CHAPTER 45

SEMICONDUCTORS AND SEMICONDUCTOR DEVICES

45.1 INTRODUCTION

We have discussed some of the properties of conductors and insulators in earlier chapters. We assumed that there is a large number of almost free electrons in a conductor which wander randomly in the whole of the body, whereas, all the electrons in an insulator are tightly bound to some nucleus or the other. If an electric field $\vec{E}$ is established inside a conductor, the free electrons experience force due to the field and acquire a drift speed. This results in an electric current. The conductivity σ is defined in terms of the electric field $\vec{E}$ existing in the conductor and the resulting current density $\vec{j}$. The relation between these quantities is

$$\vec{j} = \sigma\vec{E}.$$

Larger the conductivity σ, better is the material as a conductor.

The conductivity σ of a conductor, such as copper, is fairly independent of the electric field applied and decreases as the temperature is increased. This is because as the temperature is increased, the random collisions of the free electrons with the particles in the conductor become more frequent. The electrons get less time to gain energy from the applied electric field. This results in a decrease in the drift speed and hence the conductivity decreases. The resistivity $\rho = 1/\sigma$ of a conductor increases as the temperature increases.

Almost zero electric current is obtained in insulators unless a very high electric field is applied.

We now introduce another kind of solid known as *semiconductor*. These solids do conduct electricity when an electric field is applied, but the conductivity is very small as compared to the usual metallic conductors. Silicon is an example of a semiconductor, its conductivity is about 10^{11} times smaller than that of copper and is about 10^{13} times larger than that of fused quartz. Another distinguishing feature about a semiconductor is that its conductivity increases as the temperature is increased. To understand the mechanism of conduction in solids, let us discuss qualitatively, formation of energy bands in solids.

45.2 ENERGY BANDS IN SOLIDS

The electrons of an isolated atom can have certain definite energies labelled as 1s, 2s, 2p, 3s, etc. Pauli exclusion principle determines the maximum number of electrons which can be accommodated in each energy level. An energy level consists of several quantum states and no quantum state can contain more than one electron. Consider a sodium atom in its lowest energy state. It has 11 electrons. The electronic configuration is $(1s)^2\ (2s)^2\ (2p)^6\ (3s)^1$. The levels 1s, 2s and 2p are completely filled and the level 3s contains only one electron although it has a capacity to accommodate 2. The next allowed energy level is 3p which can contain 6 electrons but is empty. All the energy levels above 3s are empty.

Now consider a group of N sodium atoms separated from each other by large distances such as in sodium vapour. There are altogether $11N$ electrons. Assuming that each atom is in its ground state, what are the energies of these $11N$ electrons ? For each atom, there are two states in energy level 1s. There are $2N$ such states which have identical energy and are filled by $2N$ electrons. Similarly, there are $2N$ states having identical energy labelled 2s, $6N$ states having identical energy labelled 2p and $2N$ states having identical energy labelled 3s. The $2N$ states of 1s, $2N$ states of 2s and $6N$ states of 2p are completely filled whereas only N of the $2N$ states of 3s are filled by the electrons and the remaining N states are empty. These ideas are shown in table (45.1) and figure (45.1).

Table 45.1 : *Quantum states in sodium vapour*

Energy level	Total states available	Total states occupied
1s	$2N$	$2N$
2s	$2N$	$2N$
2p	$6N$	$6N$
3s	$2N$	N
3p	$6N$	0

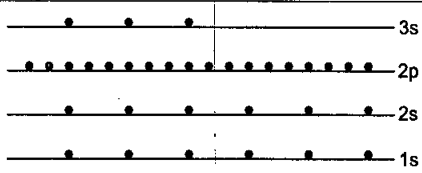


Figure 45.1

The value of energy in a particular state of an isolated sodium atom is determined by the mutual interactions among the nucleus and the 11 electrons. In the collection of the N sodium atoms that we have considered, it is assumed that the atoms are widely separated from each other and hence the electrons of one atom do not interact with those of the others to any appreciable extent. As a result, the energy of 1s states of each atom is the same as that for an isolated atom. All the 1s states, therefore, have identical energy. Similarly, all the 2s, 2p, 3s states have identical energies, respectively. Now suppose, the atoms are drawn closer to one another to the extent that the outer 3s electron of one atom starts interacting with the 3s electrons of the neighbouring atoms. Because of these interactions, the energy of the 3s states will change. It turns out that the changes in energy in all the $2N$ states of 3s level are not identical. Some of the states are shifted up in energy and some are pushed down. The magnitude of change is also different for different states of the 3s level. As a result, what was a sharply defined 3s energy, now becomes a combination of several closely spaced energies. We say that these $2N$ states have formed an *energy band*. We label this band as 3s band. The inner electrons interact weakly with each other so that this splitting of sharp energy levels into bands is less for inner electrons.

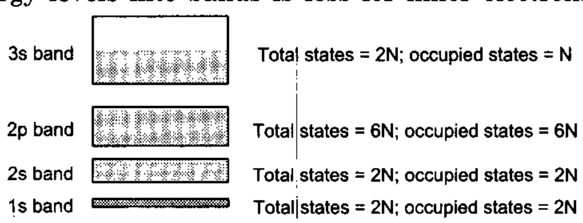


Figure 45.2

Figure (45.2) shows schematically this splitting of energy levels in bands. We have a 3s band which contains $2N$ states with slightly different energies, N of them are occupied by the N electrons of sodium atoms and the remaining N states are empty. Similarly, we talk of the 2p band which contains $6N$ states with slightly different energies and all these states are filled. Similar is the case for other inner bands. The difference between the highest energy in a band and the lowest energy in the next higher band is called the *band gap* between the two bands.

Sodium was taken only as an example. We have energy bands separated by band gaps in all solids. At 0 K, the energy is the lowest and the electrons fill the bands from the bottom according to the Pauli exclusion principle till all the electrons are accommodated. As the temperature is raised, the electrons may collide with each other and with ions to exchange energy. At an absolute temperature T, the order of energy exchanged is kT where k is the Boltzmann constant. This is known as thermal energy. At room temperature (300 K), kT is about 0·026 eV. Suppose the band gaps are much larger than kT. An electron in a completely filled band does not find an empty state with a slightly higher or a slightly lower energy. It, therefore, cannot accept or donate energy of the order of kT and hence does not take part in processes involving energy exchange. This is the case with inner bands which are, in general, completely filled. The outermost electrons which are in the highest occupied energy band, may take up this energy $\approx kT$ if empty states are available in the same band. For example, a 3s electron in sodium can take up thermal energy and go to an empty state at a slightly more energy.

Similar is the scenario when an electric field is applied by connecting the sodium metal to a battery. The electric field, in general, can supply only a small amount of energy to the electrons. Only the electrons in the highest occupied band can accept this energy. These electrons can acquire kinetic energy and move according to the electric field. This results in electric current. The electrons in the inner bands cannot accept small amounts of energy from the electric field and hence do not take part in conduction.

The energy band structure in solids may be classified in four broad types as shown in figure (45.3).

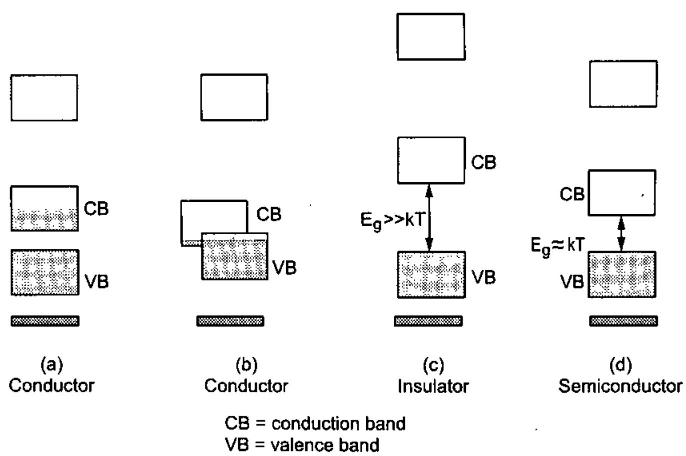


Figure 45.3

(a) The highest occupied energy band is only partially filled at 0 K (figure 45.3a). Sodium is an example of this kind. If the electronic configuration is such that the outermost subshell contains odd number of electrons, we get this type of band structure. They are good conductors of electricity because as an electric field is applied, the electrons in the partially filled band can receive energy from the field and drift accordingly.

(b) The highest occupied energy level is completely filled at 0 K and the next higher level is completely empty when the atoms are well-separated. But as the atoms come closer and these levels split into bands, the bands overlap with each other (figure 45.3b). Zinc is an example of this kind. The electronic configuration of zinc is $(1s)^2$ $(2s)^2$ $(2p)^6$ $(3s)^2$ $(3p)^6$ $(3d)^{10}$ $(4s)^2$. The highest energy level—that contains any electron when the zinc atoms are well-separated—is the 4s level and all the $2N$ states in it are occupied by electrons. However, in solid zinc, the 4p band overlaps with the 4*s* band. In this case also, there are empty states at energies close to the occupied states and hence these solids are also good conductors.

(c) The highest occupied energy band is completely filled and the next higher band, which is empty, is well above it (figure 45.3c). The band gap between these two bands is large. The electrons do not have empty states at an energy slightly above or below their existing energies. If an electric field is applied by connecting the two ends of such a solid to a battery, the electrons will refuse to receive energy from the field. This is because they do not find an empty state at a slightly higher energy. Diamond is an example of this kind. The gap between the lowest empty band and the highest filled band is about 6 eV. The electric field needed to supply 6 eV energy to an electron is of the order of 10^7 V m^{-1} in copper (see example 45.1). Assuming the same value for diamond; if we take a 10 cm slab of diamond, we will have to use a battery of 10^6 volts to get response from an electron. These solids are, therefore, insulators.

(d) The highest occupied band is completely filled at 0 K but the next higher band, which is empty, is only slightly above the filled band (figure 45.3d). The band structure is very similar to that of an insulator but the band gap between these two bands is small. An example is silicon in which the band gap is 1·1 eV. It is still difficult for an ordinary battery to supply an energy of the order of 1·1 eV to an electron. However, at temperatures well above 0 K, thermal collisions may push some of the electrons from the highest occupied band to the next empty band. These few electrons, in the otherwise empty band, can respond to even a weak battery because they have a large number of empty states just above their existing energy. As electrons from a filled band are pushed up in energy to land into a higher energy band, empty states are created in this filled band. These empty states allow some movement of electrons in that band and thus promote conduction. As the total number of electrons that can receive energy from the electric field is small, the conductivity is quite small as compared to common conductors. Such solids are called *semiconductors*.

The energy bands which are completely filled at 0 K are called *valence bands*. The bands with higher energies are called *conduction bands*. We are generally concerned with only the highest valence band and the lowest conduction band. So when we say valence band, it means the highest valence band. Similarly, when we say conduction band, it means the lowest conduction band. Study the labels 'conduction band (CB)' and 'valence band (VB)' in figure (45.3).

Example 45.1

The mean free path of conduction electrons in copper is about 4×10^{-8} m. *For a copper block, find the electric field which can give, on an average,* 1 eV *energy to a conduction electron.*

Solution : Let the electric field be E. The force on an electron is eE. As the electron moves through a distance d, the work done on it is eEd. This is equal to the energy transferred to the electron. As the electron travels an average distance of 4×10^{-8} m before a collision, the energy transferred is $eE(4 \times 10^{-8}$ m). To get 1 eV energy from the electric field,

$$eE(4 \times 10^{-8}\ \text{m}) = 1\ \text{eV}$$

or,
$$E = 2{\cdot}5 \times 10^{7}\ \text{V m}^{-1}.$$

Let us now consider the physical picture of conductors, insulators and semiconductors in a Bohr-type model. The inner electrons are tightly bound to the nuclei and move in their well-defined orbits. In a conductor, the outermost subshell is not completely filled and the electrons moving around one nucleus can jump to a similar orbit around some other nucleus (figure 45.4a). This is possible because there is an empty state there to accommodate the electron. For example, a 3s electron of one sodium atom can jump to the 3s orbit of some other sodium atom because out of the two 3s states only one, in general, is filled. Similar is the case with zinc-type metals. The 4p orbits in zinc atoms are, in general, empty. As the 4p band overlaps with the 4*s* band, the energy of a 4p state is not too different from a 4s state. Thus, without demanding for excessive energy, a 4s electron can jump

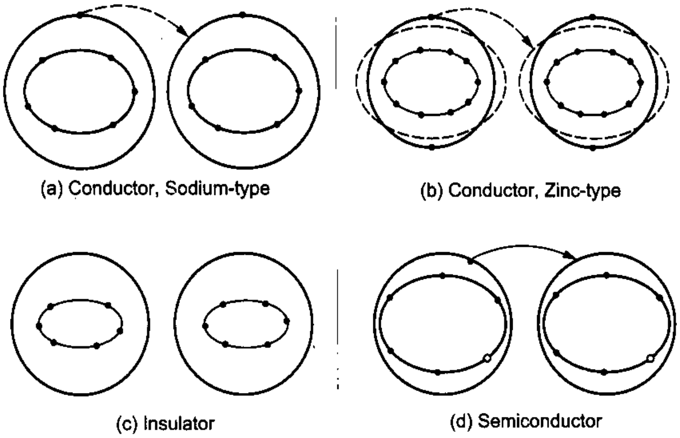


Figure 45.4

into the 4p orbit of its own atom or of some other atom (figure 45.4b).

In insulators, even the outermost electrons are tightly bound to their respective nuclei. The subshell in which they lie is completely filled and the next higher orbit is at a much higher energy. No drift is then possible (figure 45.4c).

In semiconductors at room temperature or above, some electrons move around the nuclei with a much larger radius. These large orbits are nearly empty and so the electrons in these orbits may jump from one atom to the other easily. These are the electrons in conduction band and are called *conduction electrons* (figure 45.4d).

