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^{10} 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).

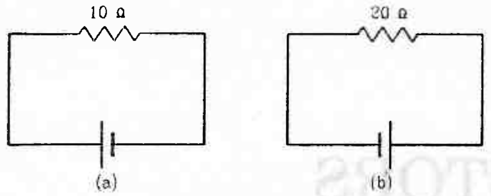


Figure 45-W3

(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 Ω = 0·1 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,

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

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.

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

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

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

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

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) $\beta = \dfrac{\Delta I_C}{\Delta I_B} = \dfrac{2 \text{ mA}}{20\ \mu\text{A}} = 100.$

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

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

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

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

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

$$= (5 \text{ k}\Omega)(2 \text{ mA}) = 10 \text{ V}.$$

The applied signal voltage = 20 mV.

Thus, the voltage gain is,

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

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

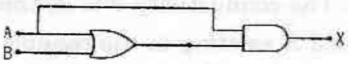


Figure 45-W4

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.

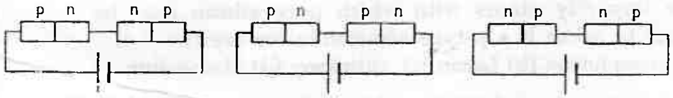


Figure 45-Q1

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

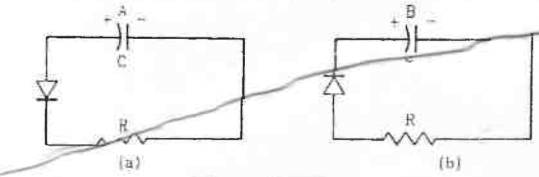


Figure 45-Q2

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'
(a) 'collector' and 'emitter' (b) '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. Calculate the number of states per cubic metre of sodium in 3s band. The density of sodium is 1013 kg/m^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 germinium 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 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

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

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.

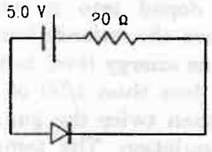


Figure 45-E1

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 ?

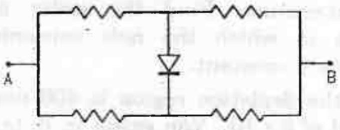


Figure 45-E2

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).

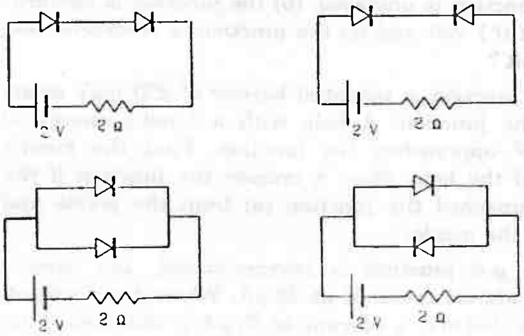


Figure 45-E3

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

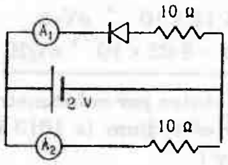


Figure 45-E4

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

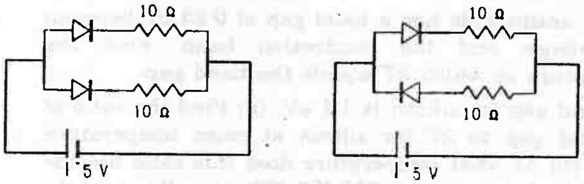


Figure 45-E5

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

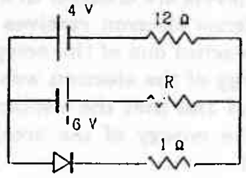


Figure 45-E6

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

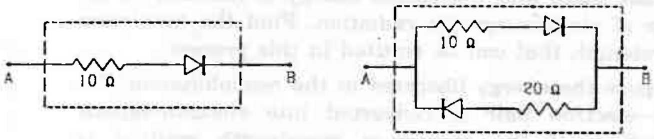


Figure 45-E7

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

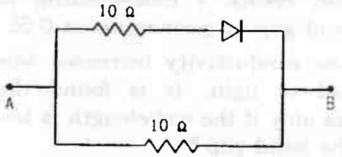


Figure 45-E8

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 $X = A\overline{B}C + B\overline{C}A + C\overline{A}B$. 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 $ABC + BCA$.

