SEMICONDUCTOR, DIODE AND TRANSISTOR

CLASSIFICATION OF METALS, SEMICONDUCTORS AND INSULATORS

1. On the Basis of Conductivity

Relative values of Resistivity and Conductivity are highly different in metals, semiconductors and insulators.

(i) **Metals :** They possess very low resistivity 'ρ' or high conductivity σ.
Resistivity $\rho = 10^{-2}\text{-}10^{-8}\ \Omega\text{m}$
Conductivity $\sigma = 10^{2}\text{-}10^{8}\ \text{Sm}^{-1}$

(ii) **Semiconductors :** They possess intermediate level of resistivity 'ρ' and conductivity 'σ'.
Resistivity $\rho = 10^{-5}\text{-}10^{0}\ \Omega\text{m}$
Conductivity $\sigma = 10^{5}\text{-}10^{0}\ \text{Sm}^{-1}$

(iii) **Insulators:** They possess very high resistivity or very low conductivity.
Resistivity $\rho = 10^{11}\text{-}10^{19}\ \Omega\text{m}$
Conductivity $\sigma = 10^{-11}\text{-}10^{-19}\ \text{Sm}^{-1}$

2. Semiconductors can be further classified on the basis of chemical composition as :

(i) **Elemental Semiconductors:** Si and Ge

(ii) **Compound Semiconductors:**
Inorganic : CdS, GaAs, CdSe, InP etc.
Organic: Anthracene, doped Pthalocyanines etc.
Organic polymers : Polyaniline, polythiophene etc.
Most of the currently available semiconductor devices are made up of elemental semiconductors Si or Ge and compound inorganic semiconductors.

Energy Bands in Solids (Conductor, Insulator and Semiconductor)

Energy Band

In a crystal due to interatomic interaction, valence electrons of one atom are shared by more than one atom in the crystal. Now, splitting of energy level takes place. The collection of these closely spaced energy levels are called an energy band.

Energy bands are formed due to the continuous energy variation in different energy levels. These different energy levels in different electrons are formed because inside the crystal, each electron has a unique position and no two electrons is exactly at the same pattern of surrounding charges.

Valence Band

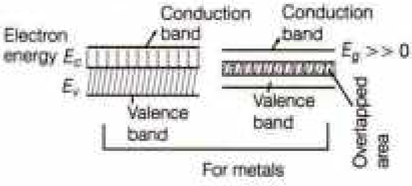
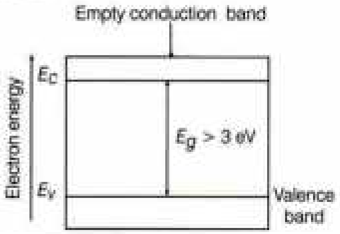
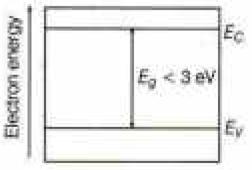
Valence band are the energy band, which includes the energy levels of the valence electrons. This band may be partially or completely filled with electrons. This band is never empty.

Conduction Band

Conduction band is the energy band above the valence band. At room temperature, this band is either empty or partially filled with electrons. Electrons can gain energy from external electric field and contribute to the electric current.

The lower completely filled band is called valence band and the upper unfilled band or partially filled is called conduction band.

Difference between Conductor, Insulator and Semiconductor on the basis of Energy Bands

Conductor (Metal)	Insulator	Semiconductor
In conductor, either there is no energy gap between the conduction band which is partially filled with electrons and valence band or the conduction band and valence band overlap each other.	In insulator, the valence band is completely filled, the conduction band is completely empty and energy gap is quite large and that energy from any other source cannot overcome it.	In semiconductor, the valence band is totally filled and the conduction band is empty but the energy gap between conduction band and valence band, unlike insulators is very small.
Thus, many electrons from below the fermi level can shift to higher energy levels above the fermi level in the conduction band and behave as free electrons by acquiring a little more energy from any other sources.	Thus, electrons are bound to valence band and are not free to move and hence, electric conduction is not possible in this type of material.	Thus, at room temperature, some electrons in the valence band acquire thermal energy greater than energy band gap and jump over to the conduction band where they are free to move under the influence of even a small electric field and acquire small conductivity.
 For metals		

Energy Band Gap

The minimum energy required for shifting electrons from valence band to conduction band is called energy band gap (E_g).