45.3 THE SEMICONDUCTOR

As discussed above, in semiconductors the conduction band and the valence band are separated by a relatively small energy gap. For silicon, this gap is 1·1 eV. For another common semiconductor germanium, the gap is 0·68 eV.

Silicon has an atomic number of 14 and electronic configuration $(1s)^2(2s)^2(2p)^6(3s)^2(3p)^2$. The chemistry of silicon tells us that each silicon atom makes covalent bonds with the four neighbouring silicon atoms. To form a covalent bond, two silicon atoms contribute one electron each and the two electrons are shared by the two atoms. Both of these electrons are in the valence band. Due to collision, one of these valence electrons may acquire additional energy and it may start orbiting the silicon nucleus at a larger radius. Thus, the bond is broken. One electron has gone into the conduction band, it is moving in an orbit of large radius and is frequently jumping from one nucleus to another.

Figure (45.5a) represents a model of solid silicon. The four outer electrons of each atom form bonds with the four neighbouring atoms. Each bond consists of two electrons. Figure (45.5b) shows a broken bond

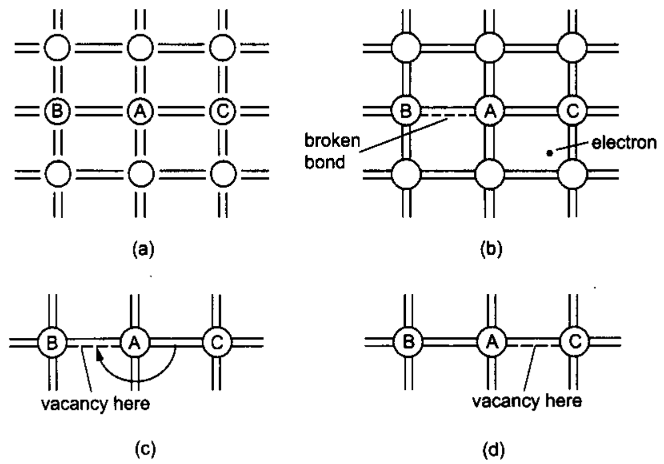


Figure 45.5

represented by the dashed line. The electron corresponding to this bond has acquired sufficient energy and has jumped into the conduction band. So there is a vacancy for an electron at the site of the broken bond. In a semiconductor, a number of such broken bonds and conduction electrons exist. Now consider the situation shown in figure (45.5c). The bond between the atoms A and B is broken. A bonding electron between A and C can make a jump towards the left and fill the broken bond between A and B. Not much energy is needed to induce such a transfer. This is because, the electron makes transition from one bond to other only and all bond electrons have roughly the same energy.

As the broken bond AB is filled, the bond AC is broken (figure 45.5d). Thus, the vacancy has shifted towards the right. Any movement of a valence electron from one bond to a nearby broken bond may be described as the movement of vacancy in the opposite direction. It is customary in semiconductor physics to treat a vacancy in valence band as a particle having positive charge $+e$. Movement of electrons in valence band is then described in terms of movement of vacancies in the opposite directions. Such vacancies are also called *holes*.

Whenever a valence electron is shifted to conduction band, a hole is created. Thus, in a pure semiconductor, the number of conduction electrons equals the number of holes. When an electric field is applied, conduction electrons drift opposite to the field and holes drift along the field. That is why, holes are assumed to have positive charge. Conduction takes place due to the drift of conduction electrons as well as of holes. Such pure semiconductors are also called *intrinsic semiconductors*. The chemical structure of germanium is the same as that of silicon and hence the above discussion is equally applicable to it.

45.4 *p*-TYPE AND *n*-TYPE SEMICONDUCTORS

In an intrinsic semiconductor, like pure silicon, only a small fraction of the valence electrons are able to reach the conduction band. The conduction properties of a semiconductor can be drastically changed by diffusing a small amount of impurity in it. The process of diffusing an impurity is also known as *doping*. Suppose a small amount of phosphorus ($Z = 15$) is diffused into a silicon crystal. Each phosphorus atom has five outer electrons in the valence band. Some of the phosphorus atoms displace the silicon atoms and occupy their place. A silicon atom has four valence electrons locked in covalent bonds with neighbouring four silicon atoms. Phosphorus comes in with five valence electrons. Four electrons are shared with the neighbouring four silicon atoms. The fifth one moves with a large radius ($\approx$ 30 Å) round the phosphorus ion. The energy of this extra electron is much higher than the valence electrons locked in covalent bonds. In fact, the energy levels for these extra electrons—known as impurity levels—are only slightly below the conduction band (0·045 eV for phosphorus in silicon). This small gap is easily covered by the electrons during thermal collisions and hence a large fraction of them are found in the conduction band. Figure (45.6) shows qualitatively the situation in such a doped semiconductor.

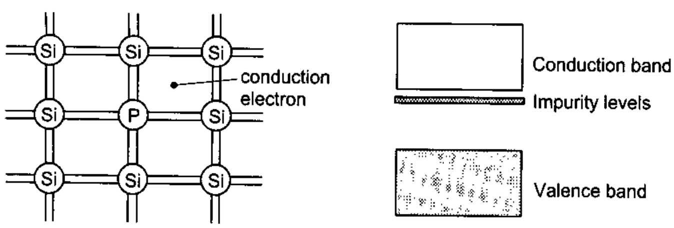


Figure 45.6

When a phosphorus atom with five outer electrons is substituted for a silicon atom, an extra electron is made available for conduction. Thus, the number of conduction electrons increases due to the introduction of a pentavalent impurity in silicon. The conduction properties are, therefore, very sensitive to the amount of the impurity. The introduction of phosphorus in the proportion of 1 in 10^6 increases the conductivity by a factor of about 10^6. Interesting desired results may be obtained by controlling the amount and distribution of impurity in a semiconductor.

Such impurities, which donate electrons for conduction, are called *donor* impurities. As the number of negative charge carriers is much larger than the number of positive charge carriers, these semiconductors are called *n-type semiconductors*. What happens if a trivalent impurity— such as aluminium— is doped into silicon ? Silicon atom with four valence electrons is substituted by an aluminium atom with three valence electrons. These three electrons are used to form covalent bonds with the neighbouring three silicon atoms but the bond with the fourth neighbour is not complete. The broken bond between the aluminium atom and its fourth neighbour can be filled by another valence electron if this electron obtains an extra energy of about 0·057 eV. A hole is then created in the valence band. We say that impurity levels are created a little above the valence band (0·057 eV for aluminium in silicon). The valence electrons can cross over to these levels leaving behind the holes, which are responsible for conduction (figure 45.7). As the energy gap ΔE between the valence band and the impurity levels is comparable to kT, large number of holes are created. The number of holes in such a doped semiconductor is much larger than the number of conduction electrons. As the majority charge carriers are holes, i.e., positive charges, these semiconductors are called *p-type semiconductors*. The impurity of this kind creates new levels which can accept valence electrons, hence these impurities are called *acceptor impurities*.

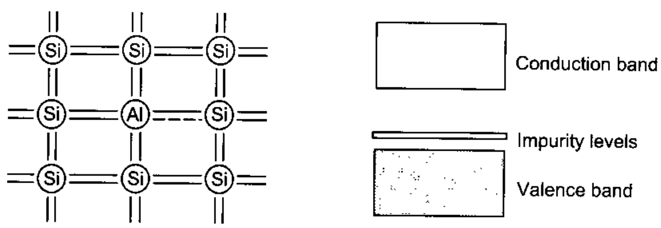
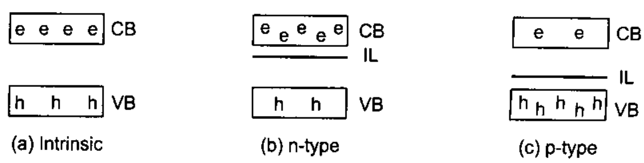


Figure 45.7

Semiconductors with an impurity doped into it are called *extrinsic semiconductor*. Figure (45.8) shows a schematic representation of intrinsic and extrinsic semiconductors.



CB = conduction band; VB = valence band; IL = impurity level

Figure 45.8

45.5 DENSITY OF CHARGE CARRIERS AND CONDUCTIVITY

Due to thermal collisions, an electron can take up or release energy. Thus, occasionally a valence electron takes up energy and the bond is broken. The electron goes to the conduction band and a hole is created. And occasionally, an electron from the conduction band loses some energy, comes to the valence band and fills up a hole. Thus, new electron–hole pairs are formed as well as old electron–hole pairs disappear. A steady-state situation is reached and the number of electron–hole pairs takes a nearly constant value. For silicon at room temperature (300 K), the number of these pairs is about $7 \times 10^{15}\ m^{-3}$. For germanium, this number is about $6 \times 10^{1}\ m^{-3}$.

Table (45.2) gives a rough estimate of the densities of charge carriers in a typical conductor and in some of the semiconductors. Note that the product of density of conduction electrons and density of holes is constant for a semiconductor when it is doped with impurities.

Table 45.2 : *Densities of charge carriers*

Material	Type	Density of conduction electrons (m^{-3})	Density of holes (m^{-3})
Copper	Conductor	9×10^{28}	0
Silicon	Intrinsic semiconductor	7×10^{15}	7×10^{15}
Silicon doped with phosphorus (1 part in 10^6)	*n*-type semiconductor	5×10^{22}	1×10^{9}
Silicon doped with aluminium (1 part in 10^6)	*p*-type semiconductor	1×10^{9}	5×10^{22}

The conductivity of a metal is given as

$$\sigma = \frac{j}{E}$$

$$= ne\left(\frac{v}{E}\right)$$

where n is the density of conduction electrons and v is the drift speed when an electric field E is applied. The quantity v/E is known as the *mobility* of the electrons. Writing the mobility as μ,

$$\sigma = ne\mu.$$

This equation is slightly modified for semiconductors. Here conduction is due to the conduction electrons as well as due to the holes. Electron mobility and hole mobility are also, in general, different. The conductivity of a semiconductor is, therefore, written as

$$\sigma = n_e e\, \mu_e + n_h e\, \mu_h$$

where n_e, n_h are the densities of conduction electrons and the holes respectively and μ_e, μ_h are their mobilities.

Example 45.2

Calculate the resistivity of an n-type semiconductor from the following data: density of conduction electrons $= 8 \times 10^{13}\ cm^{-3}$, *density of holes* $= 5 \times 10^{12}\ cm^{-3}$, *mobility of conduction electron* $= 2{\cdot}3 \times 10^{4}\ cm^{2}\ V^{-1}s^{-1}$ *and mobility of holes* $= 100\ cm^{2}\ V^{-1}s^{-1}$.

Solution : The conductivity of the semiconductor is

$$\sigma = e(n_e\, \mu_e + n_h \mu_h)$$

$$= (1{\cdot}6 \times 10^{-19}\ C)\ [(8 \times 10^{19}\ m^{-3}) \times (2{\cdot}3\ m^{2}\ V^{-1}s^{-1}) + (5 \times 10^{18}\ m^{-3}) \times (10^{-2}\ m^{-2}\ V^{-1}s^{-1})]$$

$$\approx 2{\cdot}94\ Cm^{-1}\ V^{-1}\ s^{-1}.$$

The resistivity is $\rho = \frac{1}{\sigma} = \frac{1}{2{\cdot}94}\ m\ Vs\ C^{-1} \approx 0{\cdot}34\ \Omega m.$

Temperature Dependence of Conductivity of a Semiconductor

If temperature is increased, the average energy exchanged in a collision increases. More valence electrons cross the gap and the number of electron–hole pairs increases. It can be shown that the number of such pairs is proportional to the factor $T^{3/2} e^{-\Delta E/2kT}$, where ΔE is the band gap. The increase in the number of electron–hole pairs results in an increase in the conductivity, i.e., a decrease in the resistivity of the material.

There is a small opposing behaviour due to the increase in thermal collisions. The drift speed and hence the mobility decreases and this contributes towards increasing the resistivity just like a conductor. However, the effect of increasing the number of charge carriers is much more prominent than the effect of the decrease in drift speed. The resultant effect is that the resistivity decreases as the temperature increases. The temperature coefficient of resistivity is, therefore, negative. Its average value for silicon is $-0{\cdot}07\ K^{-1}$. This behaviour is opposite to that of a conductor where resistivity increases with increasing temperature.

45.6 *p-n* JUNCTION

When a semiconducting material such as silicon or germanium is doped with impurity in such a way that one side has a large number of acceptor impurities and the other side has a large number of donor impurities, we obtain a *p-n* junction. To construct a *p-n* junction, one may diffuse a donor impurity to a pure semiconductor so that the entire sample becomes *n*-type. The acceptor impurity may then be diffused in higher concentration from one side to make that side *p*-type. Figure (45.9) shows the physical structure of a typical *p-n* junction.

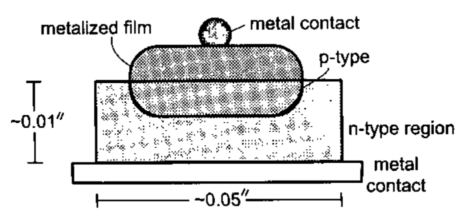


Figure 45.9

Consider the idealized situation of a *p-n* junction at the time of its formation shown in figure (45.10).

The symbol e represents a conduction electron and h represents a hole. Suppose that at the time of formation, the left-half is made p-type and the right-half n-type semiconductor. These two portions may be called p-side and n-side respectively.

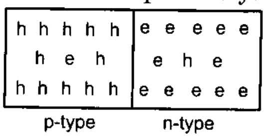


Figure 45.10

This cannot be the equilibrium situation. As there is a large concentration of holes in the left-half and only a small concentration of holes in the right-half, there will be diffusion of holes towards the right. Physically, this means that some of the valence electrons just to the right of the junction may fill up the vacancies just to the left of the junction. Similarly, because of the concentration difference, conduction electrons diffuse from the right to the left. The ions as such do not move because of their heavy masses. As the two halves (left-half and right-half) were electrically neutral in the beginning, diffusion of holes towards the right and diffusion of electrons towards the left make the right-half positively charged and the left-half negatively charged. This creates an electric field near the junction from the right to the left. Any hole near the junction is pushed by the electric field into the left-half. Similarly, any conduction electron near the junction is pushed by the electric field into the right-half. Thus, no charge carrier can remain in a small region near the junction. This region is called the *depletion layer* (figure 45.11).

