of intensity. [For high intensity beams, however, the situation is more complicated and need not concern us here.]

10.15 Sound waves require a medium for propagation. Thus even though the situations (i) and (ii) may correspond to the same relative motion (between the source and the observer), they are not identical physically since the motion of the observer *relative to the medium* is different in the two situations. Therefore, we cannot expect Doppler formulas for sound to be identical for (i) and (ii). For light waves in vacuum, there is clearly nothing to distinguish between (i) and (ii). Here only the relative motion between the source and the observer counts and the relativistic Doppler formula is the same for (i) and (ii). For light propagation in a medium, once again like for sound waves, the two situations are *not* identical and we should expect the Doppler formulas for this case to be different for the two situations (i) and (ii).

10.16 3.4×10^{-4} m.

10.17 (a) The size reduces by half according to the relation: size ~ λ/d. Intensity increases four fold.

(b) The intensity of interference fringes in a double-slit arrangement is modulated by the diffraction pattern of each slit.

(c) Waves diffracted from the edge of the circular obstacle interfere constructively at the centre of the shadow producing a bright spot.

(d) For diffraction or bending of waves by obstacles/apertures by a large angle, the size of the latter should be comparable to wavelength. If the size of the obstacle/aperture is much too large compared to wavelength, diffraction is by a small angle. Here the size is of the order of a few metres. The wavelength of light is about 5×10^{-7} m, while sound waves of, say, 1 kHz frequency

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have wavelength of about 0.3 m. Thus, sound waves can bend around the partition while light waves cannot.

(e) Justification based on what is explained in (d). Typical sizes of apertures involved in ordinary optical instruments are much larger than the wavelength of light.

10.18 12.5 cm.

10.19 0.2 nm.

10.20 (a) Interference of the direct signal received by the antenna with the (weak) signal reflected by the passing aircraft.

(b) Superposition principle follows from the linear character of the (differential) equation governing wave motion. If y_1 and y_2 are solutions of the wave equation, so is any linear combination of y_1 and y_2. When the amplitudes are large (e.g., high intensity laser beams) and non-linear effects are important, the situation is far more complicated and need not concern us here.

10.21 Divide the single slit into n smaller slits of width $a' = a/n$. The angle $\theta = n\lambda/a = \lambda/a'$. Each of the smaller slits sends zero intensity in the direction θ. The combination gives zero intensity as well.

Chapter 11

11.1 (a) 7.24×10^{18} Hz (b) 0.041 nm

11.2 (a) $0.34 \text{ eV} = 0.54 \times 10^{-19}$ J (b) 0.34 V (c) 344 km/s

11.3 $1.5 \text{ eV} = 2.4 \times 10^{-19}$ J

11.4 (a) 3.14×10^{-19} J, 1.05×10^{-27} kg m/s (b) 3×10^{16} photons/s
(c) 0.63 m/s

11.5 4×10^{21} photons/m^2 s

11.6 6.59×10^{-34} J s

11.7 (a) 3.38×10^{-19} J = 2.11 eV (b) 3.0×10^{20} photons/s

11.8 2.0 V

11.9 No, because $\nu < \nu_o$

11.10 4.73×10^{14} Hz

11.11 $2.16 \text{ eV} = 3.46 \times 10^{-19}$ J

11.12 (a) 4.04×10^{-24} kg m s^{-1} (b) 0.164 nm

11.13 (a) 5.92×10^{-24} kg m s^{-1} (b) 6.50×10^6 m s^{-1} (c) 0.112 nm

11.14 (a) 6.95×10^{-25} J = 4.34 μeV (b) 3.78×10^{-28} J = 0.236 neV

11.15 (a) 1.7×10^{-35} m (b) 1.1×10^{-32} m (c) 3.0×10^{-23} m

11.16 (a) 6.63×10^{-25} kg m/s (for both) (b) 1.24 keV (c) 1.51 eV

11.17 (a) 6.686×10^{-21} J = 4.174×10^{-2} eV (b) 0.145 nm

11.18 $\lambda = h/p = h/(h\nu/c) = c/\nu$

11.19 0.028 nm

11.20 (a) Use $eV = (m\,v^2/2)$ i.e., $v = [(2eV/m)]^{1/2}$; $v = 1.33 \times 10^7$ m s^{-1}.

(b) If we use the same formula with $V = 10^7$ V, we get $v = 1.88 \times 10^9$ m s^{-1}. This is clearly wrong, since nothing can move with a speed greater than the speed of light ($c = 3 \times 10^8$ m s^{-1}). Actually, the above formula for kinetic energy $(m\,v^2/2)$ is valid only when $(v/c) << 1$. At very high speeds when (v/c) is comparable to (though always less than) 1, we come to the relativistic domain

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where the following formulae are valid:

Relativistic momentum $p = m\,v$

Total energy $E = m\,c^2$

Kinetic energy $K = m\,c^2 - m_0\,c^2$,

where the relativistic mass m is given by $m = m_0\left(1 - \frac{v^2}{c^2}\right)^{-1/2}$

m_0 is called the rest mass of the particle. These relations also imply:

$E = (p^2c^2 + m_0^2\,c^4)^{1/2}$

Note that in the relativisitc domain when v/c is comparable to 1, K or energy $\geq m_0c^2$ (rest mass energy). The rest mass energy of electron is about 0.51 MeV. Thus a kinetic energy of 10 MeV, being much greater than electron's rest mass energy, implies relativistic domain. Using relativistic formulas, v (for 10 MeV kinetic energy) = 0.999 c.