35. Show that $AB + AB$ 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. $5{\cdot}3 \times 10^{-20}$, $2{\cdot}65 \times 10$
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. $2{\cdot}3 \times 10^{-23}$, almost zero
11. approximately 10^{483}
12. 1 in about $3{\cdot}5 \times 10$
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) $\frac{}{ei_0} e$ (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

□

CHAPTER - 45
SEMICONDUCTOR AND SEMICONDUCTOR DEVICES

1. $f = 1013\ \text{kg/m}^3$, $V = 1\ \text{m}^3$

   $m = fV = 1013 \times 1 = 1013\ \text{kg}$

   No.of atoms = $\dfrac{1013 \times 10^3 \times 6 \times 10^{23}}{23}$ = 264.26×10^{26}.

   a) Total no.of states = $2\ N = 2 \times 264.26 \times 10^{26} = 528.52 = 5.3 \times 10^{28} \times 10^{26}$

   b) Total no.of unoccupied states = 2.65×10^{26}.

2. In a pure semiconductor, the no.of conduction electrons = no.of holes

   Given volume = 1 cm × 1 cm × 1 mm

   $= 1 \times 10^{-2} \times 1 \times 10^{-2} \times 1 \times 10^{-3} = 10^{-7}\ \text{m}^3$

   No.of electrons = $6 \times 10^{19} \times 10^{-7} = 6 \times 10^{12}$.

   Hence no.of holes = 6×10^{12}.

3. $E = 0.23\ \text{eV}$, $K = 1.38 \times 10^{-23}$

   $KT = E$

   $\Rightarrow 1.38 \times 10^{-23} \times T = 0.23 \times 1.6 \times 10^{-19}$

   $\Rightarrow T = \dfrac{0.23 \times 1.6 \times 10^{-19}}{1.38 \times 10^{-23}} = \dfrac{0.23 \times 1.6 \times 10^{4}}{1.38} = 0.2676 \times 10^4 = 2670.$

4. Bandgap = 1.1 eV, T = 300 K

   a) Ratio = $\dfrac{1.1}{KT} = \dfrac{1.1}{8.62 \times 10^{-5} \times 3 \times 10^2} = 42.53 = 43$

   b) $4.253' = \dfrac{1.1}{8.62 \times 10^{-5} \times T}$ or $T = \dfrac{1.1 \times 10^5}{4.253 \times 8.62} = 3000.47\ \text{K}.$

5. 2KT = Energy gap between acceptor band and valency band

   $\Rightarrow 2 \times 1.38 \times 10^{-23} \times 300$

   $\Rightarrow E = (2 \times 1.38 \times 3) \times 10^{-21}\ \text{J} = \dfrac{6 \times 1.38}{1.6} \times \dfrac{10^{-21}}{10^{-19}}\ \text{eV} = \left(\dfrac{6 \times 1.38}{1.6}\right) \times 10^{-2}\ \text{eV}$

   $= 5.175 \times 10^{-2}\ \text{eV} = 51.75\ \text{meV} = 50\ \text{meV}.$

6. Given :

   Band gap = 3.2 eV,

   $E = hc / \lambda = 1242 / \lambda = 3.2$ or $\lambda = 388.1\ \text{nm}$.