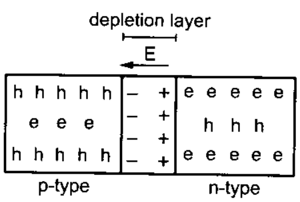


Figure 45.11

Diffusion Current

Because of the concentration difference, holes try to diffuse from the p-side to the n-side. In figure (45.11), this is from the left to the right. However, the electric field at the junction exerts a force on the holes towards the left as they come to the depletion layer. Only those holes which start moving towards the right with a high kinetic energy are able to cross the junction. Similarly, diffusion of electrons from the right to the left is opposed by the field and only those electrons which start towards the left with high kinetic energy are able to cross the junction. The electric potential of the n-side is higher than that of the p-side, the variation in potential is sketched in figure (45.12).

We say that there is a *potential barrier* at the junction which allows only a small amount of diffusion. Nevertheless, there are some energetic holes and electrons which surmount the barrier and some diffusion does take place. This diffusion results in an electric current from the p-side to the n-side known as *diffusion current.*

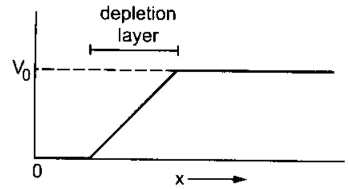


Figure 45.12

Drift Current

Because of thermal collisions, occasionally a covalent bond is broken and the electron jumps to the conduction band. An electron–hole pair is thus created. Also, occasionally a conduction electron fills up a vacant bond so that an electron–hole pair is destroyed. These processes continue in every part of the material. However, if an electron–hole pair is created in the depletion region, the electron is quickly pushed by the electric field towards the n-side and the hole towards the p-side. There is almost no chance of recombination of a hole with an electron in the depletion region. As electron–hole pairs are continuously created in the depletion region, there is a regular flow of electrons towards the n-side and of holes towards the p-side. This makes a current from the n-side to the p-side. This current is called the *drift current.*

The drift current and the diffusion current are in opposite directions. In steady state, the diffusion current equals the drift current in magnitude and there is no net transfer of charge at any cross-section. This is the case with a p-n junction kept in a cupboard.

45.7 *p-n* JUNCTION DIODE

Let us now discuss what happens if a battery is connected to the ends of a p-n junction. Figure (45.13) shows situations when (a) no battery is connected to the junction, (b) a battery is connected with its positive terminal connected to the p-side and the negative terminal connected to the n-side and (c) a battery is connected with its positive terminal connected to the n-side and the negative terminal connected to the p-side. If the positive terminal of the battery is connected to the p-side and the negative terminal to the n-side, we say that the junction is *forward-biased* (figure 45.13b). The potential of the n-side is higher than that of the p-side when no battery is connected to the junction. Due to the forward-bias connection, the potential of the p-side is raised and hence the height of the potential barrier decreases. The width of the depletion region is also reduced in forward bias (figure 45.13b).

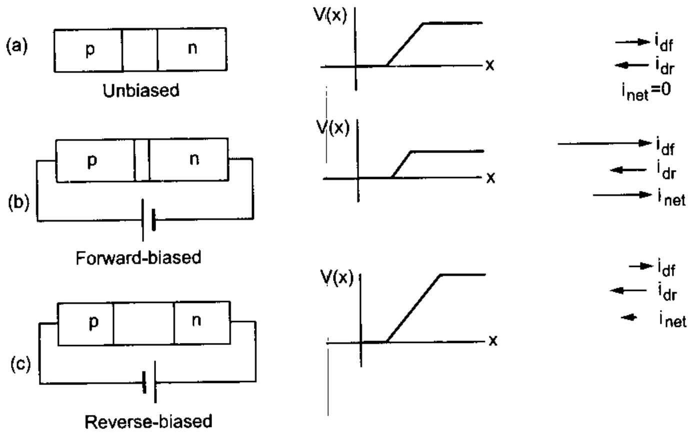


Figure 45.13

This allows more diffusion to take place. The diffusion current thus increases by connecting a battery in forward bias. The drift current remains almost unchanged because the rate of formation of new electron–hole pairs is fairly independent of the electric field unless the field is too large. Thus, the diffusion current exceeds the drift current and there is a net current from the p-side to the n-side. The diffusion increases as the applied potential difference is increased and the barrier height is decreased. When the applied potential difference is so high that the potential barrier is reduced to zero or is reversed, the diffusion increases very rapidly. The current i in the circuit thus changes nonlinearly with the applied potential difference. A p-n junction does not obey Ohm's law.

If the p-side of the junction is connected to the negative terminal and the n-side to the positive terminal of a battery, the junction is said to be *reverse-biased*. In this case, the potential barrier becomes higher as the battery further raises the potential of the n-side (figure 41.13c). The width of the depletion region is increased. Diffusion becomes more difficult and hence the diffusion current decreases. The drift current is not appreciably affected and hence it exceeds the diffusion current. So, there is a net current from the n-side to the p-side. However, this current is small as the drift current itself is small (typically in microamperes) and the net current is even smaller. Thus, during reverse bias, only a small current is allowed by the junction. We say that the junction offers a large resistance when reverse-biased.

Figure (45.14) shows a qualitative plot of current versus potential difference for a p-n junction. This is known as an *i–V characteristic* of the p-n junction. Note that the scales for the current are different for positive and negative current.

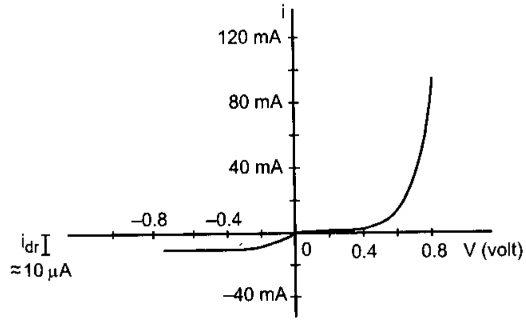


Figure 45.14

We see that the junction offers a little resistance if we try to pass an electric current from the p-side to the n-side and offers a large resistance if the current is passed from the n-side to the p-side. Any device which freely allows electric current in one direction but does not allow it in the opposite direction is called a diode. Thus, a p-n junction acts as a diode. An ideal diode should not allow any current in the reverse direction. A p-n junction diode is close to an ideal diode because the current in reverse bias is very small (few microamperes). The diode is symbolised as , the arrow pointing in the direction in which the current can pass freely. For a p-n junction diode, the arrow points from the p-side to the n-side. We have already studied a vacuum-tube diode based on thermionic emission in an earlier chapter.

Dynamic Resistance

The dynamic resistance of a p-n junction diode is defined as

$$R = \frac{\Delta V}{\Delta i}$$

where ΔV denotes a small change in the applied potential difference and Δi denotes the corresponding small change in the current. The dynamic resistance is a function of the operating potential difference. It is equal to the reciprocal of the slope of the i–V characteristic shown in figure (45.14).

Example 45.3

The i–V characteristic of a p-n junction diode is shown in figure (45.15). Find the approximate dynamic resistance of the p-n junction when (a) a forward bias of 1 volt is applied, (b) a forward bias of 2 volt is applied.

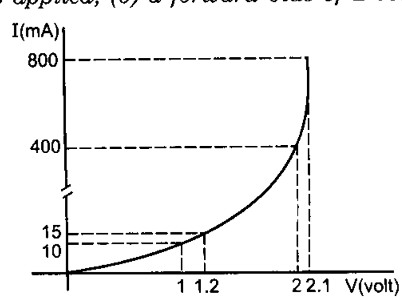


Figure 45.15

Solution : (a) The current at 1 volt is 10 mA and at 1·2 volt it is 15 mA. The dynamic resistance in this region is

$$R = \frac{\Delta V}{\Delta i} = \frac{0 \cdot 2 \text{ volt}}{5 \text{ mA}} = 40\ \Omega.$$

(b) The current at 2 volt is 400 mA and at 2·1 volt it is 800 mA. The dynamic resistance in this region is

$$R = \frac{\Delta V}{\Delta i} = \frac{0 \cdot 1 \text{ volt}}{400 \text{ mA}} = 0 \cdot 25\ \Omega.$$

Photodiode

Photodiode is a *p-n* junction whose function is controlled by the light allowed to fall on it. Suppose, the wavelength is such that the energy of a photon, hc/λ, is sufficient to break a valence bond. When such light falls on the junction, new hole–electron pairs are created. The number of charge carriers increases and hence the conductivity of the junction increases. If the junction is connected in some circuit, the current in the circuit is controlled by the intensity of the incident light.

Light-emitting Diode (LED)

When a conduction electron makes a transition to the valence band to fill up a hole in a *p-n* junction, the extra energy may be emitted as a photon. If the wavelength of this photon is in the visible range (380 nm–780 nm), one can see the emitted light. Such a *p-n* junction is known as *light-emitting diode* abbreviated as LED. For silicon or germanium, the wavelength falls in the infrared region. LEDs may be made from semiconducting compounds like gallium such as, arsenide or indium phosphide. LEDs are very commonly used in electronic gadgets as indicator lights.

Zener Diode

If the reverse-bias voltage across a *p-n* junction diode is increased, at a particular voltage the reverse current suddenly increases to a large value. This phenomenon is called *breakdown* of the diode and the voltage at which it occurs is called the *breakdown voltage*. At this voltage, the rate of creation of hole–electron pairs is increased leading to the increased current.

There are two main processes by which breakdown may occur. The holes in the n-side and the conduction electrons in the p-side are accelerated due to the reverse-bias voltage. If these minority carriers acquire sufficient kinetic energy from the electric field and collide with a valence electron, the bond will be broken and the valence electron will be taken to the conduction band. Thus a hole–electron pair will be created. Breakdown occurring in this manner is called *avalanche breakdown*. Breakdown may also be produced by direct breaking of valence bonds due to high electric field. When breakdown occurs in this manner it is called *zener breakdown.*

A diode meant to operate in the breakdown region is called an *avalanche diode* or a *zener diode* depending on the mechanism of breakdown. Once the breakdown occurs, the potential difference across the diode does not increase even if the applied battery potential is increased. Such diodes are used to obtain constant voltage output. Figure (45.16) shows the i–V characteristic of a zener diode including the breakdown region and a typical circuit which gives constant voltage V_0 across the load resistance R_L. Even if there is a small change in the input voltage V_i, the current through R_L remains almost the same. The current through the diode changes but the voltage across it remains essentially the same. Note the symbol used for the zener diode.

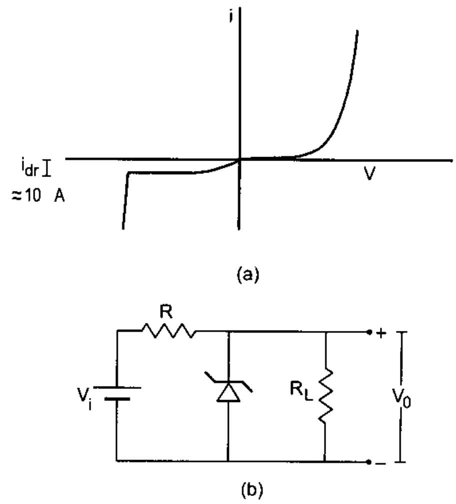


Figure 45.16

45.8 *p-n* JUNCTION AS A RECTIFIER

A rectifier is a device which converts an alternating voltage into a direct voltage. A *p-n*

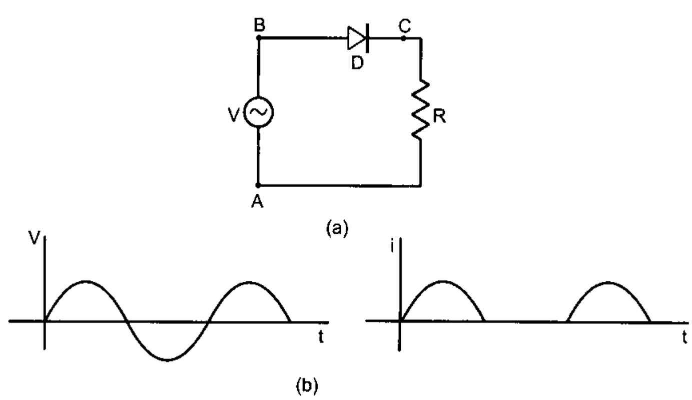


Figure 45.17

junction can be used as a rectifier because it permits current in one direction only. Figure (45.17a) shows an AC source connected to a load resistance through a *p-n* junction. The potential at the point *A* is taken to be zero. The potential at *B* varies with time as $V = V_0 \sin(\omega t + \varphi)$. During the positive half-cycle, $V > 0$ and *B* is at a higher potential than *A*. In this case, the junction is forward-biased and a current *i* is established in the resistance in the direction *C* to *A*.

The current through the resistance during this half-cycle is given by

$$i = \frac{V_0 \sin(\omega t + \varphi)}{R + R_{junction}}$$

and the potential difference across it is

$$\frac{RV_0 \sin(\omega t + \varphi)}{R + R_{junction}}.$$

Here $R_{junction}$ is the resistance offered by the *p-n* junction.

In forward bias, $R_{junction} << R$ so that

$$i \approx \frac{V_0}{R} \sin(\omega t + \varphi).$$

During the next half-cycle, $V < 0$ and the potential at the point *B* becomes smaller than that at *A*. The junction is thus reverse-biased and offers a large resistance during this half-cycle and there is only a negligible current in the circuit. The current in the resistance is thus unidirectional. The variations in voltage and current with time are sketched in figure (45.17b).