11.21 (a) 22.7 cm

(b) No. As explained above, a 20 MeV electron moves at relativistic speed. Consequently, the non-relativistic formula $R = (m_0 v/e\,B)$ is not valid. The relativistic formula is

$$R = p/eB = mv/eB \quad \text{or} \quad R = m_0 v/\left(eB\sqrt{1 - v^2/c^2}\right)$$

11.22 We have $e\,V = (m\,v^2/2)$ and $R = (m\,v/e\,B)$ which gives $(e/m) = (2V/R^2B^2)$; using the given data $(e/m) = 1.73 \times 10^{11}$ C kg^{-1}.

11.23 (a) 27.6 keV (b) of the order of 30 kV

11.24 Use $\lambda = (hc/E)$ with $E = 5.1 \times 1.602 \times 10^{-10}$J to get $\lambda = 2.43 \times 10^{-16}$ m.

11.25 (a) For $\lambda = 500$ m, $E = (h\,c/\lambda) = 3.98 \times 10^{-28}$J. Number of photons emitted per second

$= 10^4$J s^{-1}/3.98 × 10^{-28}J $\simeq 3 \times 10^{31}$ s^{-1}

We see that the energy of a radiophoton is exceedingly small, and the number of photons emitted per second in a radio beam is enormously large. There is, therefore, negligible error involved in ignoring the existence of a minimum quantum of energy (photon) and treating the total energy of a radio wave as continuous.

(b) For $\nu = 6 \times 10^{14}$ Hz, $E \simeq 4 \times 10^{-19}$J. Photon flux corresponding to minimum intensity

$= 10^{-10}$ W m^{-2}/4×10^{-19}J $= 2.5 \times 10^8$ m^{-2} s^{-1}

Number of photons entering the pupil per second = $2.5 \times 10^8 \times 0.4 \times 10^{-4}$ s^{-1} = 10^4 s^{-1}. Though this number is not as large as in (a) above, it is large enough for us never to 'sense' or 'count' individual photons by our eye.

11.26 $\phi_0 = h\,\nu - e\,V_0 = 6.7 \times 10^{-19}$J = 4.2 eV; $\nu_0 = \frac{\phi_0}{h} = 1.0 \times 10^{15}$ Hz; $\lambda = 6328$Å corresponds to $\nu = 4.7 \times 10^{14}$ Hz $< \nu_0$. The photo-cell will not respond howsoever high be the intensity of laser light.

11.27 Use $e\,V_0 = h\,\nu - \phi_0$ for both sources. From the data on the first source, ϕ_0 = 1.40 eV. Use this value to obtain for the second source V_0 = 1.50 V.

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11.28 Obtain V_0 versus ν plot. The slope of the plot is (h/e) and its intercept on the ν-axis is ν_0. The first four points lie nearly on a straight line which intercepts the ν-axis at $\nu_0 = 5.0 \times 10^{14}$ Hz (threshold frequency). The fifth point corresponds to $\nu < \nu_0$; there is no photoelectric emission and therefore no stopping voltage is required to stop the current. Slope of the plot is found to be 4.15×10^{-15} V s. Using $e = 1.6 \times 10^{-19}$ C, $h = 6.64 \times 10^{-34}$ J s (standard value $h = 6.626 \times 10^{-34}$ J s), $\phi_0 = h\,\nu_0 = 2.11$V.

11.29 It is found that the given incident frequency ν is greater than ν_0 (Na), and ν_0 (K); but less than ν_0 (Mo), and ν_0 (Ni). Therefore, Mo and Ni will not give photoelectric emission. If the laser is brought closer, intensity of radiation increases, but this does not affect the result regarding Mo and Ni. However, photoelectric current from Na and K will increase in proportion to intensity.

11.30 Assume one conduction electron per atom. Effective atomic area $\sim 10^{-20}\,\text{m}^2$

Number of electrons in 5 layers

$$= \frac{5 \times 2 \times 10^{-4}\,\text{m}^2}{10^{-20}\,\text{m}^2} = 10^{17}$$

Incident power

$= 10^{-5}\,\text{W m}^{-2} \times 2 \times 10^{-4}\,\text{m}^2 = 2 \times 10^{-9}\,\text{W}$

In the wave picture, incident power is uniformly absorbed by all the electrons continuously. Consequently, energy absorbed per second per electron

$= 2 \times 10^{-9}/10^{17} = 2 \times 10^{-26}\,\text{W}$

Time required for photoelectric emission

$= 2 \times 1.6 \times 10^{-19}\text{J}/2 \times 10^{-26}\text{W} = 1.6 \times 10^{7}\,\text{s}$

which is about 0.5 year.

Implication: Experimentally, photoelectric emission is observed nearly instantaneously ($\sim 10^{-9}$ s): Thus, the wave picture is in gross disagreement with experiment. In the photon-picture, energy of the radiation is not continuously shared by all the electrons in the top layers. Rather, energy comes in discontinuous 'quanta'. and absorption of energy does not take place gradually. A photon is either not absorbed, or absorbed by an electron nearly instantly.

11.31 For $\lambda = 1$ Å, electron's energy = 150 eV; photon's energy = 12.4 keV. Thus, for the same wavelength, a photon has much greater energy than an electron.