7. $\lambda = 820\ \text{nm}$

   $E = hc / \lambda = 1242/820 = 1.5\ \text{eV}$

8. Band Gap = 0.65 eV, λ =?

   $E = hc / \lambda = 1242 / 0.65 = 1910.7 \times 10^{-9}\ \text{m} = 1.9 \times 10^{-5}\ \text{m}.$

9. Band gap = Energy need to over come the gap

   $\dfrac{hc}{\lambda} = \dfrac{1242\text{eV} - \text{nm}}{620\text{nm}} = 2.0\ \text{eV}.$

10. Given $n = e^{-\Delta E / 2KT}$, ΔE = Diamon → 6 eV ; ΔE Si → 1.1 eV

    Now, $n_1 = e^{-\Delta E_1 / 2KT} = e^{\frac{-6}{2 \times 300 \times 8.62 \times 10^{-5}}}$

    $n_2 = e^{-\Delta E_2 / 2KT} = e^{\frac{-1.1}{2 \times 300 \times 8.62 \times 10^{-5}}}$

    $\dfrac{n_1}{n_2} = \dfrac{4.14772 \times 10^{-51}}{5.7978 \times 10^{-10}} = 7.15 \times 10^{-42}.$

    Due to more ΔE, the conduction electrons per cubic metre in diamond is almost zero.

11. $\sigma = T^{3/2}\ e^{-\Delta E/2KT}$ at 4°K

$\sigma = 4^{3/2} = e^{\frac{-0.74}{2\times 8.62\times 10^{-5}\times 4}} = 8 \times e^{-1073.08}$.

At 300 K,

$\sigma = 300^{3/2} e^{\frac{-0.67}{2\times 8.62\times 10^{-5}\times 300}} = \frac{3\times 1730}{8} e^{-12.95}$.

Ratio = $\frac{8\times e^{-1073.08}}{[(3\times 1730)/8]\times e^{-12.95}} = \frac{64}{3\times 1730} e^{-1060.13}$.

12. Total no.of charge carriers initially = $2 \times 7 \times 10^{15} = 14 \times 10^{15}$/Cubic meter

Finally the total no.of charge carriers = $14 \times 10^{17}\ /\ m^3$

We know :

The product of the concentrations of holes and conduction electrons remains, almost the same.

Let x be the no.of holes.

So, $(7 \times 10^{15}) \times (7 \times 10^{15}) = x \times (14 \times 10^{17} - x)$

$\Rightarrow 14x \times 10^{17} - x^2 = 79 \times 10^{30}$

$\Rightarrow x^2 - 14x \times 10^{17} - 49 \times 10^{30} = 0$

x = $\frac{14\times 10^{17} \pm 14^2 \times \sqrt{10^{34} + 4\times 49\times 10^{30}}}{2} = 14.00035 \times 10^{17}$.

= Increased in no.of holes or the no.of atoms of Boron added.

$\Rightarrow$ 1 atom of Boron is added per $\frac{5\times 10^{28}}{1386.035\times 10^{15}} = 3.607 \times 10^{-3} \times 10^{13} = 3.607 \times 10^{10}$.

13. (No. of holes) (No.of conduction electrons) = constant.

At first :

No. of conduction electrons = 6×10^{19}

No.of holes = 6×10^{19}

After doping

No.of conduction electrons = 2×10^{23}

No. of holes = x.

$(6 \times 10^{19})(6 \times 10^{19}) = (2 \times 10^{23})x$

$\Rightarrow \frac{6\times 6\times 10^{19+19}}{2\times 10^{23}} = x$

$\Rightarrow x = 18 \times 10^{15} = 1.8 \times 10^{16}$.

14. $\sigma = \sigma_0 e^{-\Delta E/2KT}$

$\Delta E = 0.650$ eV, T = 300 K

According to question, $K = 8.62 \times 10^{-5}$ eV

$$\sigma_0 e^{-\Delta E/2KT} = 2\times \sigma_0 e^{\frac{-\Delta E}{2\times K\times 300}}$$

$\Rightarrow e^{\frac{-0.65}{2\times 8.62\times 10^{-5}\times T}} = 6.96561 \times 10^{-5}$

Taking in on both sides,

We get, $\frac{-0.65}{2\times 8.62\times 10^{-5}\times T'} = -11.874525$

$\Rightarrow \frac{1}{T'} = \frac{11.574525\times 2\times 8.62\times 10^{-5}}{0.65}$

$\Rightarrow$ T’ = 317.51178 = 318 K.