This is called half-wave rectification because there is practically no current during alternate half-cycles. A full-wave rectification can be achieved by using two diodes as shown in figure (45.18). The AC potential difference is obtained across the secondary of a transfomer and is connected in the circuit. In one half-cycle, $V_A > V_C > V_B$ so that the junction D_1 conducts but D_2 does not. The current is from *A* to D_1 to *E* to *C*. In the next half-cycle, $V_B > V_C > V_A$ so that D_2 conducts whereas D_1 does not. The current is from *B* to D_2 to *E* to *C*. In both the half-cycles, the current in the load resistance is from *E* to *C*.

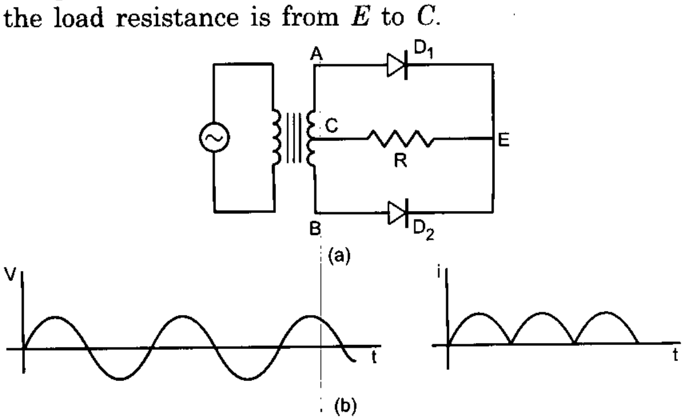


Figure 45.18

45.9 JUNCTION TRANSISTORS

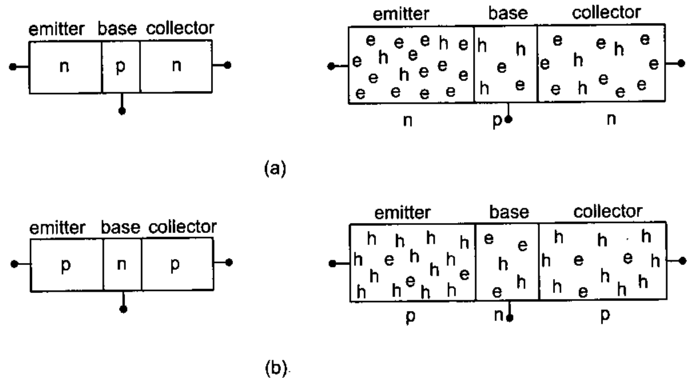


Figure 45.19

A junction transistor is formed by sandwiching a thin layer of a *p*-type semiconductor between two layers of *n*-type semiconductors or by sandwiching a thin layer of an *n*-type semiconductor between two layers of *p*-type semiconductors. In figure (45-19a), we show a transistor in which a thin layer of a *p*-type semiconductor is sandwiched between two *n*-type semiconductors. The resulting structure is called an *n-p-n* transistor. In figure (45.19b), we show a *p-n-p* transistor, where an *n*-type thin layer is sandwiched between two *p*-type layers. In actual design, the middle layer is very thin (≈ 1 μm) as compared to the widths of the two layers at the sides. The middle layer is called the *base* and is very lightly doped with impurity. One of the outer layers is heavily doped and is called *emitter*. The other outer layer is moderately doped and is called *collector*. Usually, the emitter–base contact area is smaller than the collector–base contact area. Terminals come out from the emitter, the base and the collector for external connections. Thus, a transistor is a three-terminal device.

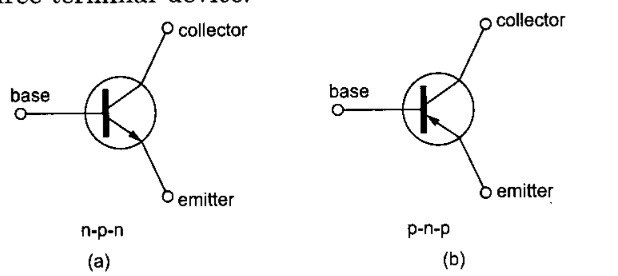


Figure 45.20

Figure (45.20) shows the symbols used for a junction transistor. In normal operation of a transistor, *the emitter–base junction is always forward-biased* whereas *the collector–base junction is reverse-biased.* The arrow on the emitter line shows the direction of the current through the emitter–base junction. In an *n-p-n* transistor, there are a large number of conduction electrons in the emitter and a large number of holes in the base. If the junction is forward-biased, the electrons will diffuse from the emitter to the base and holes will diffuse from the base to the emitter. The direction of electric current at this junction is, therefore, from the base to the emitter. This is indicated by the outward arrow on the emitter line in figure (45.20a). Similarly, for a *p-n-p* transistor the current is from the emitter to the base when this junction is forward-biased which is indicated by the inward arrow in figure (45.20b).

Biasing

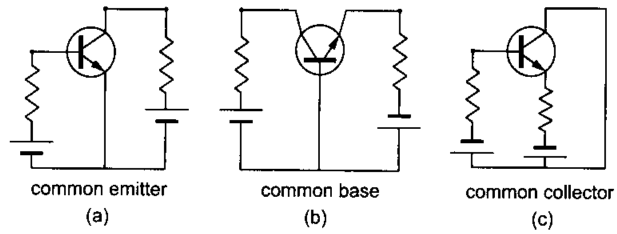


Figure 45.21

Suitable potential differences should be applied across the two junctions to operate the transitor. This is called *biasing* the transistor. A transistor can be operated in three different modes: common-emitter (or grounded-emitter), common-collector (or grounded-collector) and common-base (or grounded-base). In common-emitter mode, the emitter is kept at zero potential and the other two terminals are given appropriate potentials (figure 45.21a). Similarly, in common-base mode, the base is kept at zero potential (figure 45-21b) whereas in common-collector mode, the collector is kept at zero potential (figure 45-21c).

Working of a Transistor

Let us consider an *n-p-n* transistor connected to the proper biasing batteries as shown in figure (45.22). In part (a) of the figure, a physical picture of the transistor is used whereas in part (b), its symbol is used. Let us look at the current due to electrons. The emitter–base junction is forward-biased, so electrons are injected by the emitter into the base. The thickness of the base region is so small that most of the electrons diffusing into the base region cross over into the collector region. The reverse bias at the base–collector junction helps this process, because, as the electrons appear near this junction they are attracted by the collector. These electrons go through the batteries V_{CC} and V_{EE} and are then back to the emitter.

The electrons going from the battery V_{EE} to the emitter constitute the electric current I_E in the opposite direction. This is known as *emitter current*. Similarly, the electrons going from the collector to the battery V_{CC} constitute the *collector current* I_C.

We have considered only the current due to the electrons. Similar is the story of the holes which move in the opposite direction but result in current in the same direction. Currents I_E and I_C refer to the net currents. However, since the base is only lightly doped, the hole concentration is very low and the current in an *n-p-n* transistor is mostly due to the electrons. As almost all the electrons injected into the emitter go through the collector, the collector current I_C is almost equal to the emitter current. In fact, I_C is slightly smaller than I_E because some of the electrons coming to the base from the emitter may find a path directly from the base to the battery V_{EE}. This constitutes a *base current* I_B. The physical design of the transistor ensures that such events are small and hence I_B is small. Typically, I_B may be 1% to 5% of I_E.

Using Kirchhoff's law, we can write

$$I_E = I_B + I_C. \qquad \ldots (45.1)$$

α and β Parameters

α and β parameters of a transistor are defined as

$$\alpha = \frac{I_C}{I_E} \text{ and } \beta = \frac{I_C}{I_B}. \qquad \ldots (45.2)$$

Using equation (45.1),

$$\frac{I_E}{I_C} = \frac{I_B}{I_C} + 1 \qquad \ldots (i)$$

or,
$$\frac{1}{\alpha} = \frac{1}{\beta} + 1$$

or,
$$\beta = \frac{\alpha}{1 - \alpha}. \qquad \ldots (45.3)$$

As I_B is about 1–5% of I_E, α is about 0·95 to 0·99 and β is about 20 to 100.

Transistor Used in an Amplifier Circuit

Figure (45.23) shows an amplifier circuit using an *n-p-n* transistor in common-emitter mode. The battery E_B provides the biasing voltage V_{BE} for the

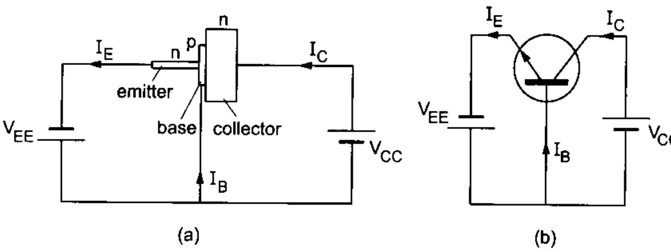


Figure 45.22

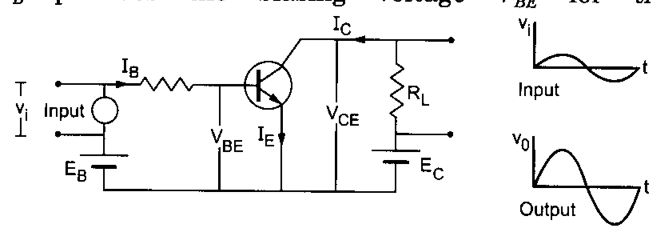


Figure 45.23

base–emitter junction. A potential difference V_{CE} is maintained between the collector and the emitter by the battery E_C. The base–emitter junction is forward-biased and so the electrons of the emitter flow towards the base. As the base region is very thin—of the order of a micrometre—and the collector is also maintained at a positive potential, most of the electrons cross the base region and move into the collector. As discussed earlier, the current I_C is about 0·95 I_E to 0·99 I_E.

The holes in the base region may diffuse into the emitter due to the forward biasing of the base–emitter junction. Also, the electrons coming from the emitter may recombine with some of the holes in the base. If the holes are lost in this way, the base will become negatively charged and will obstruct the incoming electrons from the emitter. If the base current I_B is increased by a small amount, the effect of hole-diffusion and hole–electron recombination may be neutralised and the collector current will be increased. Thus, a small change in the current I_B in the base circuit controls the larger current I_C in the collector circuit. This is the basis of amplification with the help of a transistor.

The input signal, to be amplified, is connected in series with the biasing battery E_B in the base circuit. A load resistor having a large resistance R_L is connected in the collector circuit and the output voltage is taken across this resistor. As the potential difference V_{BE} changes with time due to the input signal, the base current I_B changes. This results in a change ΔI_C in the collector current. The *current gain,* defined as $\Delta I_C / \Delta I_B$, is typically of the order of 50. The change in the voltage across R_L is, accordingly,

$$\Delta V = R_L \Delta I_C.$$

Thus, an amplified output is obtained across R_L.

Voltage gain, current gain and power gain

When a signal voltage v_i is added in the base circuit, the voltage across the load resistance changes by v_o. The ratio $\frac{v_o}{v_i}$ is called the *voltage gain* of the amplifier.

Suppose the input signal has a voltage v_i at an instant. This produces a change in the base current I_B. As the base–emitter junction is forward-biased, it offers a small dynamic resistance R_{BE}. The change in the current in the base circuit is

$$\Delta I_B = \frac{v_i}{R_{BE}}.$$

The resistance R_{BE} is also called the *input-resistance* of the circuit.

The collector current I_c is related to I_B as

$$I_c = \beta I_B.$$

Thus, the change in current I_C due to the signal voltage is,

$$\Delta I_C = \beta \Delta I_B = \beta \frac{v_i}{R_{BE}}.$$

The output voltage, i.e., the change in the voltage across the load resistance is

$$v_o = \Delta V = R_L \, \Delta I_C = \frac{\beta v_i R_L}{R_{BE}}.$$

The voltage gain is

$$\frac{v_o}{v_i} = \beta \frac{R_L}{R_{BE}}.$$

As β is of the order of 50 and R_L may be much larger than R_{BE}, the voltage gain is high.

As mentioned earlier, the current gain is defined as the change in the collector current divided by the change in the base current when the signal is added in the base circuit.

Thus, the current gain is

$$\frac{\Delta I_C}{\Delta I_B} = \beta.$$

Power gain = voltage gain × current gain

$$= \frac{\beta^2 R_L}{R_{BE}}.$$

Transfer conductance

To have a large amplification, a small change in V_{BE} should result in a large change in the collector current I_C. This property is measured by a quantity *transfer conductance* g_m defined as

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}}.$$

It is also known as *transconductance.*

Transistor Used in an Oscillator Circuit

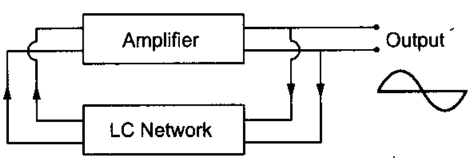


Figure 45.24

The function of an oscillator circuit is to produce an alternating voltage of desired frequency when only DC batteries are available. Figure (45.24) shows a schematic representation of an oscillator circuit. The basic parts in this circuit are (a) an amplifier and (b) an LC network.

The amplifier section is just a transistor used in common-emitter mode. The LC network consists of an inductor and a capacitance. This network resonates at a frequency

$$\nu_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}\,.$$

Batteries are used to bias the transistor and no external input signal is fed to the amplifying section. A part of the output signal is fed back to the input section after going through the LC network. This signal is amplified by the transistor and a part is again fed back to its input section. Thus, it is a self-sustaining device. The component with the proper frequency ν_0 gets resonantly amplified and the output acts as a source of alternating voltage of that frequency. The frequency can be varied by varying L or C.

Transistor Characteristics

Let us consider an *n-p-n* transistor in common-emitter configuration as in figure (45.23). We can view this circuit as made of an input section and an output section. The input section contains the base–emitter junction and the voltage source there whereas the output section contains the base–colletcor junction and the voltage source there. The current I_B may then be called the *input current* and the current I_C the *output current*. The voltage applied to the base–emitter junction, i.e., in the input section is V_{BE} and that applied to the base–collector junction, i.e., in the output section, is V_{CE}. When the input current I_B is plotted against the voltage V_{BE} between the base and the emitter, we get the input characteristics. Similarly, when the output current I_C is plotted against the voltage V_{CE}, we get the output characteristics.