11.32 (a) $\lambda = \dfrac{h}{p} = \dfrac{h}{\sqrt{2\,mK}}$ Thus, for same K, λ decreases with m as $(1/\sqrt{m})$. Now $(m_n/m_e) = 1838.6$; therefore for the same energy, (150 eV) as in Ex. 11.31, wavelength of neutron $= \left(1/\sqrt{1838.6}\right) \times 10^{-10}$ m $= 2.33 \times 10^{-12}$ m. The interatomic spacing is about a hundred times greater. A neutron beam of 150 eV energy is therefore not suitable for diffraction experiments.

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(b) $\lambda = 1.45 \times 10^{-10}$ m [Use $\lambda = (h/\sqrt{3\,m\,k\,T})$] which is comparable to interatomic spacing in a crystal.

Clearly, from (a) and (b) above, thermal neutrons are a suitable probe for diffraction experiments; so a high energy neutron beam should be first thermalised before using it for diffraction.

11.33 $\lambda = 5.5 \times 10^{-12}$ m

λ (yellow light) = 5.9×10^{-7}m

Resolving Power (RP) is inversely proportional to wavelength. Thus, RP of an electron microscope is about 10^5 times that of an optical microscope. In practice, differences in other (geometrical) factors can change this comparison somewhat.

11.34 $p = \dfrac{h}{\lambda} = \dfrac{6.63\times10^{-34}\text{Js}}{10^{-15}\text{m}} = 6.63 \times 10^{-19}$ kg m s^{-1}

Use the relativistic formula for energy:

$E^2 = c^2p^2 + m_0^2\,c^4 = 9 \times (6.63)^2 \times 10^{-22} + (0.511 \times 1.6)^2 \times 10^{-26}$

$\simeq 9 \times (6.63)^2 \times 10^{-22}$,

the second term (rest mass energy) being negligible.

Therefore, $E = 1.989 \times 10^{-10}$ J = 1.24 BeV. Thus, electron energies from the accelerator must have been of the order of a few BeV.

11.35 Use $\lambda = \dfrac{h}{\sqrt{3\,m\,k\,T}}$; $m_{He} = \dfrac{4\times10^{-3}}{6\times10^{23}}$ kg

This gives $\lambda = 0.73 \times 10^{-10}$ m. Mean separation

$r = (V/N)^{1/3} = (kT/p)^{1/3}$

For $T = 300$ K, $p = 1.01 \times 10^5$ Pa, $r = 3.4 \times 10^{-9}$ m. We find $r >> \lambda$.

11.36 Using the same formula as in Exercise 11.35, $\lambda = 6.2 \times 10^{-9}$ m which is much greater than the given inter-electron separation.

11.37 (a) Quarks are thought to be confined within a proton or neutron by forces which grow stronger if one tries to pull them apart. It, therefore, seems that though fractional charges may exist in nature, observable charges are still integral multiples of e.

(b) Both the basic relations $e\,V = (1/2)\,m\,v^2$ or $e\,E = m\,a$ and $e\,B\,v = m\,v^2/r$, for electric and magnetic fields, respectively, show that the dynamics of electrons is determined not by e, and m separately but by the combination e/m.

(c) At low pressures, ions have a chance to reach their respective electrodes and constitute a current. At ordinary pressures, ions have no chance to do so because of collisions with gas molecules and recombination.

(d) Work function merely indicates the minimum energy required for the electron in the highest level of the conduction band to get out of the metal. Not all electrons in the metal belong to this level. They occupy a continuous band of levels. Consequently, for the same incident radiation, electrons knocked off from different levels come out with different energies.

(e) The absolute value of energy E (but not momentum p) of any particle is arbitrary to within an additive constant. Hence, while λ is physically significant, absolute value of ν of a matter wave of an electron has no direct physical meaning. The phase speed $\nu\lambda$

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is likewise not physically significant. The group speed given by

$$\frac{dv}{d(1/\lambda)} = \frac{dE}{dp} = \frac{d}{dp}\left(\frac{p^2}{2m}\right) = \frac{p}{m}$$

is physically meaningful.

CHAPTER 12

12.1 (a) No different from

(b) Thomson's model; Rutherford's model

(c) Rutherford's model

(d) Thomson's model; Rutherford's model

(e) Both the models

12.2 The nucleus of a hydrogen atom is a proton. The mass of it is 1.67×10^{-27} kg, whereas the mass of an incident α-particle is 6.64×10^{-27} kg. Because the scattering particle is more massive than the target nuclei (proton), the α-particle won't bounce back in even in a head-on collision. It is similar to a football colliding with a tenis ball at rest. Thus, there would be no large-angle scattering.

12.3 820 nm.

12.4 5.6×10^{14} Hz

12.5 13.6 eV; –27.2 eV

12.6 9.7×10^{-8} m; 3.1×10^{15} Hz.

12.7 (a) 2.18×10^{6} m/s; 1.09×10^{6} m/s; 7.27×10^{5} m/s

(b) 1.52×10^{-16} s; 1.22×10^{-15} s; 4.11×10^{-15} s.

12.8 2.12×10^{-10} m; 4.77×10^{-10} m

12.9 Lyman series: 103 nm and 122 nm; Balmer series: 656 nm.

12.10 2.6×10^{74}

12.11 (a) About the same.

(b) Much less.

(c) It suggests that the scattering is predominantly due to a single collision, because the chance of a single collision increases linearly with the number of target atoms, and hence linearly with thickness.

(d) In Thomson's model, a single collision causes very little deflection. The observed average scattering angle can be explained only by considering multiple scattering. So it is wrong to ignore multiple scattering in Thomson's model. In Rutherford's model, most of the scattering comes through a single collision and multiple scattering effects can be ignored as a first approximation.