15. Given band gap = 1 eV

Net band gap after doping = $(1 - 10^{-3})$eV = 0.999 eV

According to the question, $KT_1 = 0.999/50$

$\Rightarrow T_1 = 231.78 = 231.8$

For the maximum limit $KT_2 = 2 \times 0.999$

$\Rightarrow T_2 = \dfrac{2 \times 1 \times 10^{-3}}{8.62 \times 10^{-5}} = \dfrac{2}{8.62} \times 10^{2} = 23.2$.

Temperature range is (23.2 – 231.8).

16. Depletion region 'd' = 400 nm = 4×10^{-7} m

Electric field E = 5×10^{5} V/m

a) Potential barrier V = E × d = 0.2 V

b) Kinetic energy required = Potential barrier × e = 0.2 eV [Where e = Charge of electron]

17. Potential barrier = 0.2 Volt

a) K.E. = (Potential difference) × e = 0.2 eV (in unbiased cond^{n})

b) In forward biasing

KE + Ve = 0.2e

$\Rightarrow$ KE = 0.2e – 0.1e = 0.1e.

c) In reverse biasing

KE – Ve = 0.2 e

$\Rightarrow$ KE = 0.2e + 0.1e = 0.3e.

18. Potential barrier 'd' = 250 meV

Initial KE of hole = 300 meV

We know : KE of the hole decreases when the junction is forward biased and increases when reverse blased in the given 'Pn' diode.

So,

a) Final KE = (300 – 250) meV = 50 meV

b) Initial KE = (300 + 250) meV = 550 meV

19. $i_1 = 25\ \mu A$, V = 200 mV, $i_2 = 75\ \mu A$

a) When in unbiased condition drift current = diffusion current

$\therefore$ Diffusion current = 25 μA.

b) On reverse biasing the diffusion current becomes 'O'.

c) On forward biasing the actual current be x.

x – Drift current = Forward biasing current

$\Rightarrow x - 25\ \mu A = 75\ \mu A$

$\Rightarrow x = (75 + 25)\ \mu A = 100\ \mu A$.

20. Drift current = 20 μA = 20×10^{-6} A.

Both holes and electrons are moving

So, no.of electrons = $\dfrac{20 \times 10^{-6}}{2 \times 1.6 \times 10^{-19}} = 6.25 \times 10^{13}$.

21. a) $e^{aV/KT} = 100$

$\Rightarrow e^{\frac{V}{8.62 \times 10^{-5} \times 300}} = 100$

$\Rightarrow \dfrac{V}{8.62 \times 10^{-5} \times 300} = 4.605 \Rightarrow V = 4.605 \times 8.62 \times 3 \times 10^{-3} = 119.08 \times 10^{-3}$

$R = \dfrac{V}{I} = \dfrac{V}{I_0(e^{ev/KT-1})} = \dfrac{119.08 \times 10^{-3}}{10 \times 10^{-6} \times (100 - 1)} = \dfrac{119.08 \times 10^{-3}}{99 \times 10^{-5}} = 1.2 \times 10^{2}$.

$V_0 = I_0 R$

$\Rightarrow 10 \times 10^{-6} \times 1.2 \times 10^{2} = 1.2 \times 10^{-3} = 0.0012$ V.

c) $0.2 = \frac{KT}{ei_0} e^{-eV/KT}$

$K = 8.62 \times 10^{-5}$ eV/K, T = 300 K

$i_0 = 10 \times 10^{-5}$ A.