Fermi Energy

It is the maximum possible energy possessed by free electrons of a material at absolute zero temperature (i.e. 0 K).

The value of fermi energy is different for different materials.

> *If λ is the wavelength of radiation used in shifting, the electron from valence band to conduction band, then energy band gap is*
>
> $$\boxed{E_g = h\nu = hc/\lambda}$$
>
> *where, h is called Planck's constant and c is the velocity of light.*
>
> *The energy gap for different materials is different.*

Semiconductors

Semiconductors are the material whose conductivity lies between metals and insulators. They are characterised by narrow energy gap (~1 eV) between the valence band and conduction band. At absolute zero temperature, all states in valence band are full and all states in conduction band are empty. An applied electric field cannot give so much energy to the valence electrons that they could cross the gap and enter the conduction band. Hence, at low temperatures, pure semiconductors are insulators.

> *Electrons and Holes in Semiconductors*
>
> *At room temperature, however some of the valence electrons acquire thermal energy greater than E_g and move into conduction band. A vacancy is created in the valence band at each place where an electron was present before moving into conduction band. This vacancy is called hole, it is a seat of positive charge of magnitude equal to the charge of an electron. Thus, free electrons in the conduction band and the holes are created in the valence band, can move even under a small applied field. The solid is therefore conducting.*

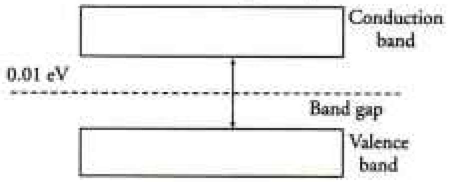
On the basis of purity, semiconductors are of two types

1. Intrinsic Semiconductors

An intrinsic semiconductor is also called an **undoped semiconductor** or ***i*-type semiconductor**. It is a pure semiconductor without any significant dopant species present. The number of charge carriers is determined by the properties of the material itself instead of the amount of impurities. The number of excited electrons is equal to number of holes i.e. $n_e = n_h$. At temperature 0 K, the valence band is full. The energy gap is 0.72 eV and the conduction band is totally empty.

Under the action of an electric field, holes move towards negative potential giving hole current I_h. The total current I is the sum of the electron current I_e and the hole current I_h.

$$I = I_e + I_h$$



2. Extrinsic Semiconductors

Those semiconductors in which some impurity atoms are embedded are known as extrinsic semiconductors.

Extrinsic semiconductors are basically of two types

(*i*) *n*-type semiconductors

(*ii*) *p*-type semiconductors

> *Doping The process of adding impurity to an intrinsic semiconductor in a controlled manner is called doping.*

(i) *n*-Type Semiconductors

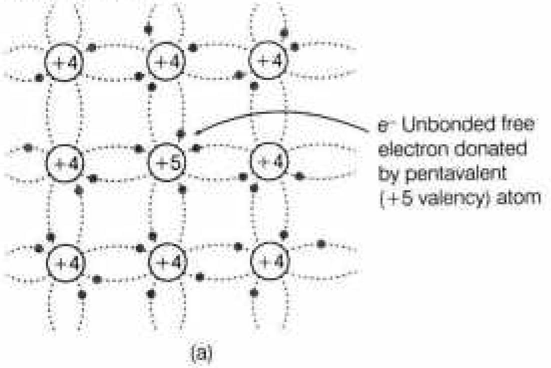
The semiconductors in which majority charge carriers are electrons and minority charge carrier are holes are called *n*-type semiconductor.

Formation of *n*-type semiconductor When we dope Si or Ge with a pentavalent element, then four of its electrons bond with the four silicon neighbours while fifth remains very weakly bound to its parent atom and hence ionisation energy required to set this electron free is very small. 0.01 eV for Ge and 0.05 eV for Si are energy required to make the electron free from the nuclear forces.