12.12 The first orbit Bohr's model has a radius a_0 given by $a_0 = \frac{4\pi\varepsilon_0(h/2\pi)^2}{m_e e^2}$. If we consider the atom bound by the gravitational force $(Gm_p m_e/r^2)$, we should replace $(e^2/4\pi\varepsilon_0)$ by $Gm_p m_e$. That is, the radius of the first Bohr orbit is given by $a_0^G = \frac{(h/2\pi)^2}{Gm_p m_e^2} \cong 1.2 \times 10^{29}$ m.

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This is much greater than the estimated size of the whole universe!

12.13 $$\nu = \frac{me^4}{(4\pi)^3 \varepsilon_0^2 (h/2\pi)^3}\left[\frac{1}{(n-1)^2} - \frac{1}{n^2}\right] = \frac{me^4 (2n-1)}{(4\pi)^3 \varepsilon_0^2 (h/2\pi)^3 n^2 (n-1)^2}$$

For large n, $\nu \cong \dfrac{me^4}{32\pi^3 \varepsilon_0^2 (h/2\pi)^3 n^3}$

Orbital frequency $\nu_c = (v/2\pi r)$. In Bohr model $v = \dfrac{n(h/2\pi)}{mr}$, and

$r = \dfrac{4\pi\varepsilon_0 (h/2\pi)^2}{me^2} n^2$. This gives $\nu_c = \dfrac{n(h/2\pi)}{2\pi m r^2} = \dfrac{me^4}{32\pi^3 \varepsilon_0^2 (h/2\pi)^3 n^3}$

which is same as ν for large n.

12.14 (a) The quantity $\left(\dfrac{e^2}{4\pi\varepsilon_0 mc^2}\right)$ has the dimensions of length. Its value is 2.82×10^{-15}m – much smaller than the typical atomic size.

(b) The quantity $\dfrac{4\pi\varepsilon_0 (h/2\pi)^2}{me^2}$ has the dimensions of length. Its value is 0.53×10^{-10}m – of the order of atomic sizes. (Note that the dimensional arguments cannot, of course, tell us that we should use 4π and $h/2\pi$ in place of h to arrive at the right size.)

12.15 In Bohr's model, $mvr = \dfrac{nh}{2\pi}$ and $\dfrac{mv^2}{r} = \dfrac{Ze^2}{4\pi\varepsilon_0 r^2}$

which give

$$T = \frac{1}{2}mv^2 = \frac{Ze^2}{8\pi\varepsilon_0 r} \;;\; r = \frac{4\pi\varepsilon_0 h^2}{Ze^2 m} n^2$$

These relations have nothing to do with the choice of the zero of potential energy. Now, choosing the zero of potential energy at infinity we have $V = -(Ze^2/4\pi\varepsilon_0 r)$ which gives $V = -2T$ and $E = T + V = -T$

(a) The quoted value of $E = -3.4$ eV is based on the customary choice of zero of potential energy at infinity. Using $E = -T$, the kinetic energy of the electron in this state is + 3.4 eV.

(b) Using $V = -2T$, potential energy of the electron is = – 6.8 eV

(c) If the zero of potential energy is chosen differently, kinetic energy does not change. Its value is + 3.4 eV independent of the choice of the zero of potential energy. The potential energy, and the total energy of the state, however, would alter if a different zero of the potential energy is chosen.

12.16 Angular momenta associated with planetary motion are incomparably large relative to h. For example, angular momentum of the earth in its orbital motion is of the order of $10^{70}h$. In terms of the Bohr's quantisation postulate, this corresponds to a very large value of n (of the order of 10^{70}). For such large values of n, the differences in the successive energies and angular momenta of the quantised levels of the Bohr model are so small compared to the energies and angular momenta respectively for the levels that one can, for all practical purposes, consider the levels continuous.

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12.17 All that is needed is to replace m_e by m_μ in the formulas of the Bohr model. We note that keeping other factors fixed, $r \propto (1/m)$ and $E \propto m$. Therefore,

$$r_\mu = \frac{r_e m_e}{m_\mu} = \frac{0.53 \times 10^{\;13}}{207} = 2.56 \times 10^{-13}\ \text{m}$$

$$E_\mu = \frac{E_e m_\mu}{m_e} = -(13.6 \times 207)\ \text{eV} \cong -2.8\ \text{keV}$$

Chapter 13

13.1 (a) 6.941 u (b) 19.9%, 80.1%

13.2 20.18 u

13.3 104.7 MeV

13.4 8.79 MeV, 7.84 MeV

13.5 1.584×10^{25} MeV or 2.535×10^{12} J

13.6 i) $^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^{4}_{2}\text{He}$ ii) $^{242}_{94}\text{Pu} \rightarrow ^{238}_{92}\text{U} + ^{4}_{2}\text{He}$

iii) $^{32}_{15}\text{P} \rightarrow ^{32}_{16}\text{S} + e^- + \bar{\nu}$ iv) $^{210}_{83}\text{B} \rightarrow ^{210}_{84}\text{Po} + e^- + \bar{\nu}$

v) $^{11}_{6}\text{C} \rightarrow ^{11}_{5}\text{B} + e^+ + \nu$ vi) $^{97}_{43}\text{Tc} \rightarrow ^{97}_{42}\text{Mo} + e^+ + \nu$

vii) $^{120}_{54}\text{Xe} + e^- \rightarrow ^{120}_{53}\text{I} + \nu$

13.7 (a) 5 T years (b) 6.65 T years

13.8 4224 years

13.9 7.126×10^{-6} g

13.10 7.877×10^{10} Bq or 2.13 Ci

13.11 1.23

13.12 (a) Q = 4.93 MeV, E_α = 4.85 MeV (b) Q = 6.41 MeV, E_α = 6.29 MeV

13.13 $^{11}_{6}\text{C} \rightarrow ^{11}_{5}\text{B} + e^+ + \nu + Q$

$Q = \left[m_N\left(^{11}_{6}\text{C}\right) - m\ ^{11}_{5}\text{B}\ - m_e\right]c^2,$

where the masses used are those of nuclei and not of atoms. If we use atomic masses, we have to add $6m_e$ in case of $^{11}_{6}\text{C}$ and $5m_e$ in case of $^{11}_{5}\text{B}$. Hence