Substituting the values in the equation and solving

We get V = 0.25

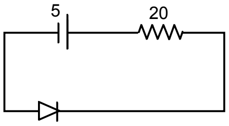
22. a) $i_0 = 20 \times 10^{-6}$A, T = 300 K, V = 300 mV

$i = i_0 e^{\frac{ev}{KT}-1} = 20 \times 10^{-6}(e^{\frac{100}{8.62}} - 1) = 2.18$ A = 2 A.

b) $4 = 20 \times 10^{-6}(e^{\frac{V}{8.62 \times 3 \times 10^{-2}}} - 1) \Rightarrow e^{\frac{V \times 10^3}{8.62 \times 3}} - 1 = \frac{4 \times 10^6}{20}$

$\Rightarrow e^{\frac{V \times 10^3}{8.62 \times 3}} = 200001 \Rightarrow \frac{V \times 10^3}{8.62 \times 3} = 12.2060$

$\Rightarrow$ V = 315 mV = 318 mV.

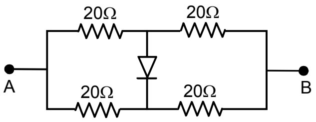


23. a) Current in the circuit = Drift current

(Since, the diode is reverse biased = 20 μA)

b) Voltage across the diode = $5 - (20 \times 20 \times 10^{-6})$

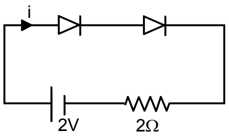
$= 5 - (4 \times 10^{-4}) = 5$ V.



24. From the figure :

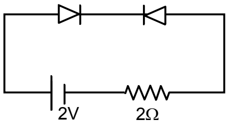
According to wheat stone bridge principle, there is no current through the diode.

Hence net resistance of the circuit is $\frac{40}{2} = 20\ \Omega$.



25. a) Since both the diodes are forward biased net resistance = 0

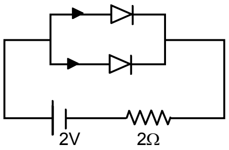
$i = \frac{2V}{2\Omega} = 1$ A



b) One of the diodes is forward biased and other is reverse biase.

Thus the resistance of one becomes ∞.

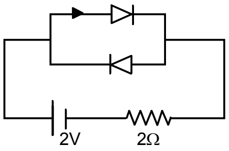
$i = \frac{2}{2 + \infty} = 0$ A.



Both are forward biased.

Thus the resistance is 0.

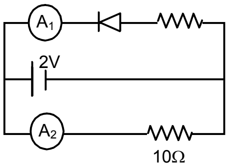
$i = \frac{2}{2} = 1$ A.



One is forward biased and other is reverse biased.

Thus the current passes through the forward biased diode.

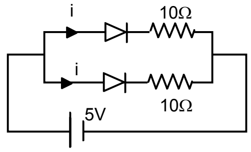
$\therefore i = \frac{2}{2} = 1$ A.



26. The diode is reverse biased. Hence the resistance is infinite. So, current through A_1 is zero.

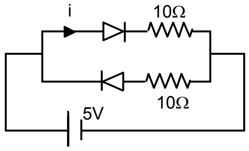
For A_2, current = $\frac{2}{10} = 0.2$ Amp.

27. Both diodes are forward biased. Thus the net diode resistance is 0.



$i = \frac{5}{(10+10)/10.10} = \frac{5}{5}$ = 1 A.

One diode is forward biased and other is reverse biased.



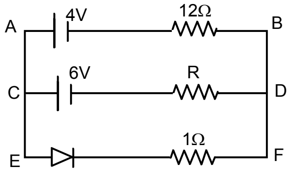
Current passes through the forward biased diode only.

$i = \frac{V}{R_{net}} = \frac{5}{10+0}$ = 1/2 = 0.5 A.

28. a) When R = 12 Ω

The wire EF becomes ineffective due to the net (–)ve voltage.