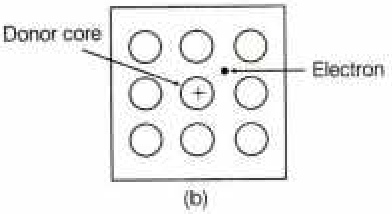
These electrons are almost free to move. In other words, we can say that these electrons are donated by the impurity atoms. So, these are also known as donor atoms and the conduction inside the semiconductor will take place with the help of the negatively charged electrons. Due to this negative charge, these semiconductors are known as *n*-type semiconductors.

When the semiconductors are placed at room temperature, then the covalent bond breakage will take place. So, more free electrons will be generated. As a result, same number of holes generation will take place. But as compared to the free electrons, the number of holes are comparatively less due to the presence of donated electrons i.e. $n_e >> n_h$.

We can say that major conduction of *n*-type semiconductors is due to electrons. So, electrons are known as **majority carriers** and the holes are known as the **minority carriers.**



Pentavalent donor atom (As, Sb, P, etc.) doped for tetravalent Si or Ge giving *n*-type semiconductor



Commonly used schematic representation for *n*-type material which shows only the fixed cores of the substituent donors with one additional effective positive charge and its associated extra electron.

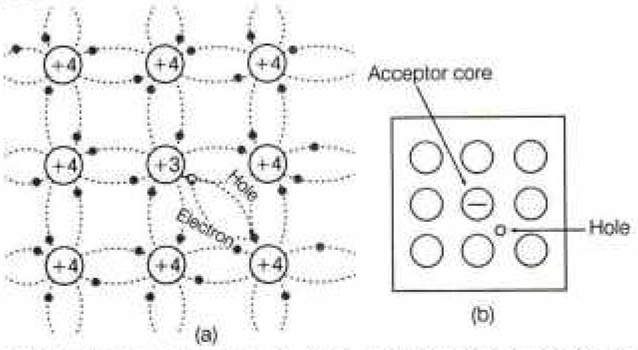
(ii) *p*-Type Semiconductors

The semiconductors in which majority charge carriers are holes i.e. positively charged and minority charge carriers are electrons are called *p*-type semiconductors.

Formation of *p*-type semiconductor In a *p*-type semiconductor, doping is done with trivalent impurity atoms. Trivalent atoms are those which have three valence electrons in their valence shell. Some examples of trivalent atoms are aluminium, boron, etc. So, the three valence electrons of the doped impure atoms will form the covalent bonds with silicon atoms. But silicon atoms have four electrons in its valence shell. So, one covalent bond will be improper.

So, one more electron is needed for the proper covalent bonding. This need of one electron is fulfilled from any of the bond between two silicon atoms. So, the bond between the silicon and impurity atoms will be completed. After bond formation, the indium will get ionised. As we know that, ions are negatively charged. So, indium will also get negative charge.

A hole was created when the electron come from silicon-silicon bond to complete the bond between indium and silicon. Now, an electron will move from any one of the covalent bond to fill the empty hole. This will result in a new hole formation. So, in *p*-type semiconductor, the holes movement results in the formation of the current. Holes are positively charged. Hence, these conductors are known as *p*-type semiconductors or acceptor type semiconductors.



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

When these conductors are placed at room temperature, then the covalent bond breakage will take place. In this type of semiconductors, the electrons are very less as compared to the holes i.e. $n_h >> n_e$. So, in *p*-type semiconductors, holes are the majority carriers and electrons are the minority carriers.

> *The electron and hole concentration in a semiconductor is thermal equilibrium is given by* $n_e n_h = n_i^2$
>
> *The energy gaps of C, Si are 5.0 eV, 1.1 eV and 0.7 eV*
> *Sn is a group IV element as its energy gaps is 0 eV.*

Example 1. *The number of silicon atoms per* m^3 *is* 5×10^{28}. *This is doped simultaneously with* 5×10^{22} atoms per m^3 *of arsenic and* 5×10^{20} per m^3 *atoms of indium. Calculate the number of electrons and holes. Given that,* $n_i = 1.5 \times 10^{16}\ \text{m}^{-3}$. *Is the material n-type or p-type?* **NCERT**

Sol. For each atom doped of arsenic, one free electron is received similarly for each atom doped of indium, a vacancy is created. So, number of free electrons introduced by pentