Chapter - 3

SEMICONDUCTOR DEVICES

✤ Classification of solids ✤

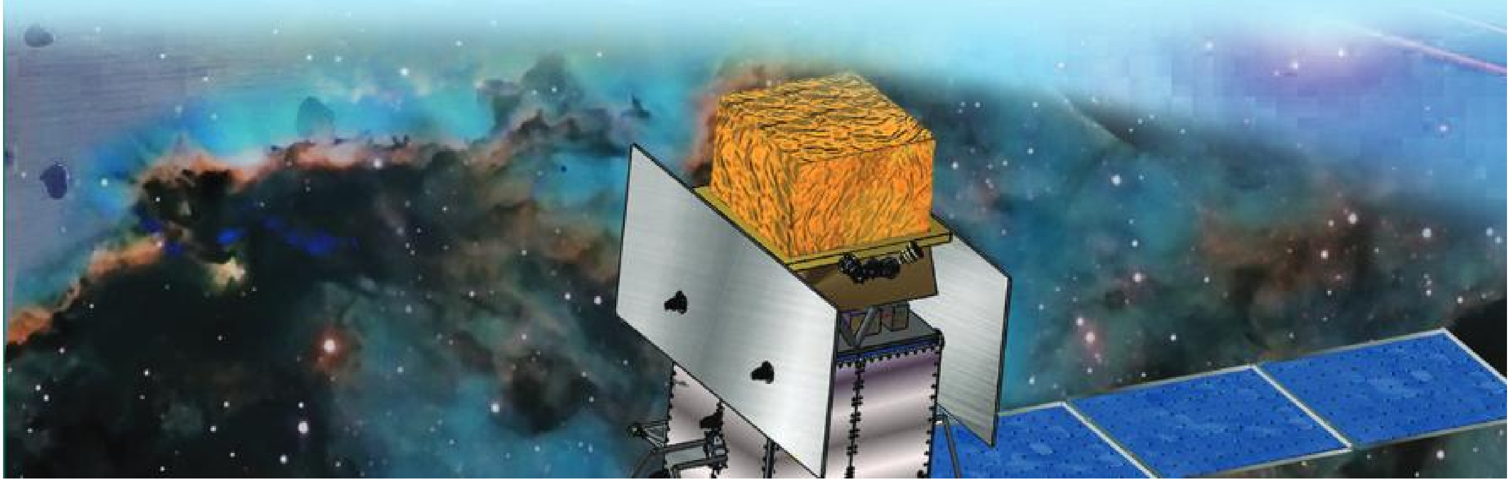
✤ Types of Semiconductors ✤ P-N Junction Diode ✤

✤ Zener Diode ✤ Junction Diode Rectifier ✤

✤ Transistor Configurations ✤ Transistor Amplifier ✤

✤ Concept of Feedback and Oscillator ✤

✤ Photo Diode, LED and Solar cell ✤



3.1 INTRODUCTION

Matter exists in three states - Solid, Liquid, Gas. Based on their electrical properties, Solids are classified as conductors, insulators and semiconductors. Germanium and silicon are semiconductors. They play a dominant role in semiconductor physics and they have revolutionised the field of electronics. The transistor invented in 1948 has placed in our hands portable radio receivers, record players etc. and played an important role for the development of computer industry. Micro electronic circuits or integrated circuits use a very thin slice of silicon crystal about 0.05 cm in thickness. It is called a silicon wafer. It is also known as chip. The various components such as resistors, capacitors, inductors, diodes, transistors, logic gates etc., can be grown over one such silicon chip.

The seed of the development of modern solid-state semiconductor electronics goes back to 1930's when it was realised that some solid-state semiconductors and their junctions offer the possibility of controlling the number and the direction of flow of charge carriers through them. Simple excitations like light, heat or small applied voltage can change the number of mobile charges in a semiconductor. Note that the supply and flow of charge carriers in the semiconductor devices are within the solid itself, while in the earlier vacuum tubes/valves, the mobile electrons were obtained from a heated cathode and they were made to flow in an evacuated space or vacuum. No external heating or large evacuated space is required by the semiconductor devices. They are small in size, consume low power, operate at low voltages and have long life and high reliability. Even the Cathode Ray Tubes (CRT) used in television and computer monitors which work on the principle of vacuum tubes are being replaced by Liquid Crystal Display (LCD) monitors with supporting solid state electronics. In the following sections, we will introduce the basic concepts of semiconductor physics and discuss some semiconductor devices like junction diodes and bipolar junction transistor. A few circuits illustrating their applications will also be described.

3.2 CRYSTALLINE AND AMORPHOUS SOLIDS

(i) Crystalline solids

Most of the solids we handle are cyrstalline. Some examples are : Sugar, common salt, mica, wood, quartz and precious stones or gems. Some of these do not appear to be crystalline to the naked eye. When examined carefully using appropriate instruments they are actually found to be crystalline in nature. By virture of their structure, crystalline materials exhibit the following properties :

a) Atoms are arranged in a regular pattern. This pattern repeats itself at regular intervals in space. They have long - range order.

b) Single crystals are anisotropic, i.e., physical properties like conductivity, refractive index, velocity of sound, depend on the direction. They have different values in different directions. Polycrystralline aggregates, like metals are isotropic.

c) Crystals have sharp and well defined freezing points.

(ii) Amorphous solids

In amorphous solids, there is no regularity or periodicity of the arrangements of atoms. Still they are bound together by strong forces. Glass is an examples of an amorphous solid. Amorphous solids are close to liquids in their structure. Their only difference lies in the freedom of molecules with reference to movement.

Amorphous solids are isotropic. Physical properties do not depend on the direction in the material. They do not have well defined melting and freezing points. High viscosity of these materials (glass) and fast rate of cooling are supposed to prevent formation of crystals while cooling down from liquid state.

3.3 CLASSIFICATION OF SOLIDS

From the electrical point of view, solids can be divided into three categories :

I. Conductors : These substances will have large number of free electrons which are not strongly hold towards nucleus.

Metals such as Gold, silver, copper, aluminium etc. are good examples of conductors.

1. Conductors have high electrical and thermal conductivities or very low resistivity.

$\rho \sim 10^{-2} \sim 10^{-8}\ \Omega\,m$

$\sigma \sim 10^{2} \sim 10^{8}\ sm^{-1}$

2. In the steady states, conductors obey Ohm's law according to which the current density $\vec{j}$ is proportional to the electrical field strength $\vec{E}$. Thus, for metals $\vec{j} \alpha \vec{E}$ or $\vec{j} = \sigma \vec{E}$ where σ is the electrical conductivity.

3. They have a positive temperature coefficient i.e., their resistance increases (or conductivity decreases) with rise of temperature.

4. Conductors obey Wiedmann-Franz law according to which the ratio of thermal and electrical conductivities at a given temperature is the same for all metals and is proportional to the absolute temperature T. Thus

$$\frac{k}{\sigma} \alpha T \quad \text{or} \quad \frac{k}{\sigma T} = \text{constant}$$

II. Insulators : Those substances whose atoms have their outermost orbits saturated are called insulators. In them, the valence electrons are tightly bound to the nucleus. They thus have practically no free electrons to act as charge carriers and hence have a high electrical resistivity. Glass, mica, quartz, ebonite etc are examples for insulator.

They have high resistivity and low conductivity

$\rho \sim 10^{11} \sim 10^{19}\ \Omega\,m$

$\sigma \sim 10^{-11} \sim 10^{-19}\ sm^{-1}$

III. Semiconductors : Those substances which have their conductivity intermediate between conductors and insulators are called semi-conductors. Their resistivity is higher than that of a conductor but lower than that of an insulator. Typical values of resistivity of a semiconductor (germanium) is 0.6 ohm metre at room temperature while for conductor (silver) it is 1.6×10^{-8} ohm metre and for insulator (quartz) it is 10^{12} ohm metre.

$\rho \sim 10^{-5} \sim 10^{6}\ \Omega\,m$

$\sigma \sim 10^{5} \sim 10^{-6}\ sm^{-1}$

i) Semiconductors have a negative temperature coefficient of resistance i.e., the electrical resistance of a semi-conductor decreases with increase in temperature. The relation between temperature and resistance is of the form $R = Ae^{-B/T}$ where R is the resistance of the semiconductor at temperature TK and A and B are constants.

ii) The electrical conductivity of a semi-conductor can be increased enormously by adding a small amount of suitable impurity.

Germanium (Ge) and silicon (Si) are the most common semi-conductors. Germanium has been used extensively in early solid state devices such as transistors, but is now being replaced by Si due to its availability in abundance. In addition to these elementary semiconductors there are compound semiconductors like cadmium sulphide (CdS), lead sulphide (PbS) and gallium arsenide (GaAs) etc. which are being used in the manufacture of solid state devices.

3.4 ENERGY BANDS IN SOLIDS-THE BAND THEORY

In case of a single isolated atom, there are discrete energy levels, 1s, 2s, 2p, 3s,..., that can be occupied by the electrons of atom, as shown in Fig 3.1(a). All the atoms of a solid, if assumed isolated from one another, can have completely identical electron schemes of their energy levels. Then the electrons fill the levels in each atom independently.

As isolated atoms are brought together to form a solid, various interactions occur between neighbouring atoms. As a result of this interaction, the higher energy levels are considerably affected i.e., the energy levels of the outer shell are slightly altered without violating Pauli's exclusion principle. There will be splitting of a single energy level of an isolated atom into a large number of energy levels as shown in Fig 3.1 (b).

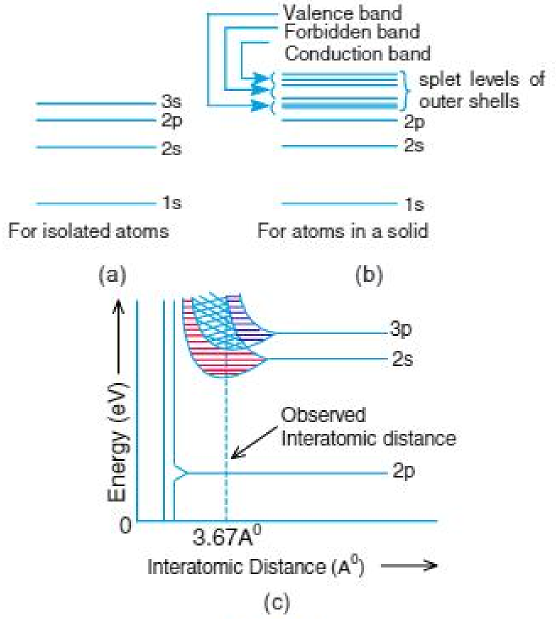


Fig 3.1

Since in a solid, many atoms ($N = 10^{23}$ atoms/cm^3) are brought together, the separation between N sub-levels (into which each discrete energy level splits due to interaction) is very small. For example, if there are 50 atoms in a piece of solid material, then there will be 50 levels of slightly different energies i.e., 50 energy level diagrams would be superimposed on each other. Consequently, the split energy levels are almost continuous and are said to form an energy band.

Figure 3.1 (c) shows the formation of energy levels for higher energy levels of isolated sodium atoms whose ground state configuration is $1s^2 2s^2 2p^6 3s^1$. The dashed line indicates the observed interatomic separation ($= 3.67$ A) in solid sodium.

It may be seen that lower levels 1s and 2s do not split at all because electrons in lower levels are the 'inner' electrons of the atoms which are not significantly affected by the presence of nearby atoms. The 2p level does not begin to split until the interatomic distance becomes smaller than actually found in sodium. The 3s level is the first occupied level to be split into a band. It is due to the fact that electrons in higher levels are the valence electrons whose wavefunctions overlap appreciably.

Now, the energy bands in a solid correspond to the energy levels in an atom. An electron in a solid can have only those discrete energies that lie within these energy bands. These bands are, therefore, called allowed energy bands. These (allowed) energy bands are, in general, separated by some gaps which have no allowed energy levels. These gaps (regions) are known as forbidden energy bands. Energy band occupied by the valence electrons is called valence band and is obviously the highest occupied band. Electrons which have left the valence band are called conduction electrons and are only weakly bound to the nucleus. The band occupied by these electrons is called the conduction band. Thus the band beyond forbidden band is called conduction band, into which, when the electrons pass, they can move freely.

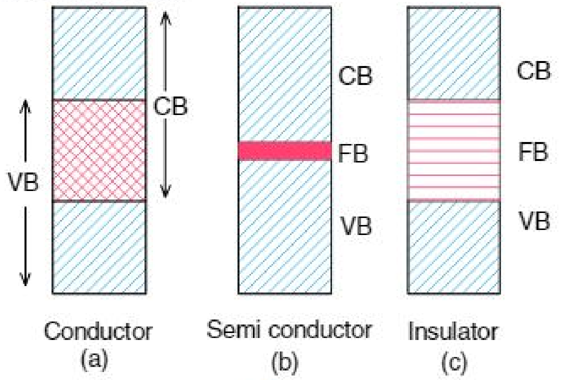


Fig 3.2

S.No	Conductors	Semi Conductors	Insulators
1.	In this, valence band and conduction band overlap each other	In this, valence band and conduction band are separated by forbidden band.	In this, valence band and conduction band are largely separated.
2.	Forbidden Energy gap = 0	Forbidden energy gap is in the order of 1 eV.	Forbidden energy gap is in the order of 6 eV
3.	At room temperature conductivity is high	At room temperature conductivity is intermediate.	At room temperature conductivity is nil.
4.	Ex : All metals	Ex : Ge, Si	Ex : Rubber, Glass, Mica.

The highest energy level which an electron can occupy at 0 K is called fermienergy level.

In the case of metals, conductors, valence band overlaps conduction band and the electrons are readily available for conduction, as shown in Fig 3.2(a). Hence, they are good conductors. In the case of insulators, there is large energy gap between valence band and conduction band, as shown in Fig 3.2(c). Therefore, the conductivity is negligible. In the case of semiconductors, the gap is small as in Fig 3.2(b) and at room temperature, some of the electrons can cross the energy gap and reach conduction band causing electrical conductivity.

3.5 TYPES OF SEMICONDUCTORS

1) Intrinsic semiconductors.
2) Extrinsic semiconductors.

3.5.1 INTRINSIC SEMICONDUCTOR

Pure form of semi conductor is called intrinsic semi conductor.

Ex : Silicon, Germanium

These atoms are tetra valent. In their crystal lattice each atom establish the covalent bonds with its neighbouring atoms as shown in the figure 3.3. Due to that valence electrons are tightly bound. So crystal has low conductivity. At low temperature, valence band is filled with electrons and conduction band is empty. Hence it acts as an insulator.

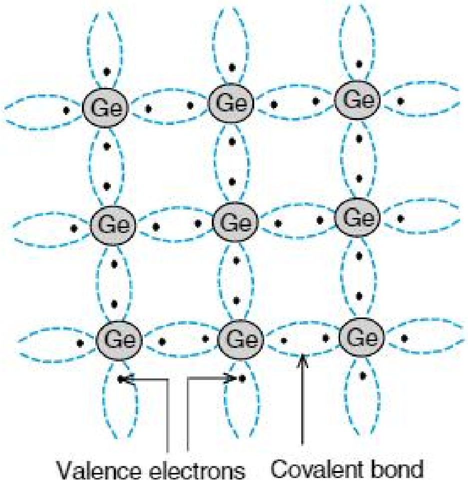


Fig 3.3

As temperature increases, covalent bond between the atoms starts to break. Hence valence band electrons get energy and jump into the conduction band. As a result in the valence band ,a vacancy is created. This vacancy of electron in the valence band is called a hole. 'Hole' behaves like positive charge and moves only in the valence band giving 'hole current' [I_h] as shown in the Fig 3.4. The excited electrons in the conduction band move in the conduction band giving 'electron current' [I_e].

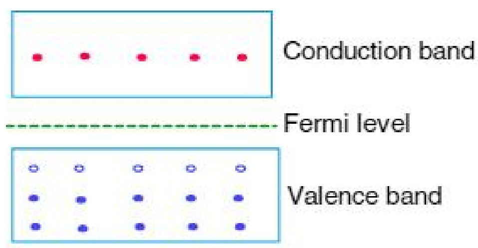


Fig 3.4

When electric field is applied the holes drift in the direction of the field and electrons drift opposite to the field with lower speed. Hence the current in a semi conductor is due to both electrons as well as holes. In intrinsic semi conductors number of electrons in the conduction band is equal to number of holes in the valance band i.e., $n_e = n_h$. Hence hole current (I_h) is equal to electron current. (I_e).

Total current $I = I_h + I_e$. Because of less concentration of electrons and holes, the total current in an intrinsic semi conductor approaches zero. In this semi conductor, Fermi energy levlel will be at the middle of the Forbidden band.

Apart from regeneration of conduction electrons and holes, recombination of holes and electrons also takes place. At equilibrium rate of regeneration will be equal to rate of recombination.

3.5.2 EXTRINSIC (DOPED) SEMICONDUCTORS

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

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

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

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

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

Extrinsic semi conductors are of two types. They are p-type and n-type semi conductors.

(a) p - type Semiconductor

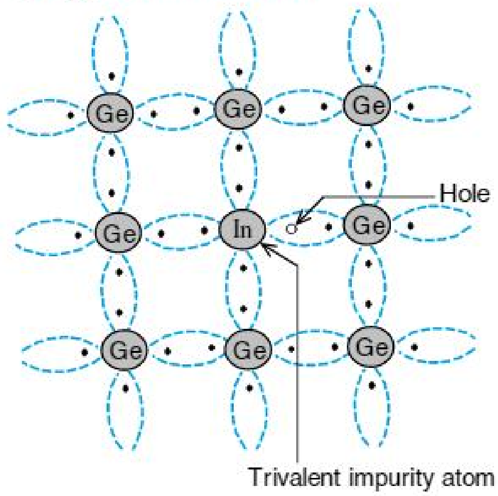


Fig 3.5

When a pure tetra valent semiconductor is doped with trivalent atoms like Al, Ga or In, then p - type semiconductor is formed. If indium is added to germanium, indium atoms occupy some of the sites instead of germanium atoms. Each indium atom establishes the three covalent bonds with germanium atoms and fourth covalent bond is incomplete as shown in Fig 3.5. So additional hole is created. Therefore, excess holes in addition to the holes formed in valance band due to the electrons going from valance band to conduction band, will also be responsible for conduction as in Fig 3.6.

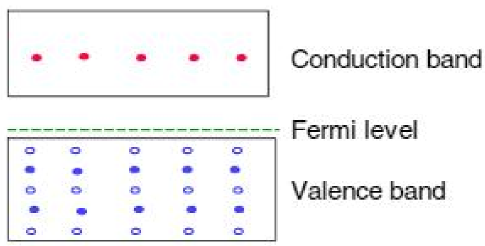


Fig 3.6

So in a p-type semiconductor, number of holes in valence band is greater than number of electrons in conduction band ($n_h > n_e$). Hence at sufficient temperature hole current is more than that of electron current.

Total current $I = I_e + I_h$, such that $n_h.n_e = n_i^2$ where n_i is number of electrons or holes in purest form of semi conductor.

Hence in p - type semiconductor, holes are called majority charge carriers and electrons are called minority charge carriers. Fermi energy level is nearer to the valence band as in Fig 3.6.

Since in p -type semiconductor trivalent impurity (eg: Indium) is ready to accept electron, it is called acceptor impurity.

(b) n - type Semiconductor

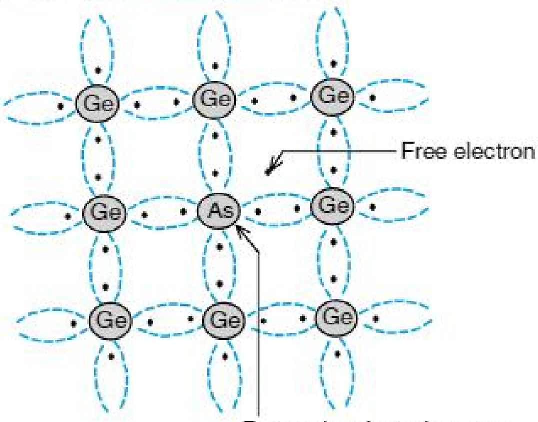


Fig 3.7

When a pure tetravalent semiconductor is doped with pentavalent atoms like phosphorus, arsenic, antimony or bismuth, then n - type semi conductor is formed. When pentavalent atom like Arsenic is added to germanium atoms, arsenic atoms occupy some of the positions instead of germanium atoms. Arsenic atom will establish four covalent bonds with neighbouring germanium atoms and its fifth electron is loosely bound as in Fig 3.7 and needs less amount of energy to become free electron. Therefore excess electrons are available for conduction in conduction band than holes in valance band and conductivity of semi conductor increases (Fig 3.8).

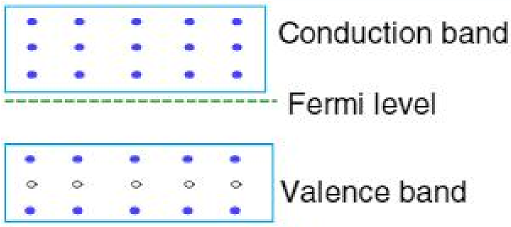


Fig 3.8

So in n-type semiconductors number of holes in valance band is less than number of electrons in conduction band ($n_h < n_e$). Hence at a sufficiently high temperarture, electron current is more than hole current.

Total current $I = I_h + I_e$, such that $n_h.n_e = n_i^2$ where n_i is number of electrons or holes in purest form of semi conductor.

In n-type semi conductor electrons are called majority charge carriers and holes are called minority charge carriers. Fermi energy level is nearer or to conduction band (Fig 3.8). In n-type semi conductor pentavalent impurity (Eg: Arsenic) is ready to donate electron hence, it is called donor impurity.

Example-3.1

Pure Si at 300 K has equal electron (n_e) and hole (n_h) concentration of 1.5×10^{16} m^{-3}. Doping by indium increases n_h to 4.5×10^{22} m^{-3}. Calculate n_e in the doped silicon.

Solution :

Here $n_i = 1.5\times10^{16}\,m^{-3}; n_h = 4.5\times10^{22}\,m^{-3}$

But $n_e n_h = n_i^2$

$$\therefore n_e = \frac{n_i^2}{n_h} = \frac{(1.5\times10^{16})^2}{4.5\times10^{22}} = 5\times10^{9}\,m^{-3}$$

3.6 EFFECT OF TEMPERATURE ON EXTRINSIC SEMI-CONDUCTOR

Let us see what happens if we increase the temperature of an N-type semiconductor. Since all the donors have already donated their free electrons at room temperature, the additional thermal energy will only increase the generation of electron-hole pairs. Thus, the concentration of minority charge carriers increases. A temperature is ultimately reached when the number of covalent bonds broken is very large such that the number of holes and electrons is almost equal. The extrinsic semi-conductor then behaves like an intrinsic semi-conductor, although its conductivity is higher. This critical temperature is 85°C for germanium and 200°C for silicon. That is why silicon semiconductor is preferred over germanium semiconductor.

The same argument can be put forward for the P-type semi-conductor. Thus, with an increase in the temperature of an extrinsic (impurity) semi-conductor, it behaves almost intrinsically.

3.7 DRIFT CURRENTS-MOBILITY AND CONDUCTIVITY

Electric current arises due to the movement of charge carriers. In a semi-conductor, charge carriers are electrons in the conduction band and holes in the valence band. Due to thermal agitation, they move randomly in all directions and hence the net current in any direction is zero.

When an electric field E is applied across a semi-conductor, every charge carrier experiences a force due to electric field and drifts in the direction of the force. Thus, a charge carrier acquires an average velocity which is called the drift velocity. It gives rise to the drift current. The average drift velocity per unit electric field is called the mobility of a charge carrier.

Thus mobility $\mu = \frac{v}{E}$ where v is the drift velocity and E is the applied electric field.

3.8 EXPRESSION FOR CONDUCTIVITY OF SEMICONDUCTOR

Let us consider a cylindrical semi-conductor of length 'l' and area of cross section 'A' (Fig 3.9).

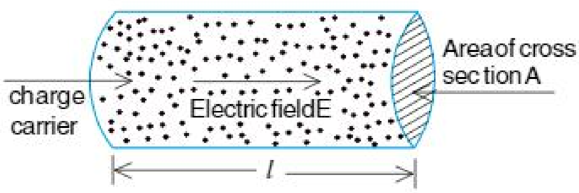


Fig 3.9

Let an electric field E be applied along the length of the cylinder due to which carriers acquire a drift velocity 'v'. Then time taken by a carrier to travel the length 'l' of the cylinder

$$t = l / v \quad \text{..... (1)}$$

If n_c is the carrier concentration, then total number of carriers inside volume 'Al' of a cylinder is $n_c Al$. Hence

Total charge inside the cylinder

$= n_c Ale$ where 'e' is the charge of a carrier.

Therefore, rate of flow of charge i.e., current flowing through the semiconductor

$$I = \frac{n_c Ale}{t} = \frac{n_c Ale}{l/v} \quad [\text{ using 1}]$$

Therefore, current density i.e., current per unit area of cross-section

$$J = \frac{I}{A} = n_c ev \quad \text{....(2)}$$

Now, if μ is the mobility of a carrier (average drift velocity per unit electrical field) then

$$\mu = \frac{v}{E} \text{ (or) } \quad v = \mu E$$

Therefore, eq. (2) for current density becomes

$$J = n_c e\mu E \quad \text{....(3)}$$

If σ is the conductivity (current density per unit applied field), then

$$\sigma = \frac{J}{E} \quad \text{....(4)}$$

Combining eq. (3) and (4), we get

$$\sigma = \frac{J}{E} = n_c \mu e$$

But in case of a semiconductor, actually two types of charge carriers are formed. One is negatively charged electron of mobility μ_n and the other is positively charged hole of mobility μ_h. These particles move in opposite directions in the presence of electric field E, but since they carry opposite charges, the currents due to electrons and holes will be in the same direction. Hence the overall conductivity of the semiconductor containing electrons and holes,

$$\sigma = \sigma_n + \sigma_h = ne\mu_n + pe\mu_h = e(n\mu_n + p\mu_h)$$

where σ_n and σ_h are the conductivity of semiconductor due to electrons and holes respectively, n is the electron concentration and p is the hole concentration.

For an intrinsic semiconductor

$$n = p = n_i$$

Therefore, conductivity of intrinsic semiconductor

$$\sigma_{int} = en_i(\mu_n + \mu_h)$$

In an N-type semiconductor, concentration of minority charge carriers i.e., holes is negligible in comparison with the concentrations of majority chare carriers i.e., electrons. Thus, n > > p and therefore, the conductivity of n-type semi-conductor

$$\sigma_{n-type} \approx en\mu_n \approx eN_d\mu_n$$

because $n = N_d \rightarrow$ density of ionized donor atoms.

For a P-type semi-conductor p > > n and its conductivity is given by

$$\sigma_{p-type} \approx ep\mu_h \approx eN_a\mu_h$$

because $p = N_a \rightarrow$ density of ionized acceptor atoms.

Example-3.2

Find the density of impurity atoms that must be added to intrinsic silicon crystal to convert it to

(i) 10^{-1} ohm - m, P-type silicon

(ii) 10^{-1} ohm - m, N-type silicon

Given for silicon $\mu_e = 0.13 m^2 / \text{volt.sec.}$,

$\mu_h = 0.05 m^2 / \text{volt.sec.}$

Solution :

(i) Density of acceptor atoms in P-type Si

$$N_a = \frac{\sigma}{e\mu_h} = \frac{1}{e\mu_h\rho} = \frac{1}{1.6\times10^{-19}\times0.05\times10^{-1}}$$

$$= 1.25\times10^{21} m^{-3}$$

(ii) Density of donor atoms in N-type Si

$$N_d = \frac{\sigma}{e\mu_e} = \frac{1}{e\mu_e\rho} = \frac{1}{1.6\times10^{-19}\times0.13\times10^{-1}}$$

$$= 4.8\times10^{20} m^{-3}$$

Example-3.3

A battery of e.m.f. 2 volt is applied across the block of a semiconductor of length 0.1 m and area of cross section 1×10^{-4} m². If the block is of intrinsic silicon at 300 K, find the magnitude of the total current. What will be the order of magnitude of total current if germanium is used instead of silicon?

Given that for Si at 300K

$\mu_e = 0.135 m^2V^{-1}s^{-1}$; $\mu_h = 0.048 m^2V^{-1}s^{-1}$,

intrinsic carrier concentration $n_i = 1.5\times10^{16} m^{-3}$

For Ge at 300 K $\mu_e = 0.39 m^2V^{-1}s^{-1}$;

$\mu_h = 0.19 m^2V^{-1}s^{-1}$, $n_i = 2.4\times10^{19} m^{-3}$

Solution :

For silicon

Total current, $I = eA(n_e v_e + n_h v_h)$

Since, drift velocity $v_e = \mu_e E$ and $v_h = \mu_h . E$

where $E = \frac{V}{l}$ $\therefore$ Total current

$$I = eA(n_e E\mu_e + n_h E\mu_h) = eA(n_e\mu_e + n_h\mu_h)\frac{V}{l}$$

where $n_i = n_e = n_h$ for intrinsic semiconductor

✯ Substituting values for silicon : $I = 8.7800\times10^{-7}$ A and for Gernanium : $I = 4.46 \times 10^{-3}$A the magnitude of current in Ge is 10^4 times higher than that in Si.

3.9 DEPENDENCE OF MOBILITY ON DOPING CONCENTRATION AND TEMPERATURE

Mobility is a very useful property for characterizing a semiconductor. Mobility μ does not depend upon the doping concentration. Mobility is a property of the semiconductor itself.

The mobility of electrons or holes is, however, influenced by scattering which in a semiconductor is caused by photons and ionized impurity atoms (donors and acceptors).

With increase in temperature, thermal vibrations of the lattice increase which scatter the moving electrons and holes. Therefore, the mobility of an electron or hole generally decreases with increasing temperature. The mobility μ_e of electron and μ_h that of hole, have the same temperature dependence as conductivity because

$$\sigma_e = ne\mu_e \text{ and } \sigma_h = ne\mu_h$$

But conductivity σ decreases with increasing temperature T. Therefore, mobility also decreases with increase in temperature.

3.10 THE P-N JUNCTION DIODE

i) Junction Diode

Diode is a device with two electrodes (di means two, and –ode means electrode). A P-n junction diode is a two terminal device made up of a semiconductor crystal. It has two terminals which act as electrodes.

When a semiconductor material such as silicon or germanium crystal is doped in such a way that one side of it becomes a p-type and the other side becomes an n-type we obtain a p-n junction diode. The plane separating the two regions is called a junction.

The fig 3.10(a) represents the circuit symbol of p-n junction diode. The arrow head shows the direction of the conventional electric current. Actual p-n junction diode is shown in fig 3.10(b).

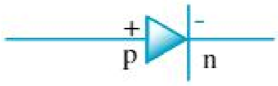


Fig 3.10 (a)

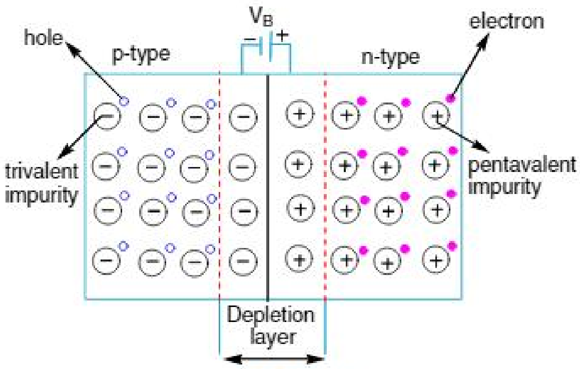


Fig 3.10 (b)

ii) p-n Junction - Depletion layer and Barrier Potential

Near the junction, the free electrons from n-region migrate towards p-region and the holes in p-region migrate towards n-region. This process is known as diffusion. This diffusion is due to concentration gradient.

iii) Due to diffusion, positive ions are left over in n-region and negative ions are left over in p-region, near the junction. These ions are immobile.

iv) Due to the immobile ions on either side of the junction an internal electric field is formed at the junction which is directed from n- region to p-region.

v) A region of no charge carriers that is formed at p-n junction due to the combination of electrons and holes is called **depletion layer**.

vi) The thickness of the depletion layer is of the order of 10^{-6} m. One-tenth of a micrometer.

vii) When the depletion layer is sufficiently built up, it prevents the further diffusion of electrons from n side to p side and holes from p to n side i.e. it acts as a barrier.

viii) The potential difference across the barrier is called potential barrier or contact potential. It behaves as a pseudo battery.

ix) The potential barrier for silicon is around 0.7 volts and for Germanium it is around 0.3 volts.

x) The potential barrier value lies in between 0.1 to 0.7 volts, which depends on (a) the nature of semiconductor, (b) doping concentration (c) temperature of the junction.