$Q = \left[m\left(^{11}_{6}\text{C}\right) - m\,^{11}_{5}\text{B}\ - 2m_e\right]c^2$ (Note m_e has been doubled)

Using given masses, Q = 0.961 MeV.

$Q = E_d + E_e + E_\nu$

The daughter nucleus is too heavy compared to e^+ and ν, so it carries negligible energy ($E_d \approx 0$). If the kinetic energy (E_ν) carried by the neutrino is minimum (i.e., zero), the positron carries maximum energy, and this is practically all energy Q; hence maximum $E_e \approx Q$).

13.14 $^{23}_{10}\text{Ne} \rightarrow ^{23}_{11}\text{Na} + e^- + \bar{\nu} + Q$; $Q = \left[m_N\left(^{23}_{10}\text{Ne}\right) - m_N\left(^{23}_{11}\text{Na}\right) - m_e\right]c^2$, where the masses used are masses of nuclei and not of atoms as in Exercise 13.13. Using atomic masses $Q = \left[m\left(^{23}_{10}\text{Ne}\right) - m\left(^{23}_{11}\text{Na}\right)\right]c^2$. Note m_e has

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been cancelled. Using given masses, Q = 4.37 MeV. As in Exercise 13.13, maximum kinetic energy of the electron (max E_e) = Q = 4.37 MeV.

13.15 (i) Q = –4.03 MeV; endothermic

(ii) Q = 4.62 MeV; exothermic

13.16 $Q = m\left({}^{56}_{26}\text{Fe}\right) - 2m\left({}^{28}_{13}\text{Al}\right) = 26.90$ MeV; not possible.

13.17 4.536×10^{26} MeV

13.18 Energy generated per gram of ${}^{235}_{92}\text{U} = \dfrac{6\times10^{23}\times200\times1.6\times10^{-13}}{235}\,\text{J g}^{-1}$

The amount of ${}^{235}_{92}\text{U}$ consumed in 5y with 80% on-time

$$= \frac{5\times0.8\times3.154\times10^{16}\times235}{1.2\times1.6\times10^{13}}\,\text{g} \quad = 1544\,\text{kg}$$

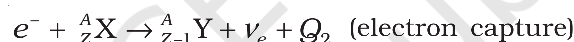
The initial amount of ${}^{235}_{92}\text{U}$ = 3088 kg.

13.19 About 4.9×10^{4} y

13.20 360 KeV

13.22 Consider the competing processes:

$${}^{A}_{Z}\text{X} \rightarrow {}^{A}_{Z-1}\text{Y} + e^{+} + \nu_e + Q_1 \quad \text{(positron emission)}$$



$$e^{-} + {}^{A}_{Z}\text{X} \rightarrow {}^{A}_{Z-1}\text{Y} + \nu_e + Q_2 \quad \text{(electron capture)}$$

$$Q_1 = \left[m_N\left({}^{A}_{Z}\text{X}\right) - m_N\left({}^{A}_{Z-1}\text{Y}\right) - m_e\right]c^2$$

$$= \left[m\left({}^{A}_{Z}\text{X}\right) - Zm_e - m\left({}^{A}_{Z-1}\text{Y}\right) - (Z-1)m_e - m_e\right]c^2$$

$$= \left[m\left({}^{A}_{Z}\text{X}\right) - m\left({}^{A}_{Z-1}\text{Y}\right) - 2m_e\right]c^2$$

$$Q_2 = \left[m_N\left({}^{A}_{Z}\text{X}\right) + m_e - m_N\left({}^{A}_{Z-1}\text{Y}\right)\right]c^2 = \left[m\left({}^{A}_{Z}\text{X}\right) - m\left({}^{A}_{Z-1}\text{Y}\right)\right]c^2$$

This means $Q_1 > 0$ implies $Q_2 > 0$ but $Q_2 > 0$ does not necessarily mean $Q_1 > 0$. Hence the result.

13.23 ${}^{25}_{12}\text{Mg}$: 9.3%, ${}^{26}_{12}\text{Mg}$: 11.7%

13.24 Neutron separation energy S_n of a nucleus ${}^{A}_{Z}\text{X}$ is

$$S_n = \left[m_N\left({}^{A-1}_{Z}\text{X}\right) + m_n - m_N\left({}^{A}_{Z}\text{X}\right)\right]c^2$$

From given data, $S_n({}^{41}_{20}\text{Ca}) = 8.36\,\text{MeV}, S_n({}^{27}_{13}\text{Al}) = 13.06\,\text{MeV}$

13.25 209 d

13.26 For ${}^{14}_{6}\text{C}$ emission

$$Q = [m_N({}^{223}_{88}\text{Ra}) - m_N({}^{209}_{82}\text{Pb}) - m_N({}^{14}_{6}\text{C})]c^2$$

$$= [m({}^{223}_{88}\text{Ra}) - m({}^{209}_{82}\text{Pb}) - m({}^{14}_{6}\text{C})]c^2 = 31.85\,\text{MeV}$$

For ${}^{4}_{2}\text{He}$ emission, $Q = [m({}^{223}_{88}\text{Ra}) - m({}^{219}_{86}\text{Rn}) - m({}^{4}_{2}\text{He})]c^2 = 5.98\,\text{MeV}$

13.27 $Q = [m({}^{238}_{92}\text{U}) + m_n - m({}^{140}_{58}\text{Ce}) - m({}^{99}_{44}\text{Ru})]c^2 = 231.1$ MeV

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13.28 (a) $Q = [m(^2_1\text{H}) + m(^3_1\text{H}) - m(^4_2\text{He}) - m_n]c^2 = 17.59\ \text{MeV}$

(b) K.E. required to overcome Coulomb repulsion = 480.0 keV

480.0 KeV = 7.68×10^{-14} J = $3kT$

$$\therefore T = \frac{7.68\times10^{-14}}{3\times1.381\times10^{-23}} \qquad (as\ k = 1.381\times10^{-23}\ \text{J K}^{-1})$$

= 1.85×10^{9} K (required temperature)

13.29 $K_{max}(\beta_1^-) = 0.284\ \text{MeV},\ K_{max}(\beta_2^-) = 0.960\ \text{MeV}$

$\nu(\gamma_1) = 2.627\times10^{20}\ \text{Hz},\ \nu(\gamma_2) = 0.995\times10^{20}\ \text{Hz},\ \nu(\gamma_3) = 1.632\times10^{20}\ \text{Hz}$

13.30 (a) Note that in the interior of Sun, four ^1_1H nuclei combine to form one ^4_2He nucleus releasing about 26 MeV of energy per event.

Energy released in fusion of 1kg of hydrogen = 39×10^{26} MeV

(b) Energy released in fission of 1kg of $^{235}_{92}\text{U} = 5.1\times10^{26}$ MeV

The energy released in fusion of 1 kg of hydrogen is about 8 times that of the energy released in the fission of 1 kg of uranium.

13.31 3.076×10^{4} kg

Chapter 14

14.1 (c)
14.2 (d)
14.3 (c)
14.4 (c)
14.5 (c)
14.6 50 Hz for half-wave, 100 Hz for full-wave
14.7 No ($h\nu$ has to be greater than E_g).
14.8 $n_e \approx 4.95\times10^{22}$; $n_h = 4.75\times10^{9}$; n-type since $n_e >> n_h$

For charge neutrality $N_D - N_A = n_e - n_h$; $n_e.n_h = n_i^2$

Solving these equations, $n_e = \frac{1}{2}\left[(N_D - N_A) + \sqrt{(N_D - N_A)^2 + 4n_i^2}\right]$

14.9 About 1×10^{5}

14.10 (a) 0.0629 A, (b) 2.97 A, (c) 0.336 Ω

(d) For both the voltages, the current I will be almost equal to I_0, showing almost infinite dynamic resistance in the reverse bias.

14.12 NOT ;

A	Y
0	1
1	0

14.13 (a) AND (b) OR
14.14 OR gate
14.15 (a) NOT, (b) AND

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INDEX

Absorption spectra 421
AC current 233
AC Generator 224
AC voltage 233
 applied to a capacitor 241
 applied to a resistor 234
 applied to an inductor 237
 applied to a series LCR circuit 244
Accelerators in India 142
Activity of radioactive substances 447
Additivity of charges 8
Alpha decay 449
Alpha particle scattering 415
Ammeter 165
Ampere 155
Amperes circuital law 147
Analog signal 491
AND gate 492
Andre, Ampere 148
Angle
 of deviation 330
 of incidence 355
 of reflection 357
 of refraction 355
Angular magnification 339
Apparent depth 318
Area element vector 26
Atomic
 mass unit 439
 number 440
 spectra 420
Aurora Borealis 139
Band gap 471
Bar magnet 174
 as solenoid 176
Barrier potential 479
Becquerel 448
Beta decay 450
Binding energy per nucleon 444
Biot-Savart law 143
Bohr magneton 163
Bohr radius 425
Bohr's model of atom 422
Bohr's postulates 424
Brewster's angle 380
Brewster's law 381
C.A. Volta 53
Capacitance 73
Capacitive reactance 241
Capacitive circuit 252
Capacitor
 parallel plate 74
 in parallel 79
 in series 78
Cartesian sign convention 311
Cassegrain telescope 341
Cells 110
 in parallel 114
 in series 113
Chain reaction 453
Charging by induction 6
Charles August de Coulomb 11
Chromatic aberration 332
Coercivity 195
Coherent source 360
Colour code of resistors 103
Combination of lenses 328
Combination of resistors
 series 107
 parallel 108
Composition of nucleus 438
Concave mirror 312
Conduction band 469
Conductivity 97, 468
Conductors 5
Conservation of charge 8
Conservative force 51
Continuous charge distribution 32