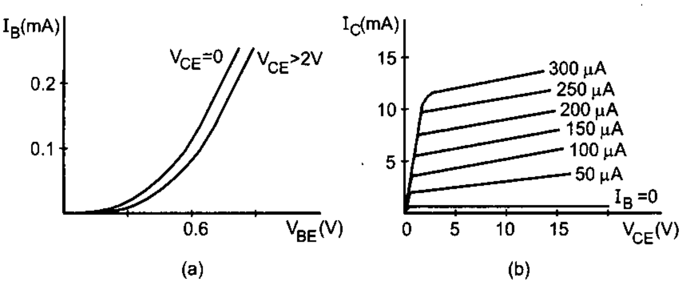


Figure 45.25

These characteristics are shown in figure (45.25). The input characteristics shown in figure (45.25a) are like those of a forward-biased *p-n* junction. If the biasing voltage is small as compared to the height of the potential barrier at the junction, the current I_B is very small. Once the voltage is more than the barrier height, the current rapidly increases. However, since most of the electrons diffused across the junction go to the collector, the net base current is very small (in microamperes) even at large values of V_{BE}.

The output characteristics are shown in figure (45.25b). For small values of the collector voltage, the collector–base junction is reverse–biased because the base is at a more positive potential. The current I_C is then small. As the electrons are forced from the emitter side, the current I_C is still quite large as compared to a single reverse-biased *p-n* junction. As the voltage V_C is increased, the current rapidly increases and becomes roughly constant once the junction is forward-biased. For higher base currents, the collector current is also high and increases more rapidly, even in forward bias.

45.10 LOGIC GATES

Logical Variables and Logical Operations

There are a number of questions which have only two answers, either YES or NO. There are a number of objects which can remain in either of two states only. An electric bulb can either be ON or OFF. A diode can either be conducting or nonconducting. A person can either be alive or dead. A statement may either be true or false. It is interesting to imagine a world in which each variable is allowed to take only two values. These values may be represented by two symbols, 0 and 1. The living state of a person is 0 if he/she is dead and is 1 if he/she is alive. The electric state of a diode is 0 if it is nonconducting and is 1 if it is conducting. Such a world may be very small because in the real world we do have quantities which assume more than two values. But let us concentrate on this small world where everything can either be answered in YES or in NO and so only two symbols 0 and 1 are needed to represent any variable.

Here is an example. A bulb, two switches and a power source are connected as shown in figure (45.26). We have three variables,

A = state of switch S_1
B = state of switch S_2
C = state of the bulb.

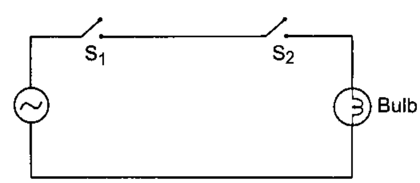


Figure 45.26

Let us assume that the variable A is 0 if the switch S_1 is open and is 1 if the switch S_1 is closed. Similar is the case for B. The variable C is 0 if the bulb is off and is 1 if it is on. Will the bulb be off or on will depend on the states of S_1 and S_2. Table (45.3) shows the dependence.

Table 45.3

Switch S_1	Switch S_2	Bulb	A	B	C
open	open	off	0	0	0
open	closed	off	0	1	0
closed	open	off	1	0	0
closed	closed	on	1	1	1

Thus, C is a *function* of A and B. If we give the value of C for all possible combinations of A and B, the function is completely specified. Thus, a function may be specified by writing a table in which the value of the function is given for all possible combinations of the values of the independent variables. Such a table is known as the *truth table* for that function.

The particular function defined by table (45.3) is written as A AND B. We say that A and B are ANDed to get C. It is also denoted by the symbol of dot. Thus $C = A \cdot B$ is the same as $C = A$ AND B. Quite often, the dot is omitted and we write just AB to mean A AND B. The function $C = A$ AND B is 1 if each of A and B is 1. If any of A and B is zero or both are zero, C is 0.

Let us take another example of a function of two variables. Figure (45.27) shows another circuit containing a power source, two switches S_1, S_2 and a bulb. Table (45.4) gives the state of the bulb for all possible combinations of the switches and the truth table for such a function.

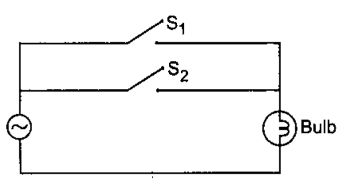


Figure 45.27

Table 45.4

Switch S_1	Switch S_2	Bulb	A	B	C
open	open	off	0	0	0
open	closed	on	0	1	1
closed	open	on	1	0	1
closed	closed	on	1	1	1

The function of A and B defined by the truth table given in table (45.4) is written as A OR B. We say that A and B are ORed to get C. It is also represented by the symbol of plus. Thus $C = A + B$ is the same as $C = A$ OR B. The function $A + B$ is 0 if each of A and B is 0. If one of the two is 1 or both of them are 1, the function is 1.

Let us now take an example of a function of a single variable. A bulb is short-circuited by a switch (figure 45.28). If the switch is open, the current goes through the bulb and it is on. If the switch is closed, the current goes through the switch and the bulb is off (we assume ideally zero resistance in the switch). Let A be the variable showing the state of the switch and B be the variable showing the state of the bulb. Then B is a function of A. Table (45.5) describes the function and its truth table.

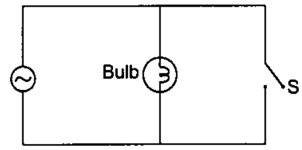


Figure 45.28

Table 45.5

Switch	Bulb	A	B
open	on	0	1
closed	off	1	0

The function of A described by this truth table is written as NOT A. The function NOT A is also written as $\overline{A}$. Thus, $B =$ NOT A is the same as $B = \overline{A}$.

A variable which can assume only two values is called a *logical variable*. A function of logical variables is called a *logical function*. AND, OR and NOT represent three basic operations on logical variables. The first two are operations between two logical variables. The third one is an operation on a single variable. A number of functions may be generated by using these operations.

Example 45.4

Write the truth table for the logical function $Z = (X$ AND $Y)$ OR X.

Solution : Z is a function of two variables X and Y. The truth table is constructed in table (45.6). The third column gives the value of $W = X$ AND Y. It is 1 when $X = Y = 1$ and is 0 otherwise. The fourth column of this table gives the value of $Z = W$ OR X.

Table 45.6

X	Y	W $= X$ AND Y	Z $= W$ OR X	X	Y	Z
0	0	0	0	0	0	0
0	1	0	0	0	1	0
1	0	0	1	1	0	1
1	1	1	1	1	1	1

In the first two rows, $W = 0$ and $X = 0$. Thus W OR $X = 0$. In the third row, $W = 0$ and $X = 1$. Thus W OR $X = 1$. In the fourth row, $W = X = 1$. Thus W OR $X = 1$. The last three columns of the table collect the values of X, Y and Z which is the required truth table.

This function may also be written as

$$Z = (X \cdot Y) + X = XY + X.$$

Logic Gates

A logic gate is an electronic circuit which evaluates a particular logical function. The circuit has one or more *input* terminals and an *output* terminal. A potential of zero (equal to the earth's potential in general) denotes the logical value 0 and a fixed positive potential V (say, + 5 V) denotes the logical value 1. Each input terminal denotes an independent variable. If zero potential is applied to an input terminal, the corresponding independent variable takes the value 0. If the positive potential V is applied to the terminal, the corresponding variable takes the value 1. The potential appearing at the output terminal denotes the value of the function. If the potential is zero, the value of the function is 0. If it is V, the value of the function is 1.

A gate may have more than one output terminals. Each output terminal then represents a separate function and the same circuit may be used to evaluate more than one functions.

Figure (45.29) shows the symbols for the logic gates to evaluate the functions AND, OR and NOT. They are known as AND gate, OR gate and NOT gate respectively. The terminals shown on the left are the input terminals and the terminal on the right is the output terminal in each case.

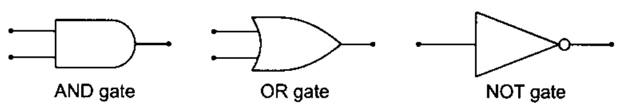


Figure 45.29

Realisation of AND and OR gates with diodes

An AND gate and an OR gate may be constructed with two *p-n* junction diodes. Figure (45.30) shows the construction for an AND gate. The circuit evaluates the function $X = A$ AND B, i.e., $X = AB$. A potential of 5 V at A denotes the logical value $A = 1$ and a potential of zero at A denotes $A = 0$, similarly for B and X.

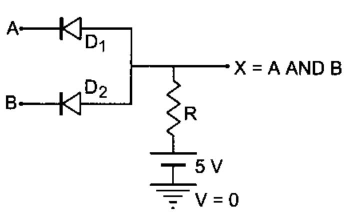


Figure 45.30

Suppose $A = 0$ and $B = 0$. The potentials at A and B are both zero so that both the diodes are forward-biased and offer no resistance. The potential at X is equal to the potential at A or B. Thus, $X = 0$. Now suppose, $A = 0$ and $B = 1$. The potential is zero at A and 5 V at B so that the diode D_1 is forward-biased. The potential at X is equal to the potential at A which is zero. Thus, if $A = 0$ and $B = 1$ then $X = 0$. Similarly, when $A = 1$ and $B = 0$ then $X = 0$. Finally, suppose $A = B = 1$. The potentials at both A and B are 5 V so that neither of the diodes is conducting. This is because if either of the diodes conducts, a current will go through the resistance R and the potential at X will become less than 5 V making the diode reverse-biased. As the diodes are not conducting, there will be no current through R and the potential at X will be equal to 5 V, i.e., $X = 1$.

Thus, the output is $X = 1$ if both the inputs A and B are 1. If any of the inputs is 0, the output is $X = 0$. Hence $X = AB$ and the circuit evaluates the AND function.

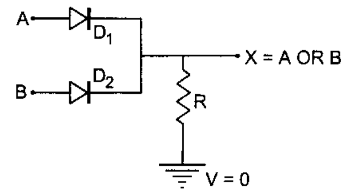


Figure 45.31

Figure (45.31) shows the construction of an OR gate using two diodes. The circuit evaluates X OR A, i.e., $X = A + B$. If $A = B = 0$, there is no potential difference anywhere in the circuit so that $X = 0$. If $A =$ 1 and $B = 0$, the potential is 5 V at A and zero at B. The diode D_1 is forward-biased and offers no resistance. Thus, the potential at X is equal to the potential at A, i.e., 5 V. Thus $X = 1$. Similarly, if $A = 0$ and $B = 1$, $X = 1$. Also, if both A and B are 1, both the diodes are forward-biased and the potential at X is the same as the common potential at A and B which is 5 V. This also gives $X = 1$. Hence the circuit evaluates $X = A$ OR $B = A + B$.

Realisation of NOT gate with a transistor

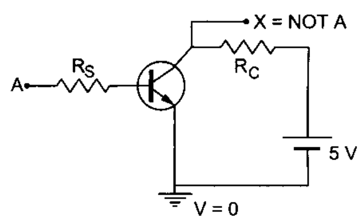


Figure 45.32

A NOT gate cannot be constructed with diodes. Figure (45.32) shows a circuit using an *n-p-n* transistor to evaluate the NOT function.

If $A = 0$, the emitter–base junction is unbiased and there is no current through it. Correspondingly, there is no current through the resistance R_C. The potential at X is equal to the potential at the positive terminal of the battery which is 5 V. Thus, if $A = 0$, $X = 1$. Note that the collector–base junction is also reverse-biased which is consistent with the fact that there is no current in the circuit.

On the other hand if the potential at A is 5 V, the base–emitter junction is forward-biased and there is a large current in the circuit. The direction of the current in the resistance R_C is from right to left in figure (45.33). The potential drops across R and its value at X becomes zero. Thus, if $A = 1, X = 0$.

NAND and NOR gates

The function $X = \text{NOT } (A \text{ AND } B)$ of two logical variables A and B is called NAND function. It is written as $X = A$ NAND B. It is also written as $X = \overline{A \cdot B}$ or simply $X = \overline{AB}$.

Tables (45.7) shows the evaluation of $\overline{AB}$ and its truth table. A NAND gate can be made by an AND gate followed by a NOT gate. Figure (45.33) shows the combination and the symbol used for a NAND gate.

Table 45.7

A	B	AB $= A$ AND B	$\overline{AB} =$ NOT(A AND B)	A	B	$\overline{AB}$
0	0	0	1	0	0	1
0	1	0	1	0	1	1
1	0	0	1	1	0	1
1	1	1	0	1	1	0

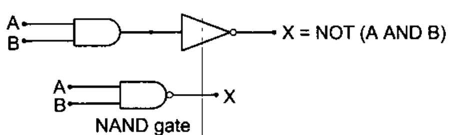


Figure 45.33

The function $X = \text{NOT } (A \text{ OR } B)$ is called a NOR function and is written as $X = A$ NOR B. It is also written as $X = \overline{A + B}$.

Table (45.8) shows the evaluation of $\overline{A + B}$ and its truth table. A NOR gate can be made by an OR gate followed by a NOT gate. Figure (45.34) shows the combination and the symbol used for a NOR gate.