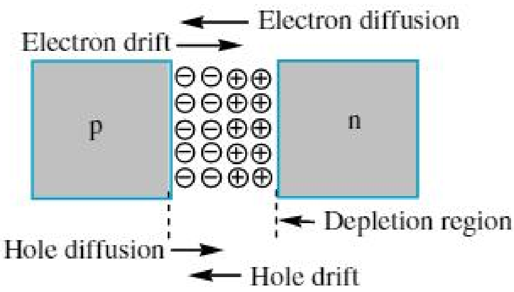
xi) If V is the barrier potential and d is the thickness of the depletion layer, then the electric field intensity across the junction is

$$\boxed{E = \frac{V}{d}} \text{ from n side to p side.}$$

Diffusion current : Due to the difference in concentration of charge carriers, holes from p-side diffuse towards n-side and electrons from n-side diffuse towards p-side. The movement of these charge carriers across the junction causes a current. This current is called diffusion current. **Diffusion current is from p-side to n-side.**

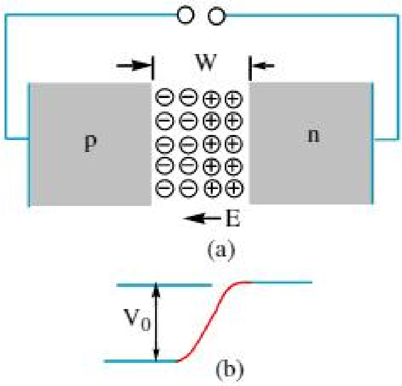
Drift current : If an electron - hole pair is created in the depletion region, the electron is quickly pushed by the electric field towards the n-side and the hole towards the p-side. There is almost no chance of recombination of a hole with an electron in the depletion region. As electron-hole pairs 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 drift current.

> ***Note :*** Two important processes occur during the formation of a p-n junction : diffusion and drift.



p-n junction formation process

Fig 3.10 (b)



(a) Diode under equilibrium (V = 0),

(b) Barrier potential under no bias.

Fig 3.11

3.11 FORWARD BIAS

When the positive terminal (high potential) of a battery is connected to P - type semiconductor and the negative terminal (low potential) of the battery is connected to N-type semiconductor. Then the junction diode is said to be in forward bias as shown in fig.

In forward bias the applied potential establishes an electric field opposite to the potential barrier.

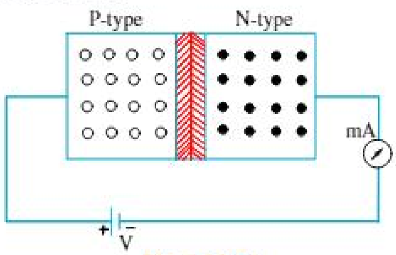


Fig 3.12(a)

In case of forward bias, the holes from P - type semiconductor are repelled by the positive terminal of battery towards the junction and simultaneously, the electrons in N-type semiconductor are repelled by negative terminal of battery towards junction. In forward bias the width of the depletion layer decreases. If V is the external applied voltage and V_B is the barrier potential then the net potential in forward bias is ($V_B \sim V$). When the battery voltage is high it gives sufficient energy to these carriers to overcome the potential barrier at the junction. Then the current in diode sharply rises.

1) In forward bias current is mainly due to flow of majority charge carriers and it is of order of milli amperes.

2) In forward bias the resistance offered by the diode is less.

3) In forward bias the current flow through the diode is mainly due to diffusion of charge carriers.

The below diagrams show forward bias of p-n junction diode.

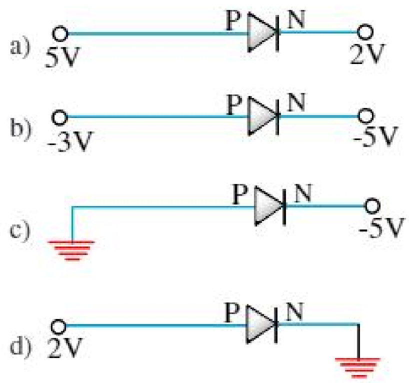
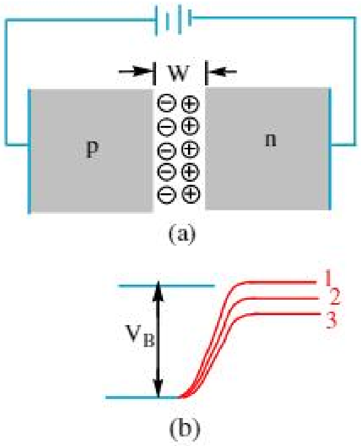


Fig 3.12(b)

> ***Note :*** The applied voltage mostly drops across the depletion region and the voltage drop across the p-side and n-side of the junction is negligible. This is because the resistance of the depletion region – a region where there are no charges-is very high compared to the resistance of n-side and p-side.) The direction of the applied voltage (V) is opposite to the built-in potential V_B. As a result, the depletion layer width decreases and the barrier height is reduced. The effective barrier height under forward bias is ($V_B - V$).



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

Fig 3.13

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

Due to this concentration gradient, the injected electrons on p-side diffuse from the junction edge of p-side to the other end of p-side. Likewise, the injected holes on n-side diffuse from the junction edge of no side to the other end of n-side.

The total diode froward current is sum of hole diffusion current and conventional current due to electron diffusion The magnitude of this current is usually in mA.

3.12 REVERSE BIAS

When the positive terminal (high potential) of a battery is connected to N-type semiconductor and the negative terminal (low potential) of the battery is connected to P-type semiconductor, then the junction diode is in reverse bias.

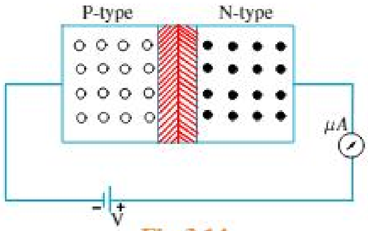


Fig 3.14

In reverse bias, the holes in P-type semiconductor are attracted by the negative terminal of the battery and they move away from the junction, simultaneously electrons in N-type semiconductor are attracted by the positive terminal of the battery and they move away from the junction. The width of the depletion layer increases in reverse bias. If V is the applied voltage and V_B is the barrier potential, then the effective barrier potential in reverse bias is $(V_B + V)$. In reverse bias diffusion of electrons from N-side to P-side and holes from P-side to N-side is more difficult and diode will not allow electric current through it. Due to minority carriers (electrons in P-type semiconductor and holes in N-type semiconductor) a small current flows. The current in germanium diode is of order of μA and in silicon diode it is in the order of nA. The resistance offered by the diode in reverse bias is high. In reverse bias the flow of current through diode is mainly drift current. The below diagrams show reverse bias of p-n junction diode.

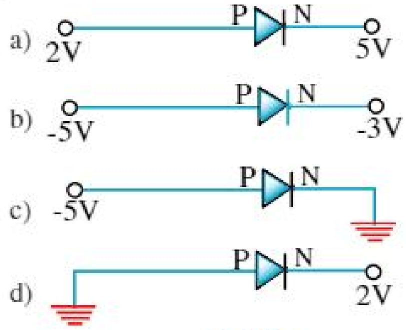
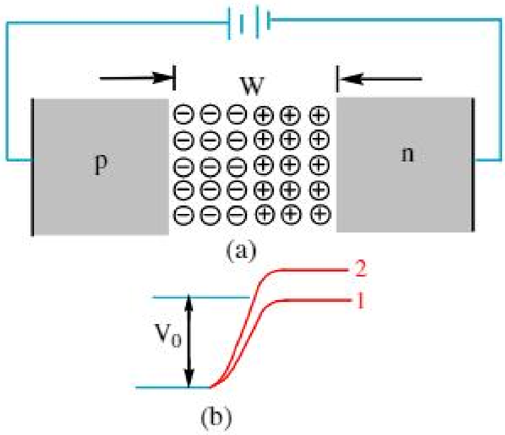


Fig 3.15



(a) Diode under reverse bias,
(b) Barrier potential under reverse bias

Fig 3.16

Note :

i) The applied voltage mostly drops across the depletion region. The direction of applied voltage is same as the direction of barrier potential. As a result, the barrier height increases and the depletion region widens due to the change in the electric field. The effective barrier height under reverse bias is $(V_B + V)$. This suppresses the flow of electrons from n $\rightarrow$ p and holes from p $\rightarrow$ n. Thus diffusion current, decreases enormously compared to the diode under forward bias.

ii) The electric field direction of the junction is such that if electrons on p-side or holes on n-side in their random motion come close to the junction, they will be swept to its majority zone. This drift of carriers give rise to current. The drift current is of the order of a few μ A.

iii) The drift current is also there under forward bias but it is negligible (μ A) when compared with current due to injected carriers which is usually in mA.

iv) The diode reverse current is not very much dependent on the applied voltage. Even a small voltage is sufficient to sweep the minority carriers from one side of the junction to the other side of the junction. The current is not limited by the magnitude of the applied voltage but is limited due to the concentration of the minority carrier on either side of the junction.

v) The current under reverse bias is essentially voltage independent up to a critical reverse bias voltage, known as breakdown voltage (V_{br}). When $V = V_{br}$, the diode reverse current increases sharply. Even a slight increase in the bias voltage causes large change in the current below the rated value (specified by the manufacturer) the p-n junction will get destroyed. Once it exceeds the rated value, the diode gets destroyed due to overheating. This can happen even for the diode under forward bias, if the forward current exceeds the rated value.

vi) In forward bias measurement, we use a milliammeter since the expected current is large while a micrometer is used in reverse bias to measure the current).

3.13 VOLTAGE-CURRENT (V-I) CHARACTERISTICS OF P-N JUNCTION DIODE

The V-I characteristics of a P-N-junction diode is the curve between voltage across the junction (taken along X-axis) and current through the circuit (taken along Y-axis) and has been shown in Fig 3.17 for a typical germanium diode. These characteristics are called the static characteristics because they describe the d.c behaviour of the diode. When the P-N-junction is forward biased, by connecting positive terminal of battery to P-type and negative terminal to N-type, the potential barrier is reduced. Practically no current flows until the barrier voltage (0.3 volt for Ge) is overcome. Then the curve has a linear rise and the current increases, with the increase in forward voltage like an ordinary conductor. With the applied voltage of about 3 volt, the majority charge carriers passing the junction gain sufficient kinetic energy to knock out valence electrons bound to the crystal lattice and raise them to the conduction band. Therefore, the forward current then increases sharply as shown in Fig 3.17. With reverse bias i.e., when positive terminal of battery is connected to N-type and negative terminal to P-type, the potential barrier at the junction is increased. Consequently, the junction resistance becomes very high which prevents the flow of current. However, a few minority charge carriers (free electrons in P-type material and holes in N-type material) are accelerated by the reverse bias voltage resulting in a very small current (of the order of μ A) in the circuit.

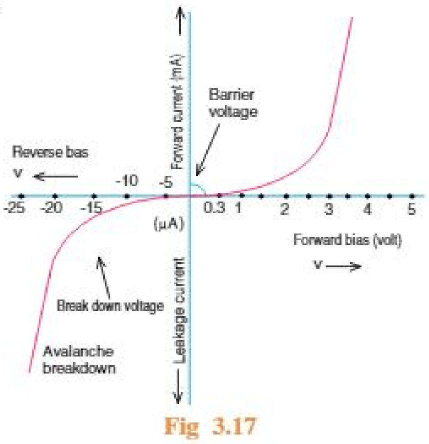


Fig 3.17

This current is called the reverse or leakage current. When reverse voltage is increased beyond a value called breakdown voltage, the reverse current increases suddenly and sharply and the diode shows almost zero resistance. It is known as 'avalanche breakdown' and is due to the fact that at a reverse voltage of about 25 volts, the excessively high temperature destroys the junction permanently.

3.14 RESISTANCE OF A DIODE

(i) Static or D.C. resistance

It is the resistance offered by the diode when only a steady d.c. current flows through it. It is simply the ratio of the d.c. voltage across the diode to the d.c. current flowing through it i.e.,

The static resistance in forward direction is symbolized by R_F while in the reverse direction it is designated by R_R. Their typical values for Ge diode are $R_F = 100\,\Omega$ and $R_R = 1\,M\Omega$. The resistance of the semiconductor diode is relatively low when it is forward biased and very high when it is biased in the reverse direction. Fig 3.18 shows the voltage-resistance characteristic of a typical semiconductor diode.

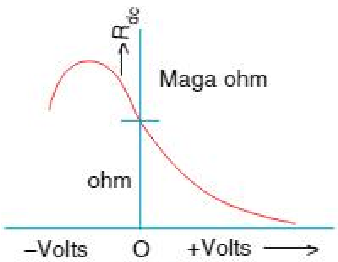


Fig 3.18

The forward and reverse resistance curves are drawn to different voltage and resistance scales. As the forward voltage is increased, the resistance falls to a low value, usually 100 ohms or less. Decreasing the forward voltage increases the resistance and near zero voltage the resistance is of the order of hundreds or thousands of ohms. As the reverse voltage is increased, the resistance passes through a peak in the order of mega - ohms and then decreases. The ratio of reverse to forward resistance of a germanium diode is 4000 : 1.

(ii) Dynamic or AC resistance

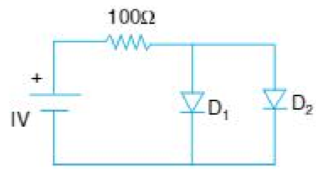
Small a.c. current may be superimposed over d.c. in a diode circuit. The resistance offered by the diode to this a.c. signal is called its dynamic or a.c. resistance. It is defined as the reciprocal of the slope of the current-voltage characteristics

i.e., $R_{ac} = \dfrac{dV}{dI} = \dfrac{\text{Change in voltage}}{\text{Resulting change in current}}$

It is not a constant quantity but depends upon the operating voltage.

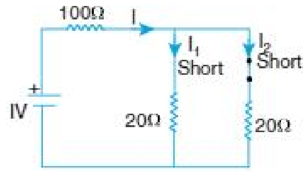
Example-3.4

Considering the circuit and data given in the diagram, calculate the currents flowing in the diodes D_1 and D_2 with linear characteristics. Forward resistance of D_1 and D_2 is $20\,\Omega$.



Solution :

Since the positive of battery is connected to P-type, both diodes D_1 and D_2 are forward biased. Hence they may be replaced by short (closed) switch associated with their forward resistances as shown in Fig.



The resistance of 20Ω and 20Ω in parallel

$$\frac{1}{R} = \frac{1}{20} + \frac{1}{20} = \frac{2}{20} \text{ (or) } R = \frac{20}{2} = 10\Omega$$

Therefore, total current I in the circuit

$$I = \frac{1}{100+10} = \frac{1}{110} \text{ amp and}$$

$$I_1 = I_2 = \frac{1}{2} \times \frac{1}{110} = \frac{1}{220} \text{ amp}$$

3.15 ZENER AND AVALANCHE BREAKDOWN

With reverse bias voltages, the following two mechanisms are responsible for breakdown in a P-N junction diode:

(a) Avalanche breakdown

In this mechanism, the minority carriers (electrons in P-region and holes in N-region) gain large kinetic energy from the applied reverse voltage to collide with valence electrons of the atom fixed in the crystal and liberate them. Thus, in this process, covalent bonds are broken and pairs of electrons and holes are generated. The new carriers so produced, in turn, generate additional carriers and thus the number of free electrons and holes goes on increasing. This cumulative phenomenon is called avalanche multiplication and produces a sharp increase in the reverse current. The diode is then said to be in the avalanche breakdown region. The magnitude of the avalanche breakdown voltage increases with increase in temperature. As the temperature increases, the amplitude of vibration of crystal atoms increases which increases the probability of collision of the carriers with the crystal atoms.

Consequently, there will be loss of energy of the carriers and, therefore, the applied reverse voltage should be increased to make up the loss of energy and to start avalanche process. This breakdown occurs in highly doped diodes at high reverse bias.

(b) Zener breakdown

Zener breakdown occurs in junctions which are heavily doped and have a very narrow depletion region, of the order of only 150-200 $\mathring{A}$. Thus, there exists a high electric field, of the order of 10^8 V/m, across the junction. This field is strong enough to break or rupture the covalent bonds thereby generating electron-hole pairs. Even a small further increase in reverse voltage is capable of producing large number of current carriers. Zener breakdown is, thus, a 'field emission' phenomenon, the strong electric field in the junction region pulling carriers from their atoms. An increase in temperature increases the energies of the valence electrons, and hence makes it easier for these electrons to escape from the covalent bonds. Therefore, less applied voltage is, required to pull these electrons from their positions in the crystal lattice and convert them into conduction electrons. The Zener breakdown voltage, therefore, decreases with an increase in temperature.