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Index

Control rods 454
Convex mirror 312
Coulomb 11
Coulomb's law 10
Critical angle 320
Curie temperature 194
Curie 448
Current 94
  density 97
  loop as a magnetic dipole 160
  sensitivity of galvanometer 165
Cut-off voltage/Stopping potential 391
Cyclotron 140
  frequency 141
Davisson & Germer Experiment 403
de Broglie
  relation 398
  wavelength 398
  explanation 430
Decay constant 446
Diamagnetism 192
Dielectrics 71
Dielectric
  constant 76
  strength 74
Diffraction 367
  single slit 368
Digital
  electronics 491
  signal 491
Dioptre 328
Dipole
  moment 28
  moment vector 28
  in uniform electric field 31
  physical significance 29
Displacement current 270
Doppler effect 358
Drift velocity 98
Earth's magnetism 185
Earthing 5
Eddy currents 218
Einstein's photoelectric equation 394
Electric
  charge 1
  current 93
  dipole 27
  displacement 77
  field 18
  field, physical significance 20
  field due to a system of charges 19
  field lines 23
  flux 25
  susceptibility 72
Electrical energy 105
Electromagnetic
  waves, sources 274
  waves, nature 275
  damping 218
  spectrum 280
Electron emission 387
Electrostatic
  analog 180
  potential 53
  shielding 69
Electrostatics 1
  of conductors 67
Electromotive force (emf) 110
Emission spectra 421
Energy
  bands 469
  generation in stars 455
  levels 427
  stored in a capacitor 80
Equipotential surfaces 60
Excited state 427
Experiments of Faraday & Henry 205
Extrinsic semiconductor 474
Farad 74
Faraday's law of Induction 207
Fast breeder reactor 453
Ferromagnetism 193
Field
  due to infinite plane sheet 38
  due to uniformly charged thin spherical shell 39
Field emission 388
Flux leakage 261
Focal length 311
Force between two parallel currents 154
Forward bias 479
Franck-Hertz experiment 428
Fringe width 364
Full-wave rectifier 483
G.S. Ohm 95
Gamma
  rays 283
  decay 451
Gauss's law 33
  its applications 37
  in magnetism 181
Gaussian surface 35
Geographic meridian 186
Gold leaf electroscope 4
Ground state 427
H.A. Lorentz 134

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Half life 448
Half-wave rectifier 483
Hallwachs' and Lenard's observations 388
Henry 220
Hertz Experiment 274
Holes 472
Horizontal component of earth's magnetic field 187
Huygen's Principle 353
Impact parameter 418
Impedence diagram 246
Inductance 219
  mutual 220
  self 222
Induction 6
  of charge 6
Inductive
  circuit 252
  reactance 238
Insulators 5
Interference
  constructive 361
  destructive 361
  fringes 363
Internal resistance 110
Intrinsic semiconductor 472
Ionisation energy 427
Isobars 441
Isotones 441
Isotopes 439
J.C. Maxwell 270
K.F. Gauss 182
Kirchhoff's rules 115
Lateral shift 317
Law
  of radioactive decay 447
  of reflection 357
  of refraction 356
LC oscillations 255
Lenz's law 210
Lens maker's formula 326
Light emitting diode 488
Limitations of Ohm's law 101
Linear
  charge density 32
  magnification/Magnifying power 336
Logic gates 491
Lorentz force 134
Magnetic
  declination 186
  dipole 177
  dipole moment of a revolving electron 162
  field 132
  field lines 175
  field on the axis of a circular current loop 145
  flux 182, 206
  force on a current carrying conductor 135
  force 133
  hysteresis 195
  inclination 187
  intensity 190
  meridian 186
  moment of a current loop 158
  moment 178
  permeability 190
  potential energy 178
  susceptibility 190
  torque 178
Magnetisation 189
Majority carriers 476
Mass
  defect 443
  number 440
  energy relation 442
Maxwell's equations 273
Mean life 448
Meter bridge 120
Michael Faraday 208
Microscope 335
  compound 337
Microwaves 281
Minority carriers 476
Mirage 321
Mirror equation 314
Mobility 100
Moderator 454
Motion in a magnetic field 137
Motional emf 212
Moving coil galvanometer 163
Multiplication factor (fission) 454
NAND gate 504
Neutrons 440
Non-polar molecules 72
NOR gate 505
North pole 174
NOT gate 491
n-type semi conductor 475
Nuclear
  binding energy 442
  density 442
  energy 451
  fission 452
  force 445
  fusion 455
  holocaust 457
  reactor 452
  size 441
  winter 457

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Index

Numerical aperture 375
Ohm 95
Ohm's law 95
Optical fibres 321
OR gate 491
Orbital magnetic moment 163
Paramagnetism 192
Permanent magnets 195
Permeability of free space 143
Permittivity
    of free space 11, 76
    of medium 76
Phasors 237
    diagram 237
Photodiode 487
Photoelectric effect 388
Photocell 399
Photoelectric emission 388
Photoelectrons 389
Photon 395
Pith ball 2
Plane polarised wave 377
p-n-p junction 478
Point charge 10
Polar molecules 72
Polarisation 71, 376
    by reflection 380
    by scattering 379
Polarity of charge 2
Polaroid 378
Potential 53
    due to an electric dipole 55
    due to a point charge 54
    due to a system of charges 57
    energy difference 53
    energy for a system of charges 61
    energy of a dipole 66
    energy of a single charge 64
    energy of a system of two charges 65
    energy 52
Potentiometer 122
Power (electrical) 106
    factor 252
    in ac circuit 252
    of lens 327
Pressurised heavy water reactors 453
Primary coil
Principal focus 311
Principle of superposition 15
Principle quantum number 425
Properties of electric charge 8
p-type semi conductor 476
Q factor/quality factor 250
Quanta of energy 393
Quantisation of charge 8
Radio waves 281
Radioactivity 446
Rainbow 333
Ray optics, validity of 375
Rayleigh scattering 334
Rectifier 483
Red shift 358
Reflection of light 310
Refraction 318
    of a plane wave 355
Refractive index 317, 356
Relation between field and potential 61
Relaxation time 98
Rententivity 195
Resistance 95
Resistivity 96, 468
    of some materials 102
Resolving power 373
    of eye 374
Resonance 248
    Sharpness 249
Resonant frequency 248
Reverse bias 480
Right hand rule 149
Root mean square (rms) or effective
    current 235
    voltage 236
Roget's spiral 156
Rutherford's model of atom 415
Saturation current 390
Scattering of light 334
Secondary wavelet 354
Semiconductors 469
    diode 479
    elemental 468
    compound 468
Shunt resistance 164
Snell's law 317, 356
Solar cell 489
Solenoid 151
South pole 174
Spectral series 421
    Brackett 422
    Fund 422
    Lyman 422
    Paschen 422
Spherical mirror 310, 311
Spin magnetic moment 163
Surface charge density 32
Telescope 339
Temperature dependence of
    resistivity 103
Tesla 135
Thermionic emission 388