Table 45.8

A	B	$A+B$	$\overline{A+B}$	A	B	$\overline{A+B}$
0	0	0	1	0	0	1
0	1	1	0	0	1	0
1	0	1	0	1	0	0
1	1	1	0	1	1	0

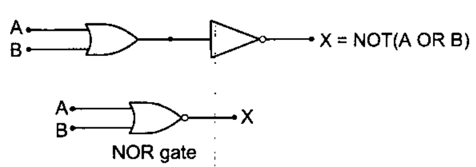


Figure 45.34

XOR gate

XOR is a function of two logical variables A and B which evaluates to 1 if one of the two variables is 0 and the other is 1. If both of the variables are 0 or both are 1, the function is zero. It is also called the *exclusive* OR function. The truth table for XOR function is given in table (45.9). Verify that

$$A \text{ XOR } B = A\overline{B} + \overline{A}B. \qquad \dots \text{(i)}$$

Table 45.9

A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

An XOR gate can be constructed with AND, OR and NOT gates as shown in figure (45.35a). The symbol for an XOR gate is shown in figure (45.35b). We have made use of equation (i) in constructing this circuit.

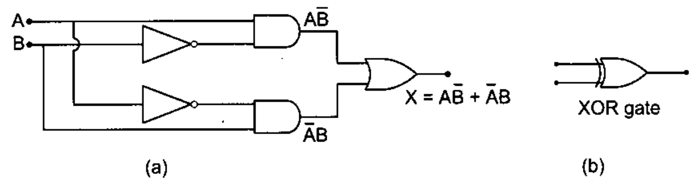


Figure 45.35

NAND and NOR as the basic building blocks

Any logical gate can be constructed by using only NAND gates or only NOR gates. In this sense, a NAND gate or a NOR gate is called a basic building block of logic circuits.

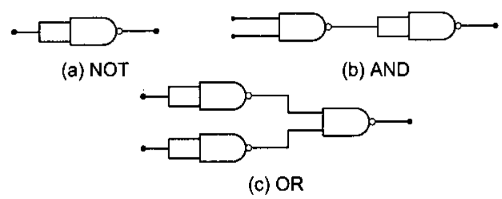


Figure 45.36

Figure (45.36) shows the construction of NOT, AND and OR gates using NAND gates. A NAND gate can be used as a NOT gate by simply connecting the two input terminals (figure 45.36a). In other words, the value of the independent variable A is fed to both the input terminals. As A AND A is A,

$$X = \overline{AA} = \overline{A}.$$

To construct an AND gate, the output of a NAND gate should be fed to a NOT gate. This is because, the output of the NAND gate is $\overline{AB}$, i.e., NOT of AB. If we pass it through a NOT gate, it is again inverted and becomes AB. Figure (45.36b) does exactly the same.

Figure (45.36c) shows the construction of an OR gate. The two input variables are first inverted by passing them through two NOT gates. The inverted signals are NANDed. Let us construct the truth table of this combination and verify that it represents an OR gate. This is done in table (45.10).

Table 45.10

A	B	$\bar{A}$	$\bar{B}$	$\bar{A}\bar{B}$	$\overline{\bar{A}\bar{B}}$
0	0	1	1	1	0
0	1	1	0	0	1
1	0	0	1	0	1
1	1	0	0	0	1

Thus, $\overline{\bar{A}\bar{B}}$ is 1 if either of A and B is 1 or both are 1. It is zero only if both A and B are zero. Thus, $\overline{\bar{A}\bar{B}} = A + B$.

Binary Mathematics : Half Adder and Full Adder

Logic gates are the basic elements in the electronic circuits used to perform mathematical calculations such as that in a computer or in a calculator. The numbers are converted into *binary system* where only two digits 0 and 1 are used. In this system, the natural numbers (1, 2, 3, 4, ... in the decimal system) are represented as 1, 10, 11, 100, 101, 110, 111, ..., etc. The mathematical operation of addition is governed by the following basic rules:

$$0 + 0 = 0$$

$$0 + 1 = 1$$

$$1 + 0 = 1$$

$$1 + 1 = 10.$$

The plus sign here represents addition of arithmetic and not the logical operation OR. When 1 is added to 1 in binary system, we get a two digit number 10. It is read as *one zero* and not as ten. It is equivalent to 'two' in decimal system. When two one-digit numbers are added and the result is a two digit number, the more significant digit (that on left) is called the *carry digit* and the less significant digit (that on right) is called the *sum digit*. The word *sum* is often used for the sum digit and *carry* for the carry digit. One should be careful about the word 'sum' because it is also used to mean the net result of addition. Table (45.11) shows the carry digit and the sum digit for the addition of one-digit binary numbers. If we treat A, B, C and S as logical variables (they can take only two values 0 and 1), each of C and S is a logical function of A and B.

Table 45.11

First number A	Second number B	Carry digit C	Sum digit S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

It can be easily verified that the carry digit C is A AND B and the sum digit S is A XOR B, i.e.,

$$C = AB$$

and $$S = A\bar{B} + \bar{A}B.$$

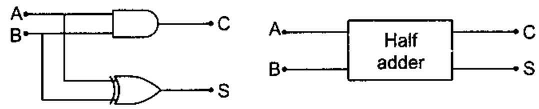


Figure 45.37

Figure (45.37) shows the circuit which takes A and B as inputs and gives C and S as outputs. Note that A and B are passed through an XOR gate to get S. The circuit described above is called a *half adder*. The symbol for a half adder is also shown in the figure.

If two numbers of more than one digit are to be added, one needs to know the addition rules for three one-digit numbers. Here are two examples, one with decimal numbers and one with binary numbers.

$$\begin{array}{r} \underline{11} \\ 768 \\ +\ 353 \\ \hline 1121 \end{array} \qquad \begin{array}{r} \underline{111} \\ 101 \\ +\ 111 \\ \hline 1100 \end{array}$$

In the first example, one has to evaluate 1 + 6 + 5 to get the sum digit as 2 and the carry digit as 1 for the second place from right. Similarly, one needs 1 + 7 + 3. In the second example, one needs the sum 1 + 0 + 1 to get the sum digit as 0 and the carry digit as 1 for the second place from right. Similarly, one needs 1 + 1 + 1 to get the sum digit as 1 and the carry digit as 1. Thus, we need a circuit which can take three inputs A_1, A_2 and A_3 and produce two outputs C and S. There are eight possible combinations of A_1, A_2 and A_3 and table (45.12) gives the values of C and S for all these combinations.

Table 45.12

A_1	A_2	A_3	C	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

One can add the digits A_1, A_2 and A_3 as follows. First add A_1 and A_2 to get the sum digit S_1 and the carry digit C_1. Now add A_3 and S_1 to get the sum digit S and the carry digit C_2. The sum digit S is the final sum digit. Now consider the two carry digits C_1 and C_2. Verify that both of C_1 and C_2 cannot be 1. If both are 0, the final carry digit is 0. If one of them is 1 and the other is 0, the final carry digit is 1. Thus, the final carry digit may be obtained as $C = C_1$ OR C_2. The circuit shown in figure (45.38) is constructed on these lines to perform the three-digit addition. Such a circuit is called a *full adder*. The symbol of full adder is also shown in figure (45.38).

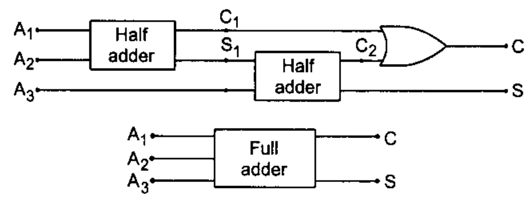


Figure 45.38

Worked Out Examples

1. *A doped semiconductor has impurity levels* 30 meV *below the conduction band. (a) Is the material n-type or p-type ? (b) In a thermal collision, an amount kT of energy is given to the extra electron loosely bound to the impurity ion and this electron is just able to jump into the conduction band. Calculate the temperature T.*

Solution : (a) The impurity provides impurity levels close to the conduction band and a number of electrons from the impurity level will populate the conduction band. Thus, the majority carriers are electrons and the material is n-type.

(b) According to the question, $kT = 30$ meV

or, $$T = \frac{30 \text{ meV}}{k}$$

$$= \frac{0{\cdot}03 \text{ eV}}{8{\cdot}62 \times 10^{-5} \text{ eV K}^{-1}} = 348 \text{ K}.$$

2. *The energy of a photon of sodium light* ($\lambda = 589$ nm) *equals the band gap of a semiconducting material. (a) Find the minimum energy E required to create a hole–electron pair. (b) Find the value of E/kT at a temperature of* 300 K.

Solution : (a) The energy of the photon is $E = \frac{hc}{\lambda}$

$$= \frac{1242 \text{ eV nm}}{589 \text{ nm}} = 2{\cdot}1 \text{ eV}.$$

Thus the band gap is 2·1 eV. This is also the minimum energy E required to push an electron from the valence band into the conduction band. Hence, the minimum energy required to create a hole–electron pair is 2·1 eV.

(b) At $T = 300$ K,

$$kT = (8{\cdot}62 \times 10^{-5} \text{ eV K}^{-1})(300 \text{ K})$$

$$= 25{\cdot}86 \times 10^{-3} \text{ eV}.$$

Thus, $$\frac{E}{kT} = \frac{2{\cdot}1 \text{ eV}}{25{\cdot}86 \times 10^{-3} \text{ eV}} = 81.$$

So it is difficult for the thermal energy to create the hole–electron pair but a photon of light can do it easily.

3. *A p-type semiconductor has acceptor levels* 57 meV *above the valence band. Find the maximum wavelength of light which can create a hole.*

Solution : To create a hole, an electron from the valence band should be given sufficient energy to go into one of the acceptor levels. Since the acceptor levels are 57 meV above the valence band, at least 57 meV is needed to create a hole.

If λ be the wavelength of light, its photon will have an energy hc/λ. To create a hole,

$$\frac{hc}{\lambda} \geq 57 \text{ meV}$$

or, $$\lambda \leq \frac{hc}{57 \text{ meV}}$$

$$= \frac{1242 \text{ eV nm}}{57 \times 10^{-3} \text{ eV}} = 2{\cdot}18 \times 10^{-5} \text{ m}.$$

4. *The band gap in germanium is* $\Delta E = 0{\cdot}68$ eV. *Assuming that the number of hole–electron pairs is proportional to* $e^{-\Delta E/2kT}$, *find the percentage increase in the number of charge carriers in pure germanium as the temperature is increased from* 300 K *to* 320 K.

Solution : The number of charge carriers in an intrinsic semiconductor is double the number of hole–electron pairs. If N_1 be the number of charge carriers at temperature T_1 and N_2 at T_2, we have

$$N_1 = N_0\, e^{-\Delta E/2kT_1}$$

and $$N_2 = N_0\, e^{-\Delta E/2kT_2}.$$

The percentage increase as the temperature is raised from T_1 to T_2 is

$$f = \frac{N_2 - N_1}{N_1} \times 100 = \left(\frac{N_2}{N_1} - 1\right) \times 100$$

$$= 100\left[e^{\frac{\Delta E}{2k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} - 1\right].$$

Now $$\frac{\Delta E}{2k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

$$= \frac{0{\cdot}68 \text{ eV}}{2 \times 8{\cdot}62 \times 10^{-5} \text{ eV K}^{-1}}\left(\frac{1}{300 \text{ K}} - \frac{1}{320 \text{ K}}\right)$$

$$= 0{\cdot}82.$$

Thus, $$f = 100 \times [e^{0{\cdot}82} - 1] \approx 127.$$

Thus, the number of charge carriers increases by about 127%.

5. *The concentration of hole–electron pairs in pure silicon at* $T = 300\ \mathrm{K}$ *is* 7×10^{15} *per cubic metre. Antimony is doped into silicon in a proportion of* 1 *atom in* 10^{7} *atoms. Assuming that half of the impurity atoms contribute electrons in the conduction band, calculate the factor by which the number of charge carriers increases due to doping. The number of silicon atoms per cubic metre is* 5×10^{28}.

Solution : The number of charge carriers before doping is equal to the number of holes plus the number of conduction electrons. Thus, the number of charge carriers per cubic metre before doping

$$= 2 \times 7 \times 10^{15} = 14 \times 10^{15}.$$

Since antimony is doped in a proportion of 1 in 10^{7}, the number of antimony atoms per cubic metre is $10^{-7} \times 5 \times 10^{28} = 5 \times 10^{21}$. As half of these atoms contribute electrons to the conduction band, the number of extra conduction electrons produced is $2{\cdot}5 \times 10^{21}$ per cubic metre. Thus, the number of charge carriers per cubic metre after the doping is

$$2{\cdot}5 \times 10^{21} + 14 \times 10^{15}$$
$$\approx 2{\cdot}5 \times 10^{21}.$$

The factor by which the number of charge carriers is increased

$$= \frac{2{\cdot}5 \times 10^{21}}{14 \times 10^{15}} = 1{\cdot}8 \times 10^{5}.$$

In fact, as the n-type impurity is doped, the number of holes will decrease. This is because the product of the concentrations of holes and conduction electrons remains almost the same. However, this does not affect our result as the number of holes is anyway too small as compared to the number of conduction electrons.

6. *A potential barrier of* $0{\cdot}50\ \mathrm{V}$ *exists across a p-n junction. (a) If the depletion region is* $5{\cdot}0 \times 10^{-7}\ \mathrm{m}$ *wide, what is the intensity of the electric field in this region? (b) An electron with speed* $5{\cdot}0 \times 10^{5}\ \mathrm{m\ s^{-1}}$ *approaches the p-n junction from the n-side. With what speed will it enter the p-side?*

Solution : (a) The electric field is $E = V/d$

$$= \frac{0{\cdot}50\ \mathrm{V}}{5{\cdot}0 \times 10^{-7}\ \mathrm{m}} = 1{\cdot}0 \times 10^{6}\ \mathrm{V\ m^{-1}}.$$

(b)

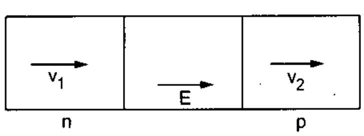


Figure 45-W1

Suppose the electron has a speed v_1 when it enters the depletion layer and v_2 when it comes out of it (figure 45-W1). As the potential energy increases by $e \times 0{\cdot}50\ \mathrm{V}$, from the principle of conservation of energy,

$$\frac{1}{2} m v_1^2 = e \times 0{\cdot}50\ \mathrm{V} + \frac{1}{2} m v_2^2$$

or, $$\frac{1}{2} \times (9{\cdot}1 \times 10^{-31}\ \mathrm{kg}) \times (5{\cdot}0 \times 10^{5}\ \mathrm{m\ s^{-2}})^{2}$$
$$= 1{\cdot}6 \times 10^{-19} \times 0{\cdot}5\ \mathrm{J} + \frac{1}{2}(9{\cdot}1 \times 10^{-31}\ \mathrm{kg})\, v_2^2$$

or, $$1{\cdot}13 \times 10^{-19}\ \mathrm{J} = 0{\cdot}8 \times 10^{-19}\ \mathrm{J} + (4{\cdot}55 \times 10^{-31}\ \mathrm{kg})\, v_2^2.$$

Solving this, $v_2 = 2{\cdot}7 \times 10^{5}\ \mathrm{m\ s^{-1}}$.

7. *The reverse-biased current of a particular p-n junction diode increases when it is exposed to light of wavelength less than or equal to* 600 nm. *Assume that the increase in carrier concentration takes place due to the creation of new hole–electron pairs by the light. Find the band gap.*

Solution : The reverse-biased current is caused mainly due to the drift current. The drift current in a p-n junction is caused by the formation of new hole–electron pairs and their subsequent motions in the depletion layer. When the junction is exposed to light, it may absorb energy from the light photons. If this energy supplied by a photon is greater than (or equal to) the band gap, a hole–electron pair may be formed. Thus, the reverse-biased current will increase if the light photons have energy greater than (or equal to) the band gap. Hence the band gap is equal to the energy of a photon of 600 nm light which is

$$\frac{hc}{\lambda} = \frac{1242\ \mathrm{eV\ nm}}{600\ \mathrm{nm}} = 2{\cdot}07\ \mathrm{eV}.$$

8. *A* 2 V *battery may be connected across the points A and B as shown in figure (45-W2). Assume that the resistance of each diode is zero in forward bias and infinity in reverse bias. Find the current supplied by the battery if the positive terminal of the battery is connected to (a) the point A (b) the point B.*

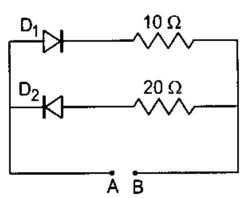


Figure 45-W2

Solution : (a) When the positive terminal of the battery is connected to the point A, the diode D_1 is forward-biased and D_2 is reverse-biased. The resistance of the diode D_1 is zero, and it can be replaced by a resistanceless wire. Similarly, the resistance of the diode D_2 is infinity, and it can be replaced by a broken wire. The equivalent circuit is shown in figure (45-W3a). The current supplied by the battery is $2\ \mathrm{V}/10\ \Omega = 0{\cdot}2\ \mathrm{A}$.

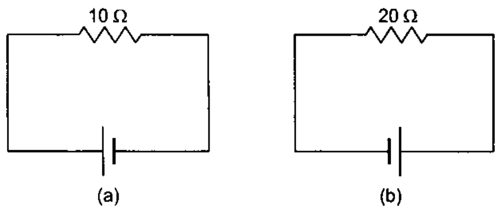


Figure 45-W3

(b) When the positive terminal of the battery is connected to the point B, the diode D_2 is forward-biased and D_1 is reverse biased. The equivalent circuit is shown in figure (45-W3b). The current through the battery is $2\ V/20\ \Omega = 0{\cdot}1\ A$.

9. *A change of* 8·0 mA *in the emitter current brings a change of* 7·9 mA *in the collector current. How much change in the base current is required to have the same change* 7·9 mA *in the collector current? Find the values of* α *and* β.

Solution : We have,

$$I_E = I_B + I_C$$

or, $$\Delta I_E = \Delta I_B + \Delta I_C.$$

From the question, when $\Delta I_E = 8{\cdot}0\ mA$, $\Delta I_C = 7{\cdot}9\ mA$.

Thus,

$$\Delta I_B = 8{\cdot}0\ mA - 7{\cdot}9\ mA = 0{\cdot}1\ mA.$$

So a change of 0·1 mA in the base current is required to have a change of 7·9 mA in the collector current.

$$\alpha = \frac{I_C}{I_E} = \frac{\Delta I_C}{\Delta I_E}$$

$$= \frac{7{\cdot}9\ mA}{8{\cdot}0\ mA} \approx 0{\cdot}99.$$

$$\beta = \frac{I_C}{I_B} = \frac{\Delta I_C}{\Delta I_B}$$

$$= \frac{7{\cdot}9\ mA}{0{\cdot}1\ mA} = 79.$$

Check if these values of α and β satisfy the equation

$$\beta = \frac{\alpha}{1-\alpha}.$$

10. *A transistor is used in common-emitter mode in an amplifier circuit. When a signal of* 20 mV *is added to the base–emitter voltage, the base current changes by* 20 μA *and the collector current changes by* 2 mA. *The load resistance is* 5 kΩ. *Calculate (a) the factor* β, *(b) the input resistance* R_{BE}, *(c) the transconductance and (d) the voltage gain.*

Solution : (a) $\beta = \dfrac{\Delta I_C}{\Delta I_B} = \dfrac{2\ mA}{20\ \mu A} = 100.$

(b) The input resistance $R_{BE} = \dfrac{\Delta V_{BE}}{\Delta I_B}$

$$= \frac{20\ mV}{20\ \mu A} = 1\ k\Omega.$$

(c) Transconductance $= \dfrac{\Delta I_C}{\Delta V_{BE}}$

$$= \frac{2\ mA}{20\ mV} = 0{\cdot}1\ \text{mho}.$$

(d) The change in output voltage is $R_L \Delta I_c$

$$= (5\ k\Omega)\,(2\ mA) = 10\ V.$$

The applied signal voltage = 20 mV.

Thus, the voltage gain is,

$$\frac{10\ V}{20\ mV} = 500.$$

11. *Construct the truth table for the function* X *of* A *and* B *represented by figure (45-W4).*

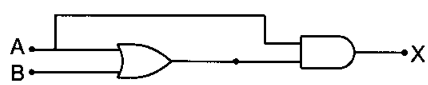


Figure 45-W4

Solution : Here an AND gate and an OR gate are used. Let the output of the OR gate be Y. Clearly, $Y = A + B$. The AND gate receives A and $A + B$ as input. The output of this gate is X. So $X = A(A + B)$. The following table evaluates X for all combinations of A and B. The last three columns give the truth table.

A	B	$Y = A + B$	$X = A(A+B)$	A	B	X
0	0	0	0	0	0	0
0	1	1	0	0	1	0
1	0	1	1	1	0	1
1	1	1	1	1	1	1

□

QUESTIONS FOR SHORT ANSWER

1. How many 1s energy states are present in one mole of sodium vapour ? Are they all filled in normal conditions ? How many 3s energy states are present in one mole of sodium vapour ? Are they all filled in normal conditions ?
2. There are energy bands in a solid. Do we have really continuous energy variation in a band or do we have very closely spaced but still discrete energy levels ?
3. The conduction band of a solid is partially filled at 0 K. Will it be a conductor, a semiconductor or an insulator ?
4. In semiconductors, thermal collisions are responsible for taking a valence electron to the conduction band. Why does the number of conduction electrons not go on increasing with time as thermal collisions continuously take place ?

5. When an electron goes from the valence band to the conduction band in silicon, its energy is increased by 1·1 eV. The average energy exchanged in a thermal collision is of the order of kT which is only 0·026 eV at room temperature. How is a thermal collision able to take some of the electrons from the valence band to the conduction band ?
6. What is the resistance of an intrinsic semiconductor at 0 K?
7. We have valence electrons and conduction electrons in a semiconductor. Do we also have 'valence holes' and 'conduction holes' ?
8. When a p-type impurity is doped in a semiconductor, a large number of holes are created. This does not make the semiconductor charged. But when holes diffuse from the p-side to the n-side in a p-n junction, the n-side gets positively charged. Explain.
9. The drift current in a reverse-biased p-n junction increases in magnitude if the temperature of the junction is increased. Explain this on the basis of creation of hole–electron pairs.
10. An ideal diode should pass a current freely in one direction and should stop it completely in the opposite direction. Which is closer to ideal—vacuum diode or a p-n junction diode ?
11. Consider an amplifier circuit using a transistor. The output power is several times greater than the input power. Where does the extra power come from ?

OBJECTIVE I

1. Electric conduction in a semiconductor takes place due to
   (a) electrons only (b) holes only
   (c) both electrons and holes
   (d) neither electrons nor holes.
2. An electric field is applied to a semiconductor. Let the number of charge carriers be n and the average drift speed be v. If the temperature is increased,
   (a) both n and v will increase
   (b) n will increase but v will decrease
   (c) v will increase but n will decrease
   (d) both n and v will decrease.
3. Let n_p and n_e be the numbers of holes and conduction electrons in an intrinsic semiconductor.
   (a) $n_p > n_e$ (b) $n_p = n_e$ (c) $n_p < n_e$ (d) $n_p \neq n_e$
4. Let n_p and n_e be the numbers of holes and conduction electrons in an extrinsic semiconductor.
   (a) $n_p > n_e$ (b) $n_p = n_e$ (c) $n_p < n_e$ (d) $n_p \neq n_e$
5. A p-type semiconductor is
   (a) positively charged (b) negatively charged
   (c) uncharged
   (d) uncharged at 0 K but charged at higher temperatures.
6. When an impurity is doped into an intrinsic semiconductor, the conductivity of the semiconductor
   (a) increases (b) decreases
   (c) remains the same (d) becomes zero.
7. If the two ends of a p-n junction are joined by a wire,
   (a) there will not be a steady current in the circuit
   (b) there will be a steady current from the n-side to the p-side
   (c) there will a steady current from the p-side to the n-side
   (d) there may or may not be a current depending upon the resistance of the connecting wire.
8. The drift current in a p-n junction is
   (a) from the n-side to the p-side
   (b) from the p-side to the n-side
   (c) from the n-side to the p-side if the junction is forward-biased and in the opposite direction if it is reverse-biased
   (d) from the p-side to the n-side if the junction is forward-biased and in the opposite direction if it is reverse-biased.
9. The diffusion current in a p-n junction is
   (a) from the n-side to the p-side
   (b) from the p-side to the n-side
   (c) from the n-side to the p-side if the junction is forward-biased and in the opposite direction if it is reverse-biased
   (d) from the p-side to the n-side if the junction is forward-biased and in the opposite direction if it is reverse-biased.
10. Diffusion current in a p-n junction is greater than the drift current in magnitude
    (a) if the junction is forward-biased
    (b) if the junction is reverse-biased
    (c) if the junction is unbiased
    (d) in no case.
11. Two identical p-n junctions may be connected in series with a battery in three ways (figure 45-Q1). The potential difference across the two p-n junctions are equal in
    (a) circuit 1 and circuit 2 (b) circuit 2 and circuit 3
    (c) circuit 3 and circuit 1 (d) circuit 1 only.

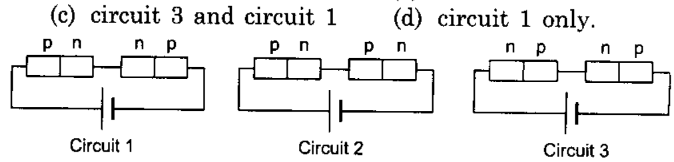


Figure 45-Q1

12. Two identical capacitors A and B are charged to the same potential V and are connected in two circuits at $t = 0$ as shown in figure (45-Q2). The charges on the

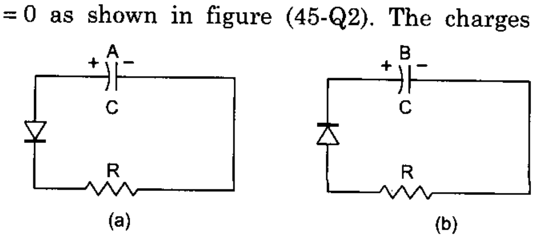


Figure 45-Q2

capacitors at a time $t = CR$ are, respectively,
(a) VC, VC (b) VC/e, VC (c) VC, VC/e (d) VC/e, VC/e.

13. A hole diffuses from the p-side to the n-side in a p-n junction. This means that
(a) a bond is broken on the n-side and the electron freed from the bond jumps to the conduction band
(b) a conduction electron on the p-side jumps to a broken bond to complete it
(c) a bond is broken on the n-side and the electron freed from the bond jumps to a broken bond on the p-side to complete it
(d) a bond is broken on the p-side and the electron freed from the bond jumps to a broken bond on the n-side to complete it.

14. In a transistor,
(a) the emitter has the least concentration of impurity
(b) the collector has the least concentration of impurity
(c) the base has the least concentration of impurity
(d) all the three regions have equal concentrations of impurity.

15. An incomplete sentence about transistors is given below: The emitter–...... junction is ___ and the collector– ...... junction is ___. The appropriate words for the dotted empty positions are, respectively,
(a) 'collector' and 'base' (b) 'base' and 'emitter'
(c) 'collector' and 'emitter' (d) 'base' and 'base'.

OBJECTIVE II

1. In a semiconductor,
(a) there are no free electrons at 0 K
(b) there are no free electrons at any temperature
(c) the number of free electrons increases with temperature
(d) the number of free electrons is less than that in a conductor.

2. In a p-n junction with open ends,
(a) there is no systematic motion of charge carriers
(b) holes and conduction electrons systematically go from the p-side to the n-side and from the n-side to the p-side respectively
(c) there is no net charge transfer between the two sides
(d) there is a constant electric field near the junction.

3. In a p-n junction,
(a) new holes and conduction electrons are produced continuously throughout the material
(b) new holes and conduction electrons are produced continuously throughout the material except in the depletion region
(c) holes and conduction electrons recombine continuously throughout the material
(d) holes and conduction electrons recombine continuously throughout the material except in the depletion region.