3.16 THE ZENER DIODE

A properly doped p-n junction diode which has sharp breakdown voltage when operated in the reverse conditions is called 'zener diode'. This diode is operated in the reverse break down region without getting damaged. Silicon is preferred over germanium while constructing zener diodes due to its high thermal stability and current compatibility. Zener diodes primarily depend for their working on Zener effect. For a heavily doped diode, the depletion layer is very narrow. When the reverse bias across the diode is increased, breaking of covalent bonds takes place by the intense electric field $(\approx 3\times10^7\ \text{V/m})$ set up across the depletion layer. It produces a large number of electron-hole pairs resulting in a sharp increase in reverse current.

(a) Current-voltage Characteristics

Typical current-voltage characteristics for a Zener diode are shown in Fig 3.19. It may be seen from the characteristics that when forward biased, its characteristics are just that of an ordinary semi-conductor diode. When reverse biased, a small reverse saturation current flows through it which remains approximately constant until a certain critical voltage, called breakdown voltage, is reached. Beyond this voltage, the reverse current I_R increases sharply to a high value. This break down voltage V_Z is called the Zener voltage and the reverse current as Zener current. The Zener voltage depends upon the amount of doping. A heavily doped diode has a narrow depletion layer and consequently a lower breakdown or Zener voltage.

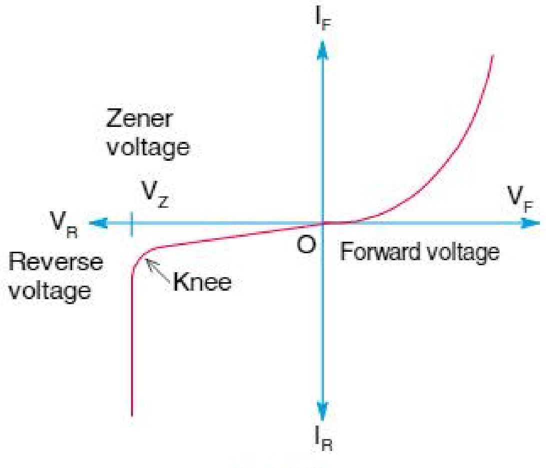


Fig 3.19

On the other hand, if the diode is lightly doped, the breakdown of the junction will occur at higher voltage. For breakdown voltages below 6 volt, the Zener effect is predomiment. For higher voltages, the avalanche multiplication is effective. Between 5 and 8 volts both effects are present. But, ordinarily, all diodes which are operated in the breakdown region of their reverse characteristics are called zener diodes.

The circuit symbol for a Zener diode is shown in Fig 3.20. It is similar to that of an ordinary diode except that the bar is turned into Z-shape.

Fig 3.20

(b) Uses of Zener diode

When a Zener diode is operated in the breakdown region, the voltage across the diode remains almost constant (equal to V_Z) for the large change of the reverse current. The voltage across a Zener diode thus serves as a reference and the diode is used as a voltage reference device for stabilizing a voltage at a predetermined value. Due to this property, Zener diodes find numerous applications in transistor circuitry. Most important of them are:

(i) as voltage regulators

(ii) as a fixed reference voltage in a network for biasing and comparison

(iii) for calibrating voltmeters

(iv) for avoiding damage by accidental application of excess voltage.

3.17 ZENER DIODE AS A VOLTAGE REGULATOR

Circuit Diagram : A simple Zener diode voltage stabilizer circuit is shown in Fig 3.21. This circuit is used to maintain a constant voltage across a load resistor R_L in spite of variations in either the supply voltage or the load current (due to a change in the load resistance) or both. In the circuit, the input is a d.c. voltage whose voltage variations are to be regulated. The P-junction of zener diode is connected to the negative of the input voltage and N-junction to the positive. The value of the series resistor R_S is so chosen that initially the diode operates in the breakdown region.

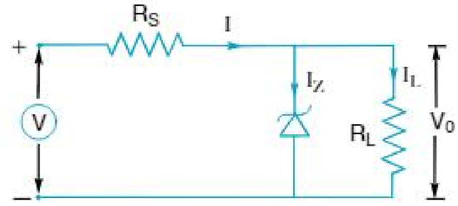


Fig 3.21

Operation

Let I be the current drawn from the supply source, I_Z the current through the Zener diode and I_L across the load resistance R_L. Then from Kirchoff's laws

$I = I_Z + I_L$ .....(1)

and $V_0 = V - IR_S$ .....(2)

and $V_0 = I_L R_L$ .....(3)

Case 1 :

When supply voltage V remains constant and load resistance R_L varies:

Since the output voltage V_0 tends to remain constant, then eq. (2) gives $\delta I=0$ (because V and R_S are constant) Then eq. (1) gives $\delta I = \delta I_Z + \delta I_L = 0$ (or) $\delta I_Z = -\delta I_L$.

Thus, if the load resistance increases, when the supply voltage is fixed, the load current I_L decreases and the Zener diode current I_Z increases by and equal amount. Thus the Voltage V_0 across the load will tend to remain constant.

Case 2 :

When load resistance R_L remains constant and supply voltage V varies :

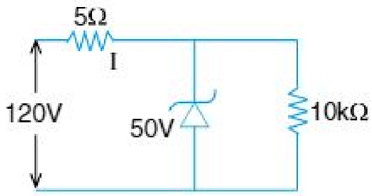
Since V_0 tends to remain constant, we get from eq. (2) $\delta V = R_S.\delta I$ Also eq.(3) gives $\delta I_L = 0$ (because R_L is constant) Therefore, eq. (1), gives $\delta I = \delta I_Z$.

Thus when the supply voltage varies but the load resistance remains constant, the total current I and the Zener current I_Z change equally to keep the load current I_L constant.

Thus if total current I decreases by δI, the diode current I_Z also decreases by the same amount, so the load current I_L remains constant and the voltage V_0 across the load will tend to remain constant.

Example-3.5

Calculate the voltage drop across 5Ω resistance and current passing through the zener diode for the circuit given below :



Solution :

Since the voltage across the zener diode, $V_z = 50$volt.

$\therefore$ Voltage drop across 5Ω resistor $= 120 - 50 = 70$ volt

$\therefore$ Current through 5Ω resistor $I = \frac{70}{5} = 14$amp

Current through load resistor of $10k\Omega$

$$I_L = \frac{V_z}{R_L} = \frac{50}{10k\Omega} = 5\times10^{-3}\text{amp.}$$

Therefore, current through the Zener diode

$$I_z = I - I_L = 14 - 5\times10^{-3}\text{amp.} = 13.995 \text{ amp.}$$

3.18 JUNCTION DIODE AS RECTIFIER

Rectification is the process of converting an alternating current into a direct current. The device used for this purpose is called rectifier. Generally an electrical device which offers a low resistance to the current in one direction but a high resistance to the current in opposite direction is called rectifier.

Junction diode can be used as a rectifier. In a half wave rectifier, a single diode is used and two diodes are used in a full wave rectifier.

3.19.1 HALF WAVE RECTIFIER

A half wave rectifier can be constructed with a single diode 'D' as shown in Fig 3.22(a). A half wave rectifier rectifies only one half cycle of the ac input. The ac supply to be rectified is applied in series with the diode and load resistance 'R_L'. The dc output is obtained across the load resistance R_L. The ac voltage across the secondary winding 'MN' changes polarity after every half cycle. During the positive half cycle, the diode is forward biased and current flows through the diode. During the negative half cycle, the diode is reverse biased and current does not flow through it. Thus current flows through the diode during positive half cycles only. Current flows in R_L only in one direction. So a half wave rectifier gives discontinues and pulsative DC output as shown in Fig 3.22(b). The number of DC pulses per second is equal to the frequency of the applied AC.

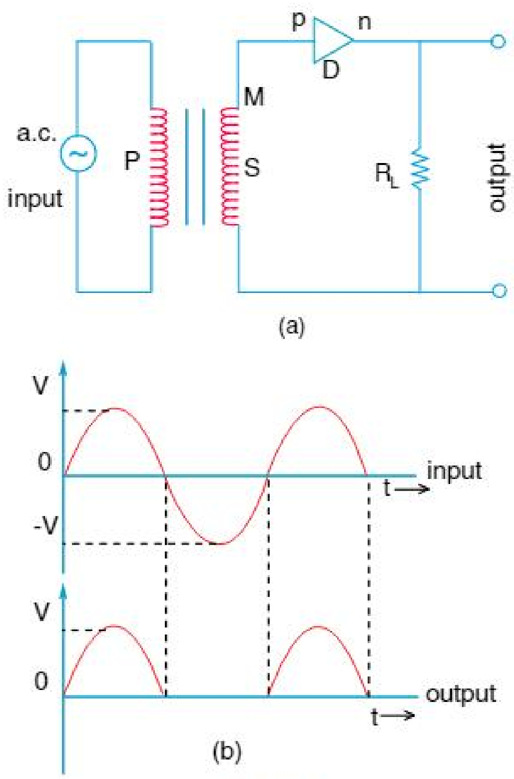


Fig 3.22

Efficiency of half wave Rectifier

Efficiency of a rectifier is the ratio of dc power output to the ac power input.

$$\text{Efficiency of rectifier}(\eta)=\frac{\text{dc power output}}{\text{ac power input}}=\frac{P_{dc}}{P_{ac}}$$

$$\text{For half wave rectifier }(\eta)=\frac{0.406\,R_L}{R_F+R_L}$$

Here R_F is forward resistance of diode and R_L is load resistance

In a half wave rectifier, a maximum of 40.6% of ac power is converted to dc power.

3.19.2 FULL WAVE RECTIFIER

A rectifier which rectifies both halves of the ac input is called full wave rectifier. Full wave rectification can be done using two junction diodes. The circuit uses two diodes D_1 and D_2 and a transformer known as centre tap transformer as shown in Fig 3.23(a).

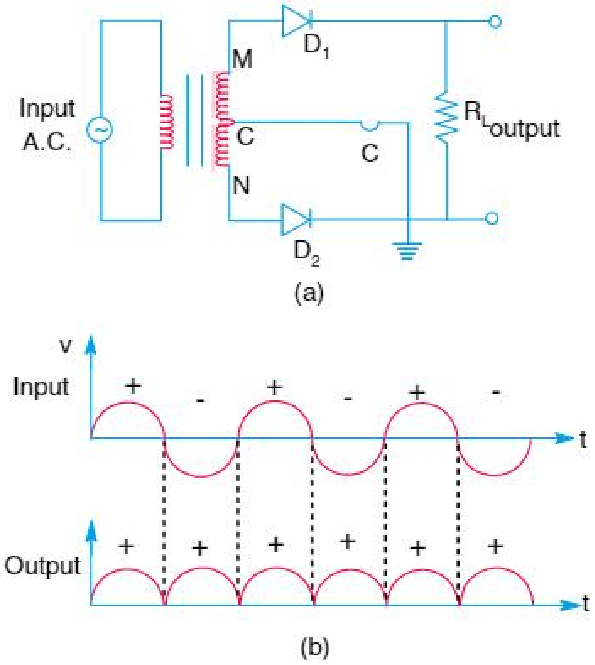


Fig 3.23

In centre tap transformer, the secondary is wound into two equal parts. Voltage at M (input of diode D_1) and N (input of diode D_2) with respect to centre tap C are out of phase with each other. Suppose the input voltage to M at any instant is positive, it is clear that, at that instant, voltage at N being out of phase will be negative and vice versa. During the positive half cycles of ac input, diode D_1 is forward biased and diode D_2 is reverse biased and D_2 will not conduct and the current flows through the load resistance R_L due to D_1. Similarly during negative half cycles of ac input, diode D_2 is forward biased and D_1 is reverse biased and will not conduct and the current flows through the load resistance R_L due to D_2. Hence, current flows through the load resistance during both the half cycles and in the same direction. Thus, using full wave rectifier, the output is continuous but pulsating as shown in Fig 3.23(b). The pulsating current can be made smooth using filter circuits. The number of dc pulses per second of the output is equal to twice the frequency of the ac input.

Efficiency of full wave Rectifier

Efficiency of a rectifier is the ratio of dc power output to the ac power input.

Efficiency of the rectifier (η)

$$=\frac{\text{dc power output}}{\text{ac power input}}=\frac{P_{dc}}{P_{ac}}$$

$$\text{For full wave rectifier }(\eta)=\frac{0.812\,R_L}{R_F+R_L}$$

Here R_F is diode forward resistance and R_L is load resistance

In a full wave rectifier, a maximum of 81.2% of ac power is converted to dc power.

3.20 ADVANTAGES OF SEMICONDUCTOR DIODES

1. p-n junction diodes are minute (very small in size). Therefore, they are used in micro circuits.
2. As they are solid state devices, no evacuation is needed like vacuum tubes.
3. Their efficiency is more than that of vacuum tubes.
4. They are also quite strong and sturdy.
5. Usually, they have long life

6. There is no filament heating and consequent power loss.
7. These can be prepared to function over wide voltage ranges and to give very large rectified currents.

3.21 TRANSISTORS

The junction transistor was invented in 1948 by J. Bardeen, W.H. Brattain and W. Shockley. A junction diode can be used as a rectifier. A device which can magnify a.c. signals is called amplifier. The junction diode is not suitable for this purpose. Some other device must be used and such a semiconductor device used for amplifying a.c signals is called transistor. The transistor may be supposed to be made up of two junction diodes with their similar sections in contact. If the n- sections of two diodes are in contact, a p-n-p transistor is formed. If the p- sections are in contact a n - p- n transistor is formed. So a transistor is a three section semiconductor. Thus the extreme sections have the same type of majority charge carriers while the middle section has majority charge carriers of the opposite sign. The three sections are respectively called emitter (E), base (B) and collector (C).

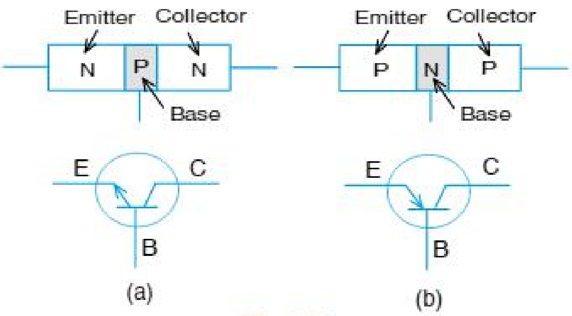


Fig 3.24

Emitter : The section at one end of transistor is called emitter. It is a heavily doped region and is of intermediate size, so that large number of charge carriers (holes or electrons) can be injected into base.

Base: The middle section of transistor is called 'base'. This is lightly doped and very thin and allows most of the charge carriers injected into it, to flow into collector without getting neutralized.

Collector: The section at the other end is called collector and is moderately doped. Physically, it is the largest of the three regions and collects charge carries from the base. The junction between emitter and base is called emitter junction and the junction between base and collector is called collector junction.

3.22 TRANSISTOR CONFIGURATIONS

In electronic circuits transistors are connected in three ways. They are

1) Common base configuration
2) Common emitter configuration
3) Common collector configuration

3.22.1 COMMON BASE CONFIGURATION

In this configuration base is common to both input and output. Base terminal is earthed and input is given across base - emitter and output is taken across base - collector as shown in Fig 3.25. This mode is called grounded base configuration.

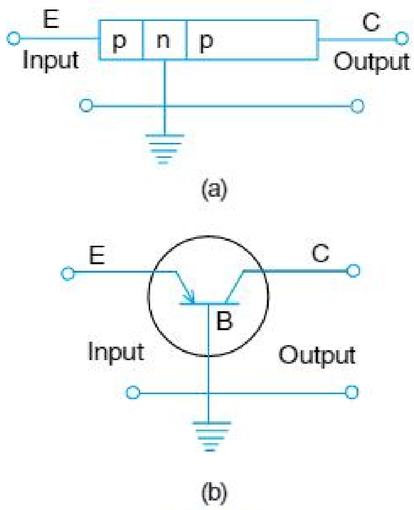


Fig 3.25

Common Base (CB) circuit

3.22.2 COMMON EMITTER CONFIGURATION

In this configuration emitter is common to both input and output. The emitter is earthed and input is given across base - emitter and output is taken across collector - emitter as shown in Fig 3.26. This mode is called grounded emitter configuration.

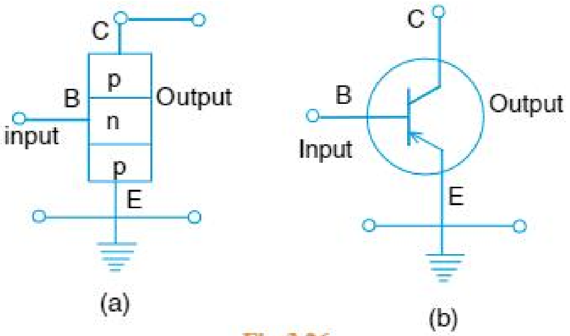


Fig 3.26

Common Emitter (CE) circuit

3.22.3 COMMON COLLECTOR CONFIGURATION

In this configuration collector is common to both input and output. The collector is earthed and input is given across base - collector and output is taken across emitter -collector as shown in Fig 3.27. This mode is called grounded collector configuration.

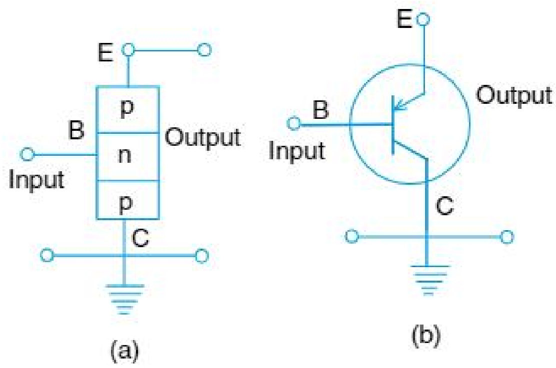


Fig 3.27

Common Collector (CC) circuit

It may be noted that in all configuration, the emitter-base junction is always forward biased and collector-base junction is reverse biased. Among all the modes, CE mode has more advantages.

3.23 WORKING OF P-N-P TRANSISTOR IN CB MODE

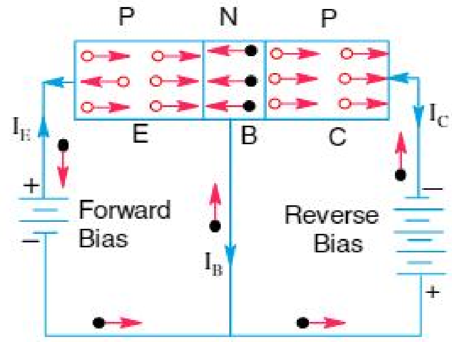


Fig 3.28

The given Fig 3.28 shows the p-n-p transistor with batteries connected in proper way for common base configuration. The emitter junction is forward biased with positive end of the battery to the emitter and negative to the base. The collector junction is reverse biased with collector negative with reference to the base.

a) The holes in the left p - region (emitter) are repelled by the positive polarity and crossing the emitter - base junction (called emitter junction) enter the base region. These constitute current through the emitter (I_E). As base is only lightly doped, majority of the holes drift across the base without combining with more electrons there.

b) Except few that are lost by recombination constituting base current (I_B), majority of the holes penetrate through the right junction between base and collector called collector junction and enter the right p -region.

c) The collector terminal at the right end rapidly sweeps the holes that enter the collector region causing a large current.

In emitter covalent bond breaks down, liberating electron that enters the positive terminal of the emitter battery and the new hole created then moves towards the collector. As each hole reaches the collector electrode, an electron is emitted from a negative battery terminal of collector and neutralizes the hole. This constitute collector current (I_C).

A continuous supply of holes injected into the emitter junction flows across the base region to the collector junction where they are collected by the negative collector electrode. Thus current conduction within the p-n-p transistor takes place by hole conduction . Therefore the majority carriers are holes in a p-n-p transistor. In the external circuit only electrons carry out the conduction.

The relation between the currents is $I_E = I_B + I_C$.

The practical value of current that reaches the collector ranges from 95 to 99 percent of current leaving the emitter. The current gain (α) is defined as the ratio of small change in collector current to small change in emitter current.

i.e., $\alpha = \dfrac{\Delta I_C}{\Delta I_E}$, α is less than unity.

3.24 WORKING OF N-P-N TRANSISTOR IN CB MODE

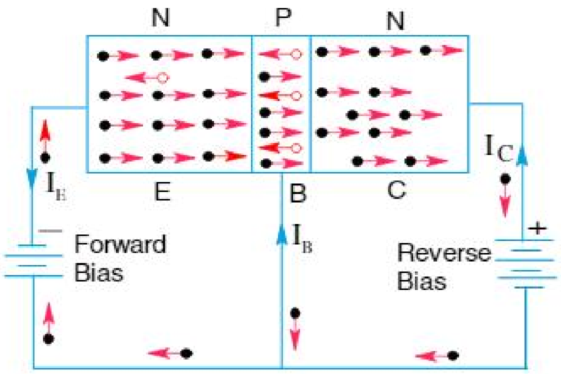


Fig 3.29

Fig 3.29 shows the npn transistor with batteries connected in proper way for common base configuration. The emitter junction is forward biased with negative end of the battery connected to the emitter and positive to the base. The collector junction is reverse biased with collector positive with reference to the base.

a) The electrons in the left n - region (emitter) are repelled by the negative polarity and crossing the emitter - base junction (called emitter junction) enter the base region. These constitute current through the emitter (I_E). As base is lightly doped, majority of the electrons drift across the base without combining with holes there.

b) Except few that are lost by recombination constituting base current (I_B), majority of the electrons penetrate through the right junction between base and collector called collector junction and enter the right n -region.

c) The collector terminal at the right end rapidly sweeps the electrons that enter the collector region causing a large current.

These electrons liberated in emitter move towards the collector and are drawn by the positive electrode of the battery at collector and finally reach the emitter terminal. Thus the current flows in the circuit continuously. In the external circuit also electrons carry out conduction.

The relation between emitter, base and collector currents is $I_E = I_B + I_C$.

Current gain $\alpha = \dfrac{\Delta I_C}{\Delta I_E}$

n p n transistors are faster in action than p n p transistors because mobility of electrons is more than that of holes.

Example-3.6

Current amplification factor of a common base configuration is 0.88. Find the value of base current when the emitter current is 1 mA.

Solution :

In a common-base arrangement, the current amplification factor.

$$\alpha = \left(\frac{\delta I_C}{\delta I_E}\right)_{V_{CB}} = \frac{I_C}{I_E}$$

(if only d.c. values are considered)

Given $\alpha = 0.88, I_E = 1\text{mA}$.

$\therefore$ Collector current

$I_C = \alpha I_E = 0.88 \times 1 = 0.88\text{mA}$.

Now since $I_E = I_B + I_C$

$\therefore$ Base current $I_B = I_E - I_C$

$= 1 - 0.88$

$= 0.12$ mA.

3.25 BASIC TRANSISTOR CIRCUIT CONFIGURATIONS AND TRANSISTOR CHARACTERISTICS

In a transistor, only three terminals are available, viz., Emitter (E), Base (B) and Collector (C). Therefore, in a circuit the input/output connections have to be such that one of these (E, B or C) is common to both the input and the output. Accordingly, the transistor can be connected in either of the following three configurations:

Common Emitter (CE), Common Base (CB), Common Collector (CC)

The transistor is most widely used in the CE configuration and we shall restrict our discussion to only this configuration. Since more commonly used transistors are n-p-n Si transistors, we shall confine our discussion to such transistors only. With p-n-p transistors the polarities of the external power supplies are to be inverted.

3.25.1 COMMON EMITTER CHARACTERISTICS

These are empirical graphs which show the relations between currents and voltages in different modes and enable us to decide about the choice of the best parameters for various electronic circuit components. Any variation in the voltage on the input and output sides results in a change in the input and output currents respectively.

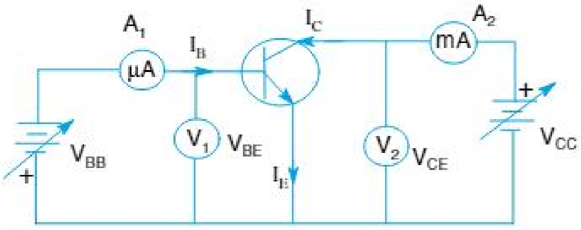


Fig 3.30

A n-p-n transistor is connected in the common emitter configuration as shown in the circuit (Fig 3.30).

To activate the transistor, the emitter junction is forward biased and collector junction is reverse biased. This is achieved by giving negative polarity to the emitter (n - type) and positive polarity to the base (p - type) through a variable source V_{BE}. This is called the input circuit. It is forward biased. To measure base current (I_b) a micro ammeter A_1 and to measure the potential difference V_{BE} between base and emitter, a voltmeter V_1 are connected.

The collector - base junction is reverse biased by giving positive polarity to collector (n - type) and negative to emitter through 'V_{CC}' . This is called output circuit, and is reverse biased. To measure collector current (I_C), a milliammeter A_2 and to measure potential difference V_{CE} across collector and emitter, a voltmeter 'V_2' are connected.

i) Input characteristics

The graph drawn between base current [I_b] on y - axis and base emitter voltage [V_{BE}] on x - axis, keeping the collector voltage [V_{CE}] constant, is called input characteristics (Fig 3.31).

The characteristics are similar to that of a forward biased diode. The dynamic resistance, or

input resistance, $R_i = \dfrac{\Delta V_{BE}}{\Delta I_B}$

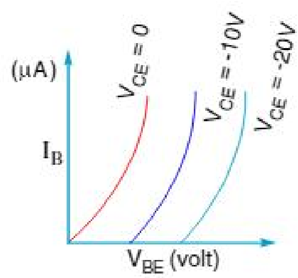


Fig 3.31

ii) Output characteristics

The graph drawn between output current [I_C] on y -axis and output voltage [V_{CE}], keeping the base current constant is called output characteristics (Fig 3.32).

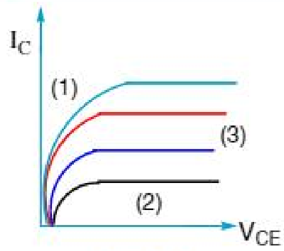


Fig 3.32

As the V_{CE} increases, I_C increases to some extent and remains constant. This region in which 'IC' increases sharply is called the 'active region'. When the transistor is operated in this region, it amplifies the input signals almost faithfully.

The ratio of change in collector emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant base current (I_B) is called output resistance. $R_0 = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_b}$

We define three different regions of operations of a transistor namely.

1) Saturation region: In this region the collector current becomes almost independent of the base current. This happens when both junctions are forward biased in graph (1).

2) Cut off region: In this region the collector current is almost zero. This happens when both the junctions are reverse biased in graph (2).

3) Active region: In this region collector current (I_C) is many times greater than base current (I_B) in graph (3).

A small change in input current (ΔI_B) produces a large change in the output current (ΔI_C). This happens when emitter junction is forward biased and collector junction is reverse biased.

The transistor works as an amplifier when operated in the active region.

When the transistor is used in the cut off (or) saturation state, it acts as a switch.

3.26 CURRENT GAIN [β] IN CE MODE

Current gain in CE mode is defined as the ratio of small change in the collector current correspond-ing to a small change in the base current, keeping the collector voltage constant.

$$\beta = \frac{\text{change in collector current}}{\text{change in base current}} = \frac{\Delta I_C}{\Delta I_B}$$

Since the input I_B is measured in μA and output I_C in mA, the common emitter configuration exhibits a current amplification. i.e., $\beta > 1$

This is also known as small signal current gain and its value is very large.

If we simply find the ratio of I_C and I_B we get what is called dc β of the transistor. Hence, $\beta_{dc} = \frac{I_C}{I_B}$.

As I_C increases with I_B almost linearly and $I_C = 0$ when $I_B = 0$, the values of both β_{dc} and β_{ac} are nearly equal. So, for calculations β_{dc} can be used. Both β_{ac} and β_{dc} vary with V_{CE} and I_B (or I_C) slightly.

Relation between α & β

$$\alpha = \text{ac current gain in C.B.} = \frac{\Delta I_C}{\Delta I_E}$$

$$\beta = \text{ac current gain in C.E.} = \frac{\Delta I_C}{\Delta I_B}$$

Since

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{\Delta I_C}{\Delta I_E - \Delta I_C} = \frac{\frac{\Delta I_C}{\Delta I_E}}{1 - \frac{\Delta I_C}{\Delta I_E}} = \frac{\alpha}{1-\alpha}$$

$$\text{(or) } \beta = \frac{\alpha}{1-\alpha}$$

α is about 0.95 to 0.99 and β is about 20 to 100

Example-3.7

For a transistor $\beta = 40$ and $I_B = 25\mu A$. Find the value of I_E.

Solution :

$$\beta = \left(\frac{\delta I_C}{\delta I_B}\right)_{V_{CE}} \quad \text{(If only d.c. values are considered)}$$

$$\therefore \quad I_C = \beta I_B = 40 \times 25 \times 10^{-6} = 1000 \times 10^{-6} \text{ A}$$

$$\therefore \quad I_E = I_B + I_C = (25 \times 10^{-6} + 1000 \times 10^{-6})\text{amp}$$

$$= 1025\mu A = 1.025 mA$$

Example-3.8

The constant α of a transistor is 0.9. What would be the change in the collector current corresponding to a change of 4 mA in the base current in a common emitter arrangement ?

Solution :

The current gain α in common base arrangement is related to the current gain β in common emitter arrangement by the relation,

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

Given, $\alpha = 0.9$,

$$\therefore \quad \beta = \frac{0.9}{1-0.9} = 9$$

But $\beta = \left(\frac{\delta I_C}{\delta I_B}\right)_{V_{CE}}$

Hence change in collector current

$\delta I_C = \beta.\delta I_B = 9 \times 4\text{mA} = 36 \text{ mA}.$

3.27 TRANSISTOR AS A DEVICE

The transistor can be used as a device for application depending on the configuration used (namely CB, CC and CE), the biasing of the E-B and B-C junction and the operation region namely cutoff, active region and saturation. As mentioned earlier we have confined only to the CE configuration and will be concentrating on the biasing and the operation region to understand the working of a device.

When the transistor is used in the cutoff or saturation state it acts as a switch. On the other hand for using the transistor as an amplifier, it has to operate in the active region.

3.28 TRANSISTOR AS AN AMPLIFIER (CE CONFIGURATION)

The process of raising the strength of a weak input signal to a strong output signal is called 'amplification'.

The power of the radio waves coming from the radio station are very weak (of the order of milliwatt). This will be picked up by the receiving antenna and will be fed to the amplifier, which amplifies it to several watts in order to produce adequate loud speaker response in the radio receiver.

The sound output from a microphone is a fraction of a watt and must be amplified hundreds of times to make it possible to fill a stadium with sound.

Amplifier has wide applications in industries, T.V, radio and communication systems.

The device which increases the weak input signal into strong output signal is called an amplifier.

Amplifiers are of two types

1) Power amplifiers
2) Voltage amplifiers

Amplifier which is used to raise the power level is known as "Power amplifier."

The amplifier which is used to raise voltage level is known as voltage amplifier.

3.29 FUNCTIONING OF COMMON EMITTER AMPLIFIER WITH BLOCK DIAGRAMS

The most commonly used circuit for amplifier is common emitter circuit.

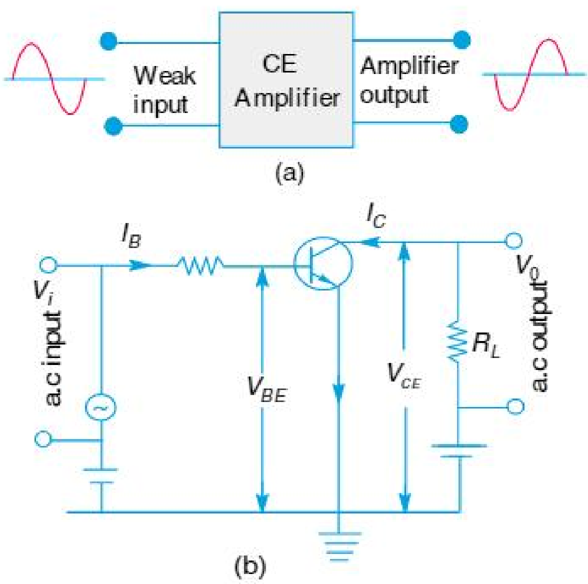


Fig 3.33

As shown in Fig 3.33, the input signal to be amplified is connected in series with the biasing battery (V_{BE}). A load resistance (R_L) is connected in the collector circuit. As the potential difference (V_{BE}) changes with time due to input signal, base current (I_B) changes. Collector current (I_C) and output voltage (V_{CE}) change accordingly.

i) **Voltage gain :** It is defined as the ratio of change in output voltage to the change in input voltage.

$$A_v = \frac{\Delta V_{CE}}{\Delta V_{BE}} = \frac{R_L(\Delta I_c)}{R_i(\Delta I_b)} = \beta\frac{R_L}{R_i}$$

Negative sign indicates input and output voltages are in opposite phase.

ii) **Power gain :** It is defined as the ratio of output power to the input power.

$$\text{power gain} = \frac{\text{output power}}{\text{input power}}$$

$$= \left[\frac{I_{out}}{I_{in}}\right] \times \left[\frac{V_{out}}{V_{in}}\right]$$

Power gain=A_P=current gain × voltage gain

Example-3.9

A voltage amplifier operated from a 12 volt battery has a collector load $6k\Omega$. Calculate the maximum collector current in the circuit.