2022-23

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Thermonuclear fusion 456
Thin lens formula 326
Threshold frequency 392
Tokamak 153
Toroid 152
Torque
  on a current loop 157
  on a dipole 31
Total internal reflection 319
Transformer 259
  Step-down 261
  Step-up 261
Truth table 491
Uncertainty Principle 400
Unpolarised wave 377
Ultraviolet rays 282
Valence band 469
Velocity selector 140
Visible rays 282
Voltage Regulator 486
Voltage sensitivity of a galvanometer 165
Voltmeter 165
Volume charge density 32
Wattless current 252
Wavefront 353
  plane 354
  spherical 354
Wheatstone bridge 118
Work function 394
X rays 283
Young's experiment 362
Zener
  diode 485
  breakdown 485

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APPENDICES

APPENDIX A 1
THE GREEK ALPHABET

Alpha	Α	α	Iota	Ι	ι	Rho	Ρ	ρ
Beta	Β	β	Kappa	Κ	κ	Sigma	Σ	σ
Gamma	Γ	γ	Lambda	Λ	λ	Tau	Τ	τ
Delta	Δ	δ	Mu	Μ	μ	Upsilon	Υ	υ
Epsilon	Ε	ε	Nu	Ν	ν	Phi	Φ	ϕ, φ
Zeta	Ζ	ς	Xi	Ξ	ξ	Chi	Χ	χ
Eta	Η	η	Omicron	Ο	ο	Psi	Ψ	ψ
Theta	Θ	θ	Pi	Π	π	Omega	Ω	ω

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APPENDIX A 2
COMMON SI PREFIXES AND SYMBOLS FOR MULTIPLES AND SUB-MULTIPLES

Multiple			Sub-Multiple		
Factor	**Prefix**	**Symbol**	**Factor**	**Prefix**	**symbol**
10^{18}	Exa	E	10^{-18}	atto	a
10^{15}	Peta	P	10^{-15}	femto	f
10^{12}	Tera	T	10^{-12}	pico	p
10^{9}	Giga	G	10^{-9}	nano	n
10^{6}	Mega	M	10^{-6}	micro	μ
10^{3}	kilo	k	10^{-3}	milli	m
10^{2}	Hecto	h	10^{-2}	centi	c
10^{1}	Deca	da	10^{-1}	deci	d

APPENDIX A 3
SOME IMPORTANT CONSTANTS

Name	Symbol	Value
Speed of light in vacuum	c	2.9979×10^{8} m s^{-1}
Charge of electron	e	1.602×10^{-19} C
Gravitational constant	G	6.673×10^{-11} N m^{2} kg^{-2}
Planck constant	h	6.626×10^{-34} J s
Boltzmann constant	k	1.381×10^{-23} J K^{-1}
Avogadro number	N_A	6.022×10^{23} mol^{-1}
Universal gas constant	R	8.314 J mol^{-1}K^{-1}
Mass of electron	m_e	9.110×10^{-31} kg
Mass of neutron	m_n	1.675×10^{-27} kg
Mass of proton	m_p	1.673×10^{-27} kg
Electron-charge to mass ratio	e/m_e	1.759×10^{11} C/kg
Faraday constant	F	9.648×10^{4} C/mol
Rydberg constant	R	1.097×10^{7} m^{-1}
Bohr radius	a_0	5.292×10^{-11} m
Stefan-Boltzmann constant	σ	5.670×10^{-8} Wm^{-2}K^{-4}
Wien's Constant	b	2.898×10^{-3} mK
Permittivity of free space	ε_0 $1/4\pi\,\varepsilon_0$	8.854×10^{-12} C^{2} N^{-1}m^{-2} 8.987×10^{9} N m^{2} C^{-2}
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ T m A^{-1} $\cong 1.257 \times 10^{-6}$ Wb A^{-1} m^{-1}

OTHER USEFUL CONSTANTS

Name	Symbol	Value
Mechanical equivalent of heat	J	4.186 J cal^{-1}
Standard atmospheric pressure	1 atm	1.013×10^{5} Pa
Absolute zero	0 K	−273.15 °C
Electron volt	1 eV	1.602×10^{-19} J
Unified Atomic mass unit	1 u	1.661×10^{-27} kg
Electron rest energy	mc^2	0.511 MeV
Energy equivalent of 1 u	1 uc^2	931.5 MeV
Volume of ideal gas (0 °C and 1atm)	V	22.4 L mol^{-1}
Acceleration due to gravity (sea level, at equator)	g	9.78049 m s^{-2}

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