4. The impurity atoms with which pure silicon may be doped to make it a p-type semiconductor are those of
(a) phosphorus (b) boron (c) antimony (d) aluminium.

5. The electrical conductivity of pure germanium can be increased by
(a) increasing the temperature
(b) doping acceptor impurities
(c) doping donor impurities
(d) irradiating ultraviolet light on it.

6. A semiconducting device is connected in a series circuit with a battery and a resistance. A current is found to pass through the circuit. If the polarity of the battery is reversed, the current drops to almost zero. The device may be
(a) an intrinsic semiconductor
(b) a p-type semiconductor
(c) an n-type semiconductor
(d) a p-n junction.

7. A semiconductor is doped with a donor impurity.
(a) The hole concentration increases.
(b) The hole concentration decreases.
(c) The electron concentration increases.
(d) The electron concentration decreases.

8. Let i_E, i_C and i_B represent the emitter current, the collector current and the base current respectively in a transistor. Then
(a) i_C is slightly smaller than i_E
(b) i_C is slightly greater than i_E
(c) i_B is much smaller than i_E
(d) i_B is much greater than i_E.

9. In a normal operation of a transistor,
(a) the base–emitter junction is forward-biased
(b) the base–collector junction is forward-biased
(c) the base–emitter junction is reverse-biased
(d) the base–collector junction is reverse-biased.

10. An AND gate can be prepared by repetitive use of
(a) NOT gate (b) OR gate
(c) NAND gate (d) NOR gate.

EXERCISES

Planck constant = $4{\cdot}14 \times 10^{-15}$ eV s,
Boltzmann constant = $8{\cdot}62 \times 10^{-5}$ eV K^{-1}.

1. Calculate the number of states per cubic metre of sodium in 3s band. The density of sodium is 1013 kgm $^{-3}$. How many of them are empty ?
2. In a pure semiconductor, the number of conduction electrons is 6×10^{19} per cubic metre. How many holes are there in a sample of size 1 cm × 1 cm × 1 mm ?
3. Indium antimonide has a band gap of 0·23 eV between the valence and the conduction band. Find the temperature at which kT equals the band gap.
4. The band gap for silicon is 1·1 eV. (a) Find the ratio of the band gap to kT for silicon at room temperature 300 K. (b) At what temperature does this ratio become one tenth of the value at 300 K ? (Silicon will not retain its structure at these high temperatures.)
5. When a semiconducting material is doped with an impurity, new acceptor levels are created. In a particular thermal collision, a valence electron receives an energy equal to $2kT$ and just reaches one of the acceptor levels. Assuming that the energy of the electron was at the top edge of the valence band and that the temperature T is equal to 300 K, find the energy of the acceptor levels above the valence band.
6. The band gap between the valence and the conduction bands in zinc oxide (ZnO) is 3·2 eV. Suppose an electron in the conduction band combines with a hole in the valence band and the excess energy is released in the form of electromagnetic radiation. Find the maximum wavelength that can be emitted in this process.
7. Suppose the energy liberated in the recombination of a hole–electron pair is converted into electromagnetic radiation. If the maximum wavelength emitted is 820 nm, what is the band gap ?
8. Find the maximum wavelength of electromagnetic radiation which can create a hole–electron pair in germanium. The band gap in germanium is 0·65 eV.
9. In a photodiode, the conductivity increases when the material is exposed to light. It is found that the conductivity changes only if the wavelength is less than 620 nm. What is the band gap ?
10. Let ΔE denote the energy gap between the valence band and the conduction band. The population of conduction electrons (and of the holes) is roughly proportional to $e^{-\Delta E/2kT}$. Find the ratio of the concentration of conduction electrons in diamond to that in silicon at room temperature 300 K. ΔE for silicon is 1·1 eV and for diamond is 6·0 eV. How many conduction electrons are likely to be in one cubic metre of diamond ?
11. The conductivity of a pure semiconductor is roughly proportional to $T^{3/2} e^{-\Delta E/2kT}$ where ΔE is the band gap. The band gap for germanium is 0·74 eV at 4 K and 0·67 eV at 300 K. By what factor does the conductivity of pure germanium increase as the temperature is raised from 4 K to 300 K ?
12. Estimate the proportion of boron impurity which will increase the conductivity of a pure silicon sample by a factor of 100. Assume that each boron atom creates a hole and the concentration of holes in pure silicon at the same temperature is 7×10^{15} holes per cubic metre. Density of silicon is 5×10^{28} atoms per cubic metre.
13. The product of the hole concentration and the conduction electron concentration turns out to be independent of the amount of any impurity doped. The concentration of conduction electrons in germanium is 6×10^{19} per cubic metre. When some phosphorus impurity is doped into a germanium sample, the concentration of conduction electrons increases to 2×10^{23} per cubic metre. Find the concentration of the holes in the doped germanium.
14. The conductivity of an intrinsic semiconductor depends on temperature as $\sigma = \sigma_0 e^{-\Delta E/2kT}$, where σ_0 is a constant. Find the temperature at which the conductivity of an intrinsic germanium semiconductor will be double of its value at $T = 300$ K. Assume that the gap for germanium is 0·650 eV and remains constant as the temperature is increased.
15. A semiconducting material has a band gap of 1 eV. Acceptor impurities are doped into it which create acceptor levels 1 meV above the valence band. Assume that the transition from one energy level to the other is almost forbidden if kT is less than 1/50 of the energy gap. Also, if kT is more than twice the gap, the upper levels have maximum population. The temperature of the semiconductor is increased from 0 K. The concentration of the holes increases with temperature and after a certain temperature it becomes approximately constant. As the temperature is further increased, the hole concentration again starts increasing at a certain temperature. Find the order of the temperature range in which the hole concentration remains approximately constant.
16. In a p-n junction, the depletion region is 400 nm wide and an electric field of 5×10^{5} V m $^{-1}$ exists in it. (a) Find the height of the potential barrier. (b) What should be the minimum kinetic energy of a conduction electron which can diffuse from the n-side to the p-side ?
17. The potential barrier existing across an unbiased p-n junction is 0·2 volt. What minimum kinetic energy a hole should have to diffuse from the p-side to the n-side if (a) the junction is unbiased, (b) the junction is forward-biased at 0·1 volt and (c) the junction is reverse-biased at 0·1 volt ?
18. In a p-n junction, a potential barrier of 250 meV exists across the junction. A hole with a kinetic energy of 300 meV approaches the junction. Find the kinetic energy of the hole when it crosses the junction if the hole approached the junction (a) from the p-side and (b) from the n-side.
19. When a p-n junction is reverse-biased, the current becomes almost constant at 25 μA. When it is forward-biased at 200 mV, a current of 75 μA is obtained. Find the magnitude of diffusion current when the diode is

(a) unbiased, (b) reverse-biased at 200 mV and (c) forward-biased at 200 mV.

20. The drift current in a *p-n* junction is 20·0 μA. Estimate the number of electrons crossing a cross section per second in the depletion region.

21. The current–voltage characteristic of an ideal *p-n* junction diode is given by

$$i = i_0 \left(e^{eV/kT} - 1\right)$$

where the drift current i_0 equals 10 μA. Take the temperature T to be 300 K. (a) Find the voltage V_0 for which $e^{eV/kT} = 100$. One can neglect the term 1 for voltages greater than this value. (b) Find an expression for the dynamic resistance of the diode as a function of V for $V > V_0$. (c) Find the voltage for which the dynamic resistance is 0·2 Ω.

22. Consider a *p-n* junction diode having the characteristic $i = i_0(e^{eV/kT} - 1)$ where $i_0 = 20$ μA. The diode is operated at $T = 300$ K. (a) Find the current through the diode when a voltage of 300 mV is applied across it in forward bias. (b) At what voltage does the current double ?

23. Calculate the current through the circuit and the potential difference across the diode shown in figure (45-E1). The drift current for the diode is 20 μA.

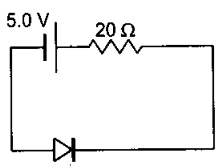


Figure 45-E1

24. Each of the resistances shown in figure (45-E2) has a value of 20 Ω. Find the equivalent resistance between A and B. Does it depend on whether the point A or B is at higher potential ?

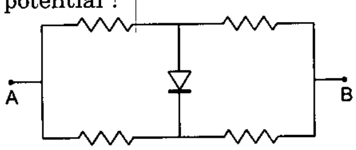


Figure 45-E2

In problems 25 to 30, assume that the resistance of each diode is zero in forward bias and is infinity in reverse bias.

25. Find the currents through the resistances in the circuits shown in figure (45-E3).

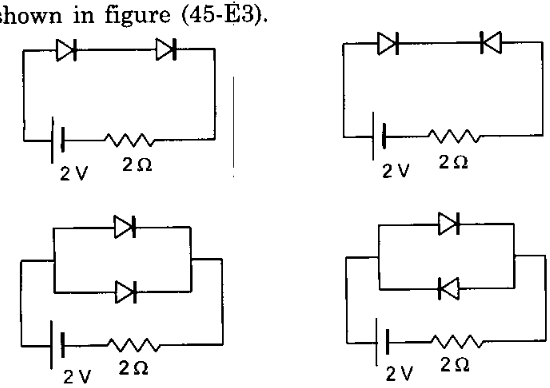


Figure 45-E3

26. What are the readings of the ammeters A_1 and A_2 shown in figure (45-E4). Neglect the resistances of the meters.

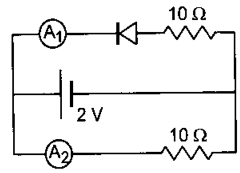


Figure 45-E4

27. Find the current through the battery in each of the circuits shown in figure (45-E5).

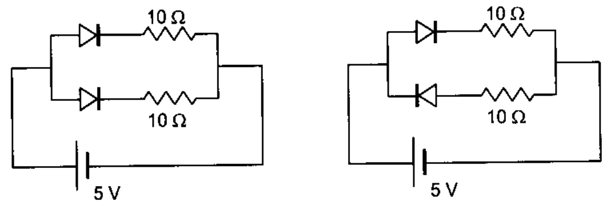


Figure 45-E5

28. Find the current through the resistance R in figure (45-E6) if (a) $R = 12$ Ω (b) $R = 48$ Ω.

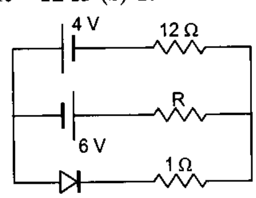


Figure 45-E6

29. Draw the current–voltage characteristics for the device shown in figure (45-E7) between the terminals A and B.

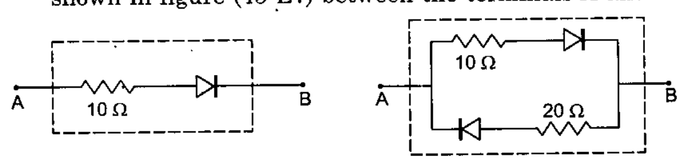


Figure 45-E7

30. Find the equivalent resistance of the network shown in figure (45-E8) between the points A and B.

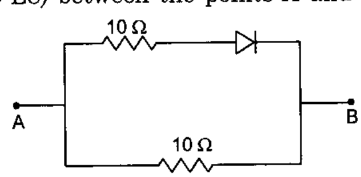


Figure 45-E8

31. When the base current in a transistor is changed from 30 μA to 80 μA, the collector current is changed from 1·0 mA to 3·5 mA. Find the current gain β.

32. A load resistor of 2 kΩ is connected in the collector branch of an amplifier circuit using a transistor in common-emitter mode. The current gain β = 50. The input resistance of the transistor is 0·50 kΩ. If the input current is changed by 50 μA, (a) by what amount does the output voltage change, (b) by what amount does the input voltage change and (c) what is the power gain ?

33. Let $X = A\overline{BC} + B\overline{CA} + C\overline{AB}$. Evaluate X for

(a) $A = 1, B = 0, C = 1$, (b) $A = B = C = 1$, and (c) $A = B = C = 0$.

34. Design a logical circuit using AND, OR and NOT gates to evaluate $A\overline{BC} + B\overline{CA}$.

35. Show that $AB + \overline{AB}$ is always 1.

□

ANSWERS

OBJECTIVE I

1. (c)	2. (b)	3. (b)	4. (d)	5. (c)	6. (a)
7. (a)	8. (a)	9. (b)	10. (a)	11. (b)	12. (b)
13. (c)	14. (c)	15. (d)			

OBJECTIVE II

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

EXERCISES

1. $5{\cdot}3 \times 10^{28}$, $2{\cdot}65 \times 10^{28}$
2. 6×10^{12}
3. 2670 K
4. (a) 43 (b) 3000 K
5. 50 meV
6. 390 nm
7. 1·5 eV
8. $1{\cdot}9 \times 10^{-6}$ m
9. 2·0 eV
10. $2{\cdot}3 \times 10^{-33}$, almost zero
11. approximately 10^{463}
12. 1 in about $3{\cdot}5 \times 10^{10}$
13. $1{\cdot}8 \times 10^{16}$ per cubic metre
14. 318 K
15. 20 to 230 K
16. (a) 0·2 V (b) 0·2 eV
17. (a) 0·2 eV (b) 0·1 eV (c) 0·3 eV
18. (a) 50 meV (b) 550 meV
19. (a) 25 μA (b) zero (c) 100 μA
20. $3{\cdot}1 \times 10^{13}$
21. (a) 0·12 V (b) $\frac{kT}{ei_0} e^{-eV/kT}$ (c) 0·25 V
22. (a) 2 A (b) 318 mV
23. 20 μA, 4·996 V ≅ 5 V
24. 20 Ω
25. (a) 1 A (b) zero (c) 1 A (d) 1 A
26. zero, 0·2 A
27. (a) 1A (b) 0·5 A
28. (a) 0·42 A, 0·13 A
30. 5 Ω if $V_A > V_B$ and 10 Ω if $V_A < V_B$
31. 50
32. (a) 5·0 V (b) 25 mV (c) 10^4
33. (a) 1 (b) 0 (c) 0

□