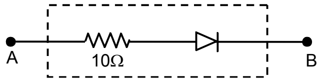
Hence, current through R = 10/24 = 0.4166 = 0.42 A.

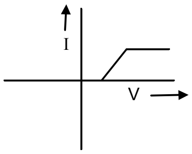


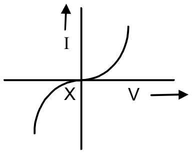
b) Similarly for R = 48 Ω.

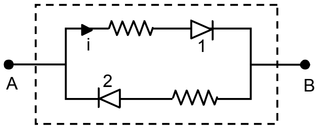
$i = \frac{10}{(48+12)}$ = 10/60 = 0.16 A.

29.

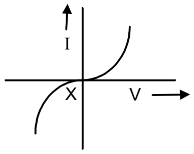


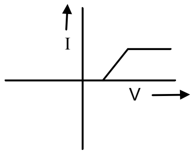




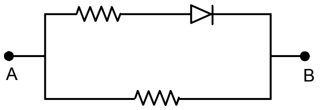


Since the diode 2 is reverse biased no current will pass through it.





30. Let the potentials at A and B be V_A and V_B respectively.



i) If $V_A > V_B$

Then current flows from A to B and the diode is in forward biased.

Eq. Resistance = 10/2 = 5 Ω.

ii) If $V_A < V_B$

Then current flows from B to A and the diode is reverse biased.

Hence Eq.Resistance = 10 Ω.

31. δI_b = 80 μA – 30 μA = 50 μA = 50×10^{-6} A

δI_c = 3.5 mA – 1 mA = –2.5 mA = 2.5×10^{-3} A

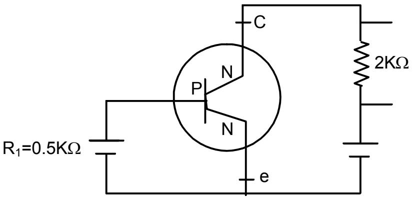
$\beta = \left(\frac{\delta I_c}{\delta I_b}\right) V_{ce}$ = constant

$\Rightarrow \frac{2.5 \times 10^{-3}}{50 \times 10^{-6}} = \frac{2500}{50}$ = 50.

Current gain = 50.

32. $\beta = 50$, $\delta I_b = 50\ \mu A$,

$V_0 = \beta \times RG = 50 \times 2/0.5 = 200$.



a) $VG = V_0/V_1 = \dfrac{V_0}{V_i} = \dfrac{V_0}{\delta I_b \times R_i} = \dfrac{200}{50 \times 10^{-6} \times 5 \times 10^2}$ = 8000 V.

b) $\delta V_i = \delta I_b \times R_i = 50 \times 10^{-6} \times 5 \times 10^2 = 0.00025$ V = 25 mV.

c) Power gain = $\beta^2 \times RG = \beta^2 \times \dfrac{R_0}{R_i} = 2500 \times \dfrac{2}{0.5}$ = 10^4.

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

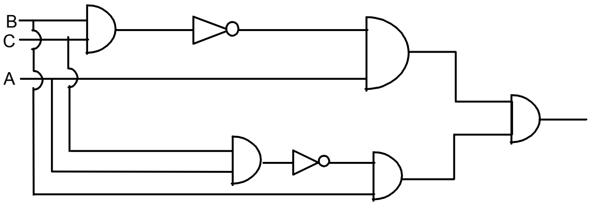
a) A = 1, B = 0, C = 1

X = 1.

b) A = B = C = 1

X = 0.

34. For $A\overline{BC} + B\overline{CA}$



35. LHS = $AB \times \overline{AB} = X + \overline{X}$ [X = AB]

If X = 0, $\overline{X}$ = 1

If $\overline{X}$ = 0, X = 1

$\Rightarrow$ 1 + 0 or 0 + 1 = 1

$\Rightarrow$ RHS = 1 (Proved)

♠ ♠ ♠