Solution :

Maximum collector current flows when whole battery voltage is dropped across collector load. Thus max. collector current

$$= \frac{\text{Battery voltage}}{\text{Collector load}} = \frac{12\text{ volt}}{6k\Omega} = 2\text{mA}$$

Example-3.10

In a single state transistor amplifier, when the signal changes by 0.02 V, the base current change by $10\mu A$ and collector current by 1mA. If collector load $R_C = 2k\Omega$ and $R_L = 10k\Omega$, Calculate : (i) Current Gain (ii) Input impedance, (iii) Effective a.c. load, (iv) Voltage gain and (v) Power gain.

Solution :

(i) Current Gain $\beta = \frac{\delta i_c}{\delta i_b} = \frac{1mA}{10\mu A} = 100$

(ii) Input impedance

$$R_i = \frac{\delta V_{BE}}{\delta i_b} = \frac{0.02}{10\mu A} = 2000\Omega = 2k\Omega$$

(iii) Effective (a.c) load

$$R_{AC} = R_C \parallel R_L = \frac{2\times 10}{2+10} = 1.66k\Omega$$

(iv) Voltage gain $A_v = \beta \times \frac{R_{AC}}{R_{in}} = \frac{100\times 1.66}{2} = 83$

(v) Power gain, Ap = Current gain × Voltage gain

$= 100 \times 83 = 8300$

3.30 CONCEPT OF FEEDBACK

When a part of the output voltage (or current) of an amplifier is injected back into the input circuit, feedback is said to exist. If the voltage feedback is in phase with the applied voltage, the feedback is said to be positive or regenerative; and if the voltage feedback is in opposite phase to the incoming signal, the feedback is said to be negative or degenerative. The voltage feedback from the output of an amplifier into the input may be proportional to either the voltage across the output load or the current through the load. The first type of feedback is called the voltage feedback and the second type the current feedback. The voltage feedback may be introduced into the input in series or in parallel with the incoming signal.

3.31 BASICPRINCIPLES OF FEEDBACK

Fig 3.34 illustrates the principles of feedback. The gain of the amplifier without feedback is A. If a signal e_S is applied at the input terminals of the amplifier, then let the output voltage be e_0. If a fraction β of this output voltage is fedback into the input in phase with the applied signal, then the actual input voltage of the amplifier, $e_g = e_s + \beta e_0$

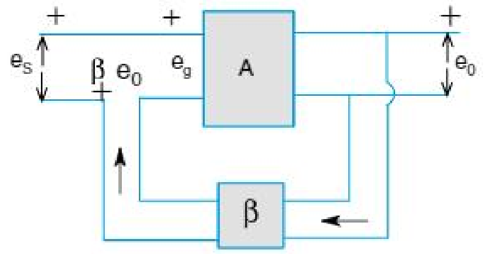


Fig 3.34

This total input voltage multiplied by the gain A of the amplifier must be equal to the output voltage i.e., $e_0 = Ae_g$

$$\text{(or)} \quad e_0 = A\left(e_s + \beta e_0\right) = Ae_s + A\beta e_0$$

$$\text{(or)}\ e_0 - A\beta e_0 = Ae_s\ \text{(or)}\ e_0(1-\beta A) = Ae_s$$

from which the gain A_f with feedback is,

$$A_f = \frac{e_0}{e_s} = \frac{A}{1-\beta A} \qquad ....(1)$$

The positive feedback thus, increases the gain of the amplifier. If too much positive feedback is applied so that $1-\beta A = 0$, the gain of the amplifier becomes infinite. In this case the amplifier becomes unstable and the output can be obtained with no external input signal, i.e., the amplifier becomes an oscillator. In the case of negative feedback the voltage feedback βe_0 is in opposite phase to the applied voltage e_S, so that gain with negative feedback becomes,

$$A_f = \frac{e_0}{e_s} = \frac{A}{1+\beta A} \qquad ....(2)$$

The application of negative feedback, therefore, decreases the gain of the amplifier A to $\dfrac{A}{A+\beta A}$ but at the same time increases stability of the amplifier, reduces phase distortion and noise and extends the range of uniform amplification. Negative feedback is, therefore, frequently employed in amplifiers. The term β is called feedback ratio whereas 'βA' is called feedback factor. The amplifier gains with feedback loop. Thus, closed loop gain is the over all gain after feed back. The term βA is also called open loop gain. Since negative feedback reduces the amplifier gain, it is called degenerative feedback.

Example-3.11

In a negative feedback amplifier, the gain without feedback is 100, feed back ratio is 1/25 and input voltage is 50 mV. Calculate

i) gain with feedback

ii) feedback factor

iii) output voltage

iv) feedback voltage

v) new input voltage so that output voltage with feed-back equals the output voltage without feedback

Solution :

(i) Gain with feedback

$$A_f = \frac{A}{1+\beta A} = \frac{100}{1+1/25\times 100} = 20$$

(ii) Feedback factor $\beta A = \frac{1}{25}\times 100 = 4$

(iii) Output voltage $V_0^{'} = A_f V_i = 20\times 50\text{mV} = 1\text{volt}$

(iv) Feedback voltage $\beta V_0^{'} = \frac{1}{25}\times 1 = 0.04\text{volt}$

(v) New increased input voltage $V_i^{'} = V_i(1+\beta A)$

$$= 50\left(1+\frac{1}{25}\times 100\right) = 250\text{mV}$$

3.32 OSCILLATORS

An oscillator is an electronic circuit associated with a transistor that provides an alternating output while deriving its input from a direct current source. Thus it converts d.c. into a.c. and, therefore, also called an inverter.

An oscillator generates alternating voltages or currents over a wide frequency range, from a few cycle per hour to millions of cycles per second. The function of an oscillator is similar to that of an amplifier. However, there is a basic difference between an amplifier and an oscillator. An amplifier produces an output signal whose waveform is similar to the input signal but whose power level is generally high. This additional power is supplied by the external d.c. source. Thus in an amplifier, the frequency, waveform and magnitude of the a.c power generated is controlled by an a.c. input signal. If there is no input signal, there is no output signal and hence there is no energy conversion. On the other hand, in an oscillator, the frequency, waveform and magnitude of the a.c. power generated are controlled by the circuit itself and it does not require an external signal either to start or maintain energy conversion process. Thus an oscillator is an amplifier which provides its own input signal. It keeps producing an output signal so long as the d.c. power source is connected, as shown in Fig 3.35(b).

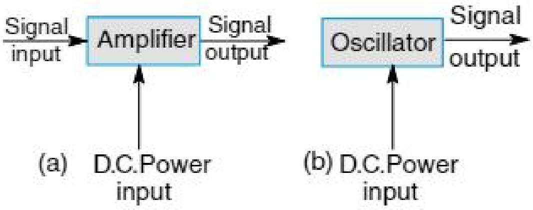


Fig 3.35

3.33 ESSENTIALS OF TRANSISTOR OSCILLATOR

(i) Tank Circuit : A simple circuit consisting of an inductance L and a capacitor C in parallel constitutes a tank circuit, in which magnetic energy oscillates with finite frequency. The oscillatory process goes on repeating itself and an oscillatory current is produced in the L-C circuit.

The values of L and C components determine the frequency of oscillation of the circuit. The frequency of oscillation $f = \dfrac{1}{2\pi\sqrt{LC}}$

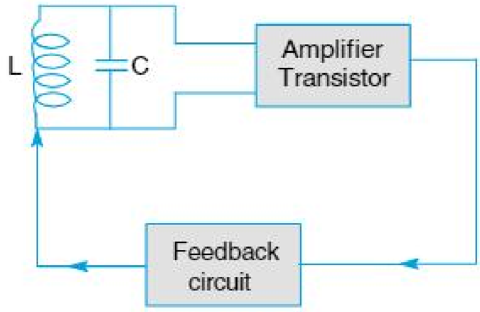


Fig 3.36

(ii) Transistor Amplifier : It changes the d.c. power received from the capacitor into a.c. power and supplies output as well as to the tank circuit to meet the losses.

(iii) Feedback circuit : It provides a positive feedback i.e., it supplies a part of collector energy to the tank circuit in correct phase to maintain the oscillations there.

3.34 TRANSISTOR AS A SWITCH

We shall try to understand the operation of the transistor as a switch by analysing the behaviour of the base-biased transistor in CE configuration as shown in Fig 3.37.

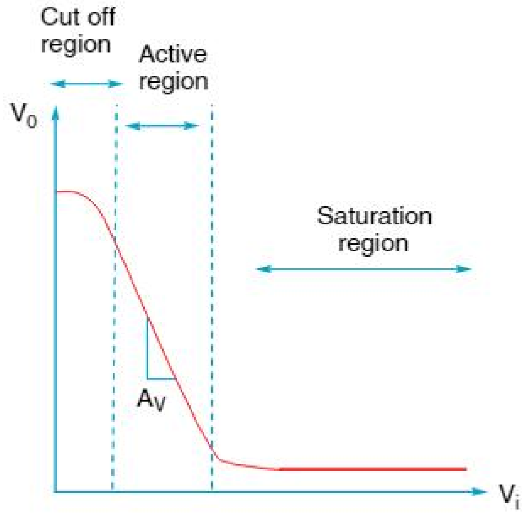


Fig 3.37

Applying Kirchhoffs voltage rule to the input and output sides of this circuit, we get

$$V_{BB} = I_B R_B + V_{BE} \text{ and}$$

$$V_{CE} = V_{CC} - I_C R_C.$$

We shall treat V_{BB} as the dc input voltage V_i and V_{CE} as the dc output voltage V_0. So, we have

$$V_i = I_B R_B + V_{BE} \text{ and}$$

$$V_o = V_{CC} - I_C R_C.$$

Let us see how V_0 changes as V_i increases from zero onwards. In the case of Si transistor, as long as input V_i is less than 0.6V, the transistor will be in cut off state and current I_C will be zero.

Hence $V_o = V_{CC}$

When V_i becomes greater than 0.6V the transistor is in active state with some current I_C in the output path and the output V0 decrease as the term $I_C R_C$ increases. With increase of V_i, I_C increases almost linearly and so V_0 decreases linearly till its value becomes less than about 1.0 V. Beyond this, the change becomes non linear and transistor goes into saturation state. With further increase in V_i the output voltage is found to decrease further towards zero though it may never become zero. If we plot the V_0 vs V_i curve. We see that between cut off state and active state and also between active state and saturation state there are regions of non-linearity showing that the transition from cutoff state to active state and from active state to saturation state are not sharply defined.

Let us see now how the transistor is operated as a switch. As long as V_i is low and unable to forward-bias the transistor, V_0 is high (at V_{CC}). If V_i is high enough to drive the transistor into saturation, then V_0 is low, very near to zero. When the transistor is not conducting it is said to be switched off and when it is driven into saturation it is said to be switched on. This shows that if we define low and high states as below and above certain voltage levels corresponding to cutoff and saturation of the transistor, then we can say that a low input switches the transistor off and a high input switches it on. Alternatively, we can say that a low input to the transistor gives a high output and a high input gives a low output. The switching circuits are designed in such a way that the transistor does not remain in active state.

3.35 OPTOELECTRONIC JUNCTION DEVICES

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

i) Photodiodes used for detecting optical signal (photodetectors).

ii) Light emitting diodes (LED) which convert electrical energy into light.

iii) Photovoltaic devices which convert optical radiation into electricity (solar cells).

3.36 PHOTO DIODE

A photo diode is essentially a reverse biased P-N junction diode which is designed to respond to photo absorption.

(a) Principle

A reverse biased P-N junction diode has a reverse saturation current which is mainly due to the flow of the minority carriers. If light is allowed to fall on such a reverse biased P-N junction diode, additional electron-hole pairs are generated in both P and N regions. It produces a very large change in minority carrier concentration and hence increases the reverse current through the diode. It is found that the current through the diode varies almost linearly with the light flux. Hence light can be detected using a reverse biased P-N junction diode known as photo diode.

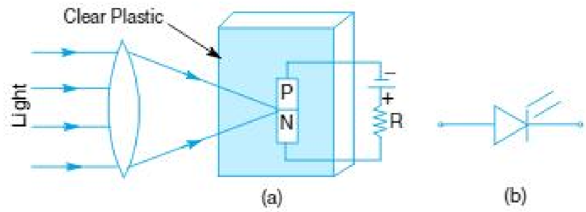


Fig 3.38

(b) Construction

A photo diode consists of a P-N junction embedded in a clear plastic capsule as shown in Fig 3.35(a). Radiation is allowed to fall upon one surface across the junction. Sometimes, a lens is placed on the junction side of the photo diode to focus the incident light on the surface for maximum activity. All the sides of the plastic capsule, except the illuminated one, are either painted black or enclosed in a metallic case. The semiconductor photo diode is extremely small and has dimensions of the order of a few mm. Fig. 3.38 shows the schematic symbol for a photo-diode. The inward arrows represent the incoming light.

(c) Working and characteristics

When photo diode is kept under dark condition and a sufficient reverse voltage is applied, an almost constant current, independent of magnitude of reverse bias, is obtained. This current corresponds to the reverse saturation current due to thermally generated minority carriers and is called dark current because it flows when no light is incident. It is proportional to the concentrations of minority carriers (holes in N and electrons in P-region) and is denoted by I_d. Majority charge carriers are not allowed to cross the junction barrier under this reverse bias condition.

When light is allowed to be incident on the diode surface, additional electron hole pairs are formed. But since the concentration of majority carriers is much greater as compared to that of minority carriers, the percentage increase of majority carriers is much smaller than the percentage increase of minority carriers. Hence, we can neglect the increase in majority density and can consider the radiation entirely as minority carrier injector. These injected minority carriers diffuse to the junction, cross and contribute to the additional current. Thus under large reverse bias conditions, the total reverse current is given by $I = I_s + I_d$ where I_s is the short circuit current and is proportional to light intensity.

Fig 3.39 represents the volt-ampere characteristic curve for three different values of illumination (intensity) for photo diode.

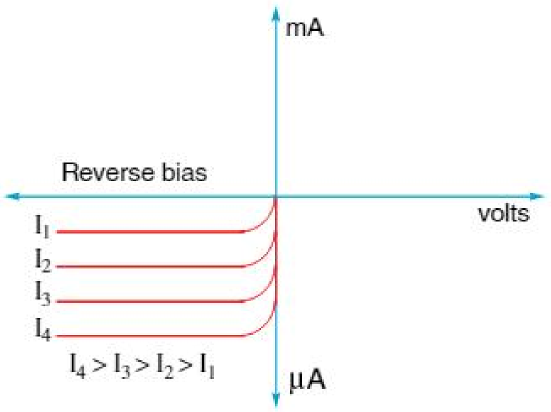


Fig 3.39

Only the curve representing the dark current passes through the origin. It may be seen that the current increases with increase in the level of illumination for given reverse voltage. Thus, the reverse current can be changed by changing the level of illumination. The reverse resistances of the diode can be changed likewise.

(d) Uses of Photo diode

1. A photo diode can turn its current ON and OFF in nanoseconds, hence it is used where light is required to be switched OFF and ON at a very fast rate.

2. A photo diode is used in light detection, in light operated switches, reading of computer punched cards and tapes etc.

3. Photo diodes find tremendous application in optical communication system.

4. They find many uses in instrumentation, control and communication.

Note : We know that when a diode is forward biased current will be more and in the order of milliampere and the current in reverse bias will be less and in the order of microampere. Inspite of this photodiode will be operated always in reverse bias.

Let us consider n type semiconductor. In this majority carrier density (n) is considerably large compared to minority carrier density (p). In other words n >> p where n and p denote number of electron per unit volume and number of holes per unit volume when photodiode is illuminated let Δn and Δp be the excess electron and excess holes generated

Now $n^1 = n + \Delta n$

and $p^1 = p + \Delta p$

When n^1 and p^1 denote the new concentration of change carriers due to illumination.

We know that $\Delta n = \Delta p$ and $n >> p$. As a result, fractional change in electron will be much less than that the fractional change in holes. It means $\frac{\Delta n}{n} << \frac{\Delta p}{p}$. The fractional change due to illumination on the minority carriers dominated reverse current can be measured very easily than the fractional change in forward current. As a result photodiodes are preferred to be operated in reverse bias for measuring intensity of light .

3.37 LIGHT-EMITTING DIODES (LED)

A light emitting diode (LED) is a specially made forward biased P-N junction diode which emits visible light when energy is released.

a) Theory

When a P-N junction diode is forward biased, the potential barrier is lowered and the majority charge carriers start crossing the junction. As soon as conduction band electrons from N-region cross the barrier and enter the P-region, they recombnine with holes. Similarly, some holes from P-region, may try to cross the junction but a conduction band electron may fall into hole before the hole crosses the junction. In either case recombine of electrons and holes take place. Now since a definite amount of energy is required to generate an electron-hole pair, the same energy is released when an electron recombines with hole. If E_g is the energy of radiation, the corresponding emission wavelength is given by

$$\lambda = \frac{hc}{E_g}$$

In case of Ge and Si the liberated energy goes into heating of the crystal and the amount of emitted light is insignificant. In case of GaAs,

band gap $E_g = 1.45$ eV and we get

$$\lambda = \frac{hc}{E_g} = \frac{6.62\times10^{-34}\times3\times10^{8}}{1.45\times1.6\times10^{-19}}$$

$$= 8500 \text{ Å}$$

Which lies in the infrared region. The band gap of Gallium Arsenide Phosphide (Ga As P) is about 1.9 eV and the radiation is of 6500 Å which is visible (red or yellow amber). Thus by a proper choice of band -gap and the material, radiation of desired wavelength may be obtained. It is possible to obtain orange, yellow and green emissions.

Gallium phosphide (GaP) gives red or green light.

(b) Construction and Working

At first an N-type layer is grown on a substrate and then a P-type layer is deposited on it by the process of diffusion. Metal contacts (Anode) are made at the outer edge of the P-layer so that more upper surface is left free for light to escape.

For making cathode connection, metal film (preferably gold) is coated at the bottom of the substrate. This film also reflects as much light as possible to the surface of the device.

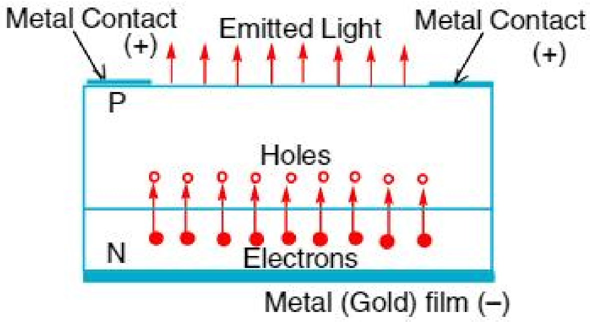


Fig 3.40

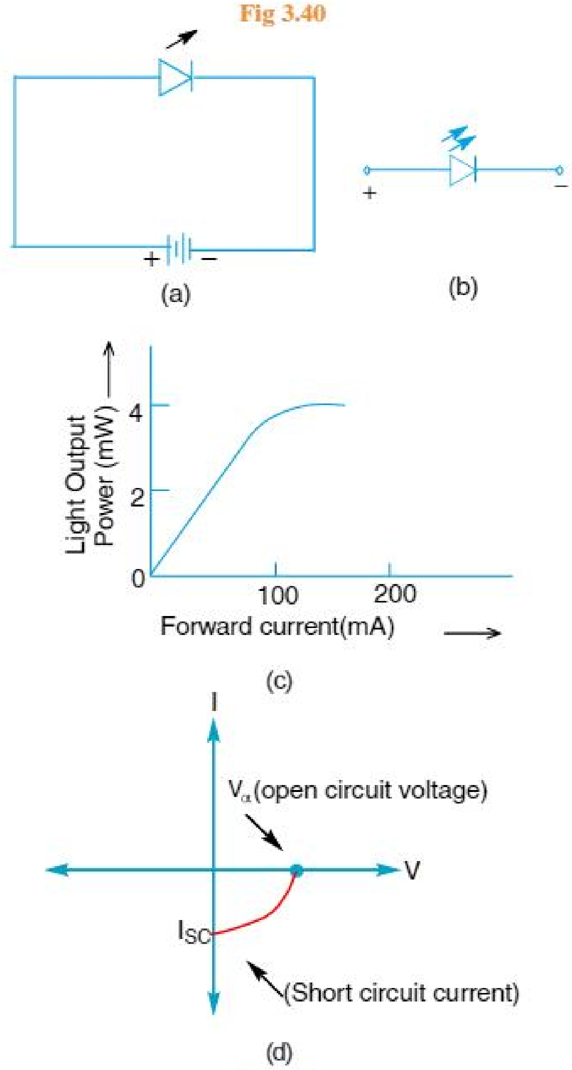


Fig 3.41

Such a specially made P-N diode (LED), gives emission in the visible region when forward biased. Fig 3.41(b) shows the schematic symbol of LED and an important characteristics of LED. LED emits light when a sufficient forward current is applied. Figure 3.41(c) shows that greater the forward current, greater is the light output of the LED. Thus amount of power output converted into light is directly proportional to forward current. LEDs emit no light when reverse biased.

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

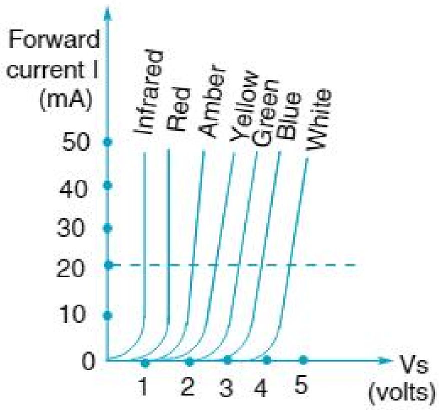


Fig 3.42

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

c) Uses of LEDS

Following are the important applications of LED :

1. The infrared LED finds applications in burglar alarm systems and other areas requiring invisible radiation.

2. LED that produce visible radiation find applications in numerical displays like watches, calculators, instrument panels, telephone switch boards etc. A seven segment display unit is made by using a number of LEDs.

3. The infrared LED is a potential source for optical fibre communication.

4. They are rapidly replacing cathode ray tubes in solid state video displays.

3.38 THE SOLAR CELLS

A solar cell or **solar battery** is basically a P-N junction diode which converts solar energy into electrical energy. It is also called a solar energy converter and is simply a photo diode operated at zero bias voltage.

Construction

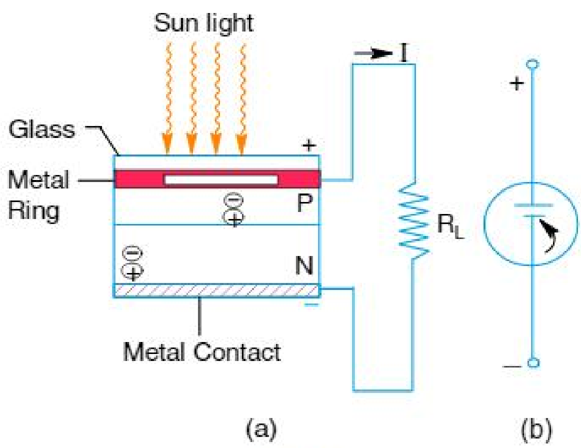


Fig 3.43

A solar cell consists of a P-N junction diode generally made of Ge or Si. It may also be constructed with many other semiconducting materials like gallium arsenide (Ga As), indium arsenide (InAs) and cadmium arsenide (CdAs).

The P-N diode so formed is packed in a can with glass window on top so that light may fall upon P and N type materials. The thickness of the P-region is kept very small so that electrons generated in this region can diffuse to the junction before recombination takes place. Thickness of N-region is also kept small to allow holes generated near the surface to diffuse to the junction before they recombine. A heavy doping of P and N regions is recommended to obtain a large photo voltage. A nickel plated ring is provided around the P-layer which acts as the positive output terminal. A metal contact at the bottom serves as the negative output terminal. Fig 3.43(b) gives the schematic symbol of a solar cell. The inward arrow indicates the incoming light.

Working

The working of solar cell may be understood with reference to Fig 3.43. When light is allowed to incident on a P-N junction diode, photons collide with valence electrons and impart them sufficient energy enabling them to leave their parent atoms. Thus electron- hole pairs are generated in both the P and the N-sides of the junction.

These electrons and holes reach the deflection region by diffusion and are then separated by the strong barrier field existing there.

However, the minority carriers, electrons in the P-side slide down the barrier to reach the N-side and the holes in the N-side move to P-side. Their flow constitutes the minority current which is directly proportional to the illumination and also depends on the surface area being exposed to light. The accumulation of electrons and holes on the two sides of the junction gives rise to an open circuit voltage V_{OC} which is a function of illumination. The open-circuit voltage produced for a silicon solar cell is typically 0.6 volt and the short circuit current is about 40 mA/cm^2 in bright noon day sun light. Many such cells are inter-connected to provide large quantities of electrical power. Solar panels providing 5 watt at 12 volt have been built to operate 24 hours a day by recharging the batteries during day light hours.

Typical V-I characteristics of a solar cell, corresponding to different levels of illumination are shown in Fig 3.44. It may be seen that for 100 mW/cm^2 illumination, the open circuit voltage is about 0.57 volt while the short circuit current is 50 mA. Maximum power output is, however obtained when the cell is operated at the knee of the curve.

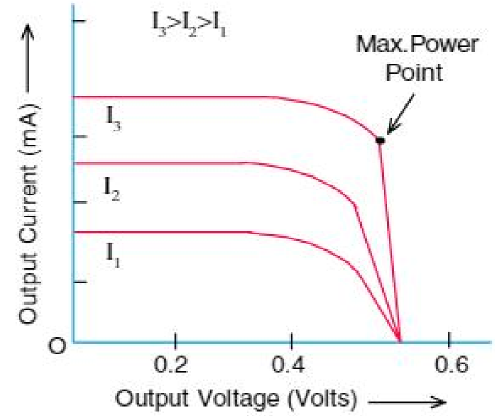


Fig 3.44

Solar cells are used extensively in satellites and space vehicles to supply power to electronic and other equipments or to charge storage batteries. They are receiving attention even for terrestrial electric power generation.

Production of low-cost photovoltaic cells for large-scale solar energy is a topic for research.

3.39 PREFERENCE OF SI AND GA AS FOR SOLAR CELLS

Solar radiation received by the earth will have the energy distribution as shown in the graph. It consists of various frequencies of the radiation with different intensities. Peak intensity corresponds to energy of 1.5 eV.

For photoexcitation, $h\nu > E$ where E corresponds to band gap in the semiconductor. So, for $E \leq 1.5$ eV better efficiency for conversion of solar energy can be observed.

For silicon E is about 1.1eV and for Ga As it is about 1.53eV. Inspite of higher band gap GaAs is superior to Si as its absorption coefficient is relatively higher. There are other materials like Cds and CdSe with band gap about 2.4eV.

But these materials are useful for photo conversion with only high energy component and as a consequence significant part of energy becomes useless. On the other hand, there are materials like Pbs with band gap about 0.4eV such that $h\nu > E$ but in this case most of the incident solar radiation will be absorbed on the top layer of solar cell and as a result, it will not reach in or near the depletion region. We know that electron hole separation due to the junction field is possible effectively if photogeneration occurs at the junction region. But with Pbs it is not possible effectively

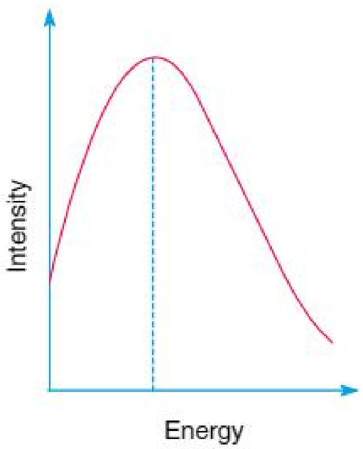


Fig 3.45

3.40 DIFFERENCE BETWEEN C AND Si OR Ge

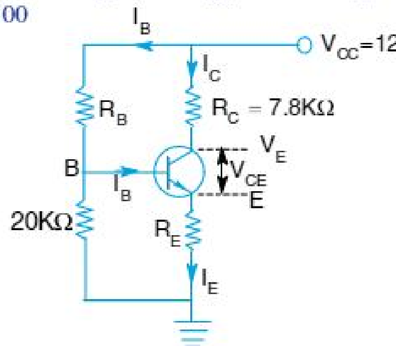
Carbon, Silicon and Germanium have same lattice structure. But we know that carbon is insulator while silicon and germanium are pure or intinsic semi conductors. In these three atoms the 4 valence electron will be in the second, third and fourth orbits respectively.

We know that energy required to take out an electron from the atom is known as ionisation energy. It is observed that ionisation energy will be least for germanium followed by silicon and highest for carbon.

As a result, the number of free electron for conduction in Germanium or silicon are siginificant and it is negligibly small in carbon.

Example-3.12

For the given transistor circuit, find V_E, R_B and R_E. Given $I_C = 1$ mA, $V_{CE} = 3V$, $V_{BE} = 0.5V$, $V_{CC} = 12V$ and $\beta = 100$



Solution :

We can write $I_C R_C + V_{CE} + I_E R_E = V_{CC}$

$\Rightarrow I_C(R_C + R_E) + V_{CE} = V_{CC}$ (assmue $I_E \approx I_C$)

$$\text{So, } (R_C + R_E) = \frac{V_{CC} - V_{CE}}{I_C} = \frac{12-3}{10^{-3}} = 9K\Omega$$

$\Rightarrow R_E = 9K\Omega - 7.8K\Omega = 1.2K\Omega$

$V_E = I_E R_E = 10^{-3} \times 1.2 \times 10^3 = 1.2V \quad (\because I_E \approx I_C)$

$V_B = V_E + V_{BE} = 1.2 + 0.5 = 1.7V \quad (\because V_{BE} = 0.5V)$

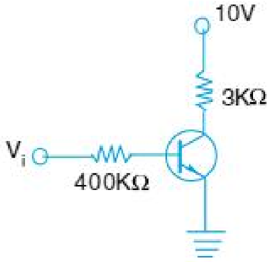
$$\text{Current through } 20K\,\Omega \text{ resistor } I = \frac{V_B}{20K\Omega} = 0.085mA$$

$$R_B = \frac{V_{CC} - V_B}{I_B + I} = \frac{12 - 1.7}{(0.01 + 0.0855) \times 10^{-3}} = 108K\,\Omega$$

$$\beta = \frac{I_C}{I_B} \Rightarrow I_B = \frac{I_C}{\beta} = \frac{10^{-3}}{100} = 0.01mA$$

Example-3.13

In the given circuit, when the input voltage of the base resistance is 10V, $V_{be} = 0$ and $V_{ce} = 0$. Find the values of I_b, I_c and β.



Solution :

As $V_{be} = 0$, PD across $R_b = 10V$

$$I_b = \frac{10}{400 \times 10^3} = 25\mu A$$

As $V_{ce} = 0$, PD across $R_c = 10V$

$$I_c = \frac{10}{3 \times 10^3} = 3.3mA$$

$$\beta = \frac{I_c}{I_b} = \frac{3.33 \times 10^{-3}}{25 \times 10^{-6}} \approx 133.2$$

EXERCISE

LONG ANSWER QUESTIONS

1. Explain p-type and n-type semi conductors with necessary diagrams.
2. What is a junction diode? Explain the formation of depletion layer at the junction. Explain the variation of depletion layer in forward and reverse-biased condition.
3. What is Zener diode? Explain how it is used as voltage regulator.
4 What is a rectifier? Explain the working of half wave and full wave rectifiers with diagrams.
5. Describe the construction a transistor and explain its working with necessary diagram.
6. What is amplification? Explain the working of a common emitter amplifier with necessary diagrams.

SHORT ANSWER QUESTIONS

1. What is the difference between metal, insulator and semiconductor? Explain this on the basis of energy band gap.
2. What are intrinsic semi conductors? Explain with energy level diagram.
3. What are n-type and p-type semiconductors? How is a semiconductor junction formed?
4. Explain why a semi-conductor acts as the insulator at OK and why its conductivity increases with increasing temperature.
5. Write the dependence of mobility on doping concentration and temperature?
6. Define Fermi energy level. Represent Fermi level on band diagram for pure semiconductor, N-type and P-type semiconductor.
7. Why is silicon preferred over germanium in the manufacture of semiconductor devices?
8. What is the effect of temperature on extrinsic semi-conductor?
9. Explain the behaviour of a p - n junction. How does a potential barrier develop at the junction?
10. Draw and explain the current - voltage (I - V) characteristic curves of a junction diode in forward and reverse bias.
11. If the doping concentration in a P-N junction diode is increased, will its zener breakdown voltage increase or decrease.
12. What is a avalanche breakdown? How does it vary with temperature?
13. Distinguish between Zener breakdown and avalanche breakdown.
14. Describe how a semi conductor diode is used as a half wave rectifier and write the expression for its efficiency.
15. Describe the full wave rectifier and write the expression for its efficiency. How is a semi conductor diode used as a full wave rectifier?
16. How does the reverse saturation current in a P-N diode vary with temperature.
17. Explain the reason for getting a constant reverse saturation current with increasing negative bias in a P-N junction diode.
18. What is a photodiode? Explain its working with a circuit diagram and draw its I-V characteristics.
19. Explain the working of LED and what are its advantages over conventional incandescent low power lamps.
20. What is the collector of a transistor made wider than emitter and base?

21. Define α and β parameters of a transistor. Derive relation between them.
22. What is an amplifier? None different types of amplifiers.
23. Give the expressions for (a) current gain (b) voltage gain (c) output resistance of a Transistor.
24. Explain what is meant by feedback. Write relation between the gain with feedback and the gain without feedback of an amplifier.
25. Explain the working of a photo diode.
26. What are LED? Give their uses and merits.
27. Write about solar cells.

VERY SHORT ANSWER QUESTIONS

1. What is the effect of temperature on the resistance of (i) metal and (ii) semi-conductors?
2. What are intrinsic and extrinsic seniconductors?
3. What are the majority and minority charge carriers in a p-type semi conductor?
4. What are the majority and minority charge carriers in an n-type semi conductor?
5. Why does the fermi energy level in an n-type semi-conductor shift towards the conduction band?
6. Why does the Fermi energy level in p-type semi-conductor shift towards the valence band?
7. When an electric field is applied on a semi-conductor how does the current flow occur?
8. Of the two types charge carries-holes and electrons which has greater mobility?
9. If n_p represents the hole concentration or the number of holes per unit volume and n_e represents the (free) electron concentration or the number of (free) electrons per unit volume, what is the relation between them in an 'intrinsic semi conductor'?
10. What is the ratio of n_p to n_e in a p-type Semi Conductor?
11. What is the ratio of n_p to n_e in an n-type semi-conductor?
12. How does the conductivity of semi conductor change with rise in temperature?
13. What is a p-n junction diode? Define depletion layer.
14. What are 1) forward bias and 2) reverse - bias?
15. What happens to the width of the depletion layer in a p-n junction diode when it is
    1) forward-biased and 2) reverse-biased?
16. To forward -bias a diode, its p-type is to be connected to the positive terminal of a cell and n-type to the negative terminal of the cell. Is it necessary?
17. To reverse -bias a diode, its p-type is to be connected to the negative terminal of a cell and n-type to the positive terminal cell. Is it necessary?
18. Which type of biasing gives a semi-conductor diode very high resistance?
19 Can we measure the potential barrier of a p-n junction diode by connecting a sensitive volt meter across its terminals?
20. Which type of break down results due to strong electric fields at the junction?
21. Is it correct to say that a diode behaves like a closed switch in the forward biased condition and behaves like an open switch in the reverse-biased condition?
22. What is Zener voltage (V_Z) and how will a Zener diode be connected in circuits generally?
23. In which bias zener diode characteristic is same as that of function diode?
24. Distinguish half wave and full wave rectifiers.
25. In which part of a cycle the diode conducts in half wave rectiffier?
26. Which rectifier produces double frequency at the output?
27. Can a zener diode be used in place junction diode in rectifier circuit?
28. i) What is a transistor?
    ii) In an n-p-n transistor, how does the p - region act ?
29. Draw the circuit symbols for p-n-p and n-p-n transistors.
30. Define amplifier and amplification factor.
31. Can two diodes combined back to back as shown in figure from a transistor?

p	n	n	p

32. Of the transistors -npn and pnp- which is faster?
33. In common base configuration, current gain (α) is defined as the ratio of collector current to emitter current i.e., $\alpha = I_C / I_E$, then what will be excepted the value of α?
34. What will be the relation between α and β?
35. Define voltage gain and power gain.
36. Write the uses of photo diode.
37. Write the uses of light emitting diode.
38. Write the uses of solar cells.

PROBLEMS

LEVEL - I

1. The electrical conductivity of a semiconductor increases when electromagnetic radiation of wavelength shorter than 2480 nm is incident on it. Find the band gap of the semiconductor. Given : h=6. 63×10^{-34} J-s, c=3.0×10^{8} ms^{-1} and 1eV=1.6×10^{-19} J.
[Ans: 0.5eV]

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 $\times$1 cm $\times$ 2 mm?
[Ans: 1.2×10^{13}]

3. Find the static resistance of a P-N junction germanium diode if temperature is 27^0C and I_s = 1 μ A for an applied forward bias of 0.2 volt.
[Ans: 2× 105 Ω]

4. In a p-n junction diode made with Ge, the thickness of depletion layer is 2×10^{-6}m and barrier potential is 0.3V. Find the strength of the electric field at the junction. **[Ans:** 1.5×10^{5} Vm^{-1} from n to p side]

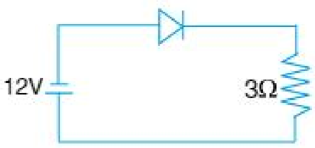
5. A potential barrier of 0.3V exists across a P-N junction (a) If the depletion region is 1μm wide, what is the intensity of electric field in this region? (b) An electron with speed 5×10^{5} m/s approaches this P-N junction from N-side, what will be its speed on entering the P-side?
[Ans: (a) 3×10^{5} v/m ; (b) 3.8×10^{5} m/s]

6. A junction diode is connected to an external resistance of 100Ω and a source of e.m.f. 3.0V. If potential barrier developed in the junction diode is 0.7, obtain the current in the circuit. **[Ans:** 23mA]

7. The junction diode shown in figure is ideal. Find the current in the circuit.

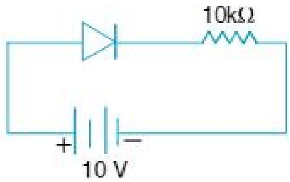
[Ans: 30mA]

8. Find the current in the circuit shown below:



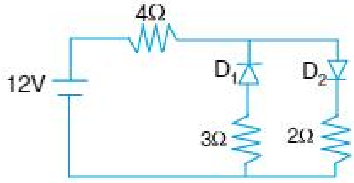
[Ans: Zero]

8. Determine the current through a silicon diode of (barrier potential = 0.7V Fig Assume that the diode resistance is negligible.



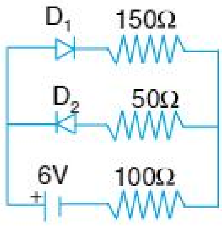
[Ans: 0.93 mA]

10. Calculate the current flowing in the circuit below which has two opposite connected ideal diodes in parallel.



[Ans: 2A]

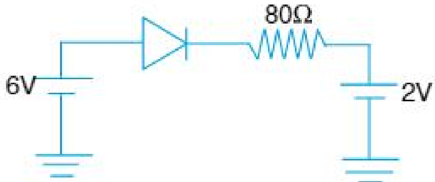
11. The circuit shown below contains two diodes, each of forward resistance, 50kΩ and with infinite backward resistance. If the battery voltage is 6V, find the current through 100Ω resistance.



[Ans: 0.02A]

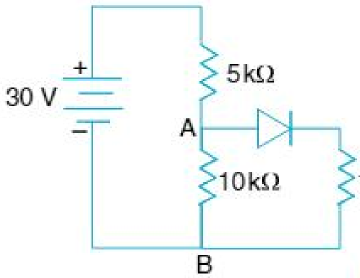
12. An ideal p-n junction diode can withstand currents up to 10mA under forward bias. The diode has a potential difference of 0.5V across it which is assumed to be independent of current. What is the maximum voltage of the battery used to forward bias the diode when resistance of 200Ω is connected in series with it. **[Ans:** 2.5 V]

13. The resistance of the diode in the forward biased condition is 20Ω and infinity in the reverse biased condition. Find the current in the given circuit.



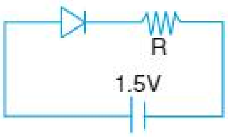
[Ans: 40mA]

14. Find maximum voltage across AB in the circuit shown in figure. Assume that the diode is ideal.



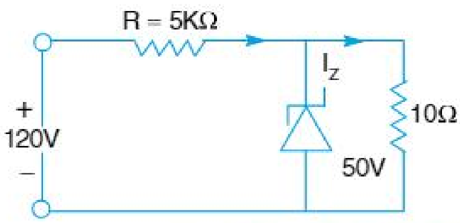
[Ans: 16.32 V]

15. A diode used in the circuit shown in fig. below, has a constant voltage drop of 0.5V at all currents and a maximum power rating of 100 mW. What should be the value of the resistance R connected in series with diode for obtaining maximum current



[Ans: 5 Ω]

16. For the circuit shown in Fig. find
1) the output voltage
2) the voltage drop across series resistance,
3) the current through Zener diode.



[Ans: 1) 50 V ; 2) 70 V ; 3) 9 mA]

17. The applied input AC power to a half wave rectifier is 100 W. The DC output power obtained is 40 W. Find the rectifier efficiency.
[Ans: 40%]

18. A p-n diode is used in a half wave rectifier with a load resistance of 1000 Ω. If the forward resistance of diode is 10 Ω, calculate the efficiency of this half wave rectifier.
[Ans: 40.2%]

19. A full wave rectifier uses two diodes with a load resistance of 100Ω. Each diode is having negligible forward resistance. Find the efficiency of this full wave rectifier.
[Ans: 81.2%]

20. A full-wave rectifier is used to convert '60' Hz A.C into D.C, find the number of pulses per second present in the rectified voltage [Ans : 120]

21. In an N-P-N transistor operating in the active region, the collector current equals 7 mA and emitter current equals 7.2 mA. Calculate the value of current gain α.
[Ans: 0.97]

22. In a common base configuration, with a base current of 0.005 mA, the emitter current is 1 mA. Calculate the value of collector current. [Ans: 0.95 mA]

23. For a transistor $\alpha = 0.98$ and emitter current $I_E = 2.5$ mA. Calculate collector current and base current
[Ans : 2.45 mA, 50 µ A]

24. In common base configuration of a transistor, a change of 200 mV in emitter voltage produces a change of 5 mA in emitter current. If base collector voltage V_{CB} remains constant, find the dynamic input resistance of transistor.
[Ans: 40 Ω]

25. In a transistor the emitter current is 1.01 times as large as the collector current. If the emitter current is 12.12 mA, find the base current.
[Ans: $I_B = I_E - I_C = 12.12 - 12 = 0.12$ mA]

26. In a transistor circuit the base current changes from $30\mu A$ to $90\mu A$. If the current gain of the transistor is 30, find the change in the collector current
[Ans: 1.8mA]

27. The constant α of a transistor is 0.9. What would be the change in collector current corresponding to change of 0.4 mA in the base current in a common emitter arrangement. [Ans: 7.6 mA]

28. For a transistor, the current gain of common-base configuration is 0.8. If the transistor is in common emitter configuration and the base current changes by 5mA, find the change in collector current.
[Ans: 20mA]

29. The current gain of a transistor in common emitter circuit is 49. Calculate its common base current gain. Find the base current when emitter current is 3 mA.
[Ans: 0.06 mA]

30. A change of 0.5 mA in the emitter current of a transistor produces a change of 0.49 mA in collector current. Calculate
(i) Common base short circuit current gain α.
(ii) common emitter short circuit current gain β.
[Ans: (i) 0.98 ; (ii) 49]

31. A change of 200mV in base-emitter voltage causes a change of $100\mu A$ in the base current. Find the input resistance of the transistor **[Ans: $2k\Omega$]**

32. For a single transistor amplifier, the collector load is $R_L = 2k\Omega$ and input resistance $R_i = 1k\Omega$. If the current gain is 50, find the voltage gain of the amplifier **[Ans: 100]**

33. A P-N-P transistor is used in common-emitter mode in an amplifier circuit. A change of $40\mu A$ in the base current brings a change of 2mA in collector current and 0.04 V in base-emitter voltage. Find the (i) input resistance (R_i) and (ii) the base current amplification factor (β). (iii) If a load of $6k\Omega$ is used, then also find the voltage gain of the amplifier. **[Ans: (i) 1k Ω ; (ii) 50 ; (iii) 300]**

34. The input resistance of a common-emitter amplifier is 600Ω and load resistance is $6k\Omega$. A change of base current by $50\mu A$ results in the change of collector current by 5mA. Find voltage gain. **[Ans: 1000]**

35. If voltage gain in CE configuration is 24. If $R_c = 10$ kΩ, $R_L = 10$kΩ, $\beta = 100$ and input resistance $R_i = 2.5$ kΩ, find the output voltage for an input voltage of 1 mV. **[Ans: 200 mV]**

LEVEL - II

1. An N-type silicon sample of width 4×10^{-3} m thickness and length 6×10^{-2} m carries a current of 4.8 mA when the voltage is applied across the length of the sample. What is the current density ? If the free electron density is 10^{22} m^{-3}, then find how much time it takes for the electrons to travel the full length of the sample. **[Ans: 4800A/m^2, 0.02s]**

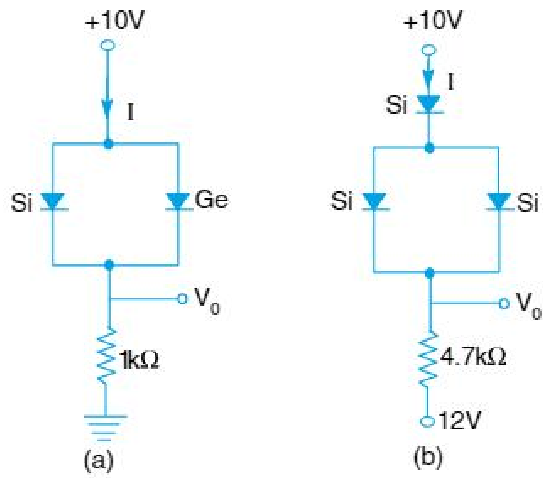
2. Determine the number of density of donor atoms which have to be added to an intrinsic germanium semiconductor to produce an N-type semi-conductor of conductivity 6.4 Ω^{-1}cm^{-1}. Given that mobility of electron in N-type Ge is 4000 cm^2/Vs. Neglect the contribution of holes to conductivity.

3. Find the concentration of holes and electrons in a P-type semiconductor at room temperature if conductivity is 100 mhos. Given that hole mobility μ_p=1800 and intrinsic concentration is 2.5×10^{13}/m^3. **[Ans: 1.8×10^{9} cm^{-3}]**

4. Calculate the conductivity of pure silicon at room temperature where the concentration of carriers is 1.6×10^{16}/m^2. Assume the mobility of electrons and holes to be 0.15 and 0.05 m^{2}V^{-1} s^{-1}. **[Ans: 5.1×10^{-5} Ω^{-1} m^{-1}]**

5. Calculate the values of drift velocities of holes and electrons at 300 K if the electric field is 100 V/cm in germanium. Given, carrier mobility for electron = 3600 cm^2/volt-sec. Carrier mobility for holes = 1700 cm^2/ volt-sec. **[Ans: 3600 m/s, 1700 m/s]**

6. Determine V_0 and I for the networks of figure.



[Ans: (a) $V_0 = 9.7V$, $I = 9.7mA$; (b) $V_0 = 14.6V$, $I = 0.553mA$]

7. In an n-p-n transistor, 10^8 electrons are emitted from the emitter in 10^{-4}s. If 2% of electrons are lost in the base, find the current gain in common-emitter configuration mode **[Ans: 49]**

8. A transistor connected in common emitter mode configuration is used as an amplifier. If $R_L = 5k\Omega$ and input resistance $R_i = 2k\Omega$ and current gain is 50. Find its power gain **[Ans: 6250]**

9. An amplifier has a voltage gain of 100 without feedback. A fraction of its output voltage is applied to input in such a way that the gain reduces to 50. Find feedback factor. **[Ans: β A = 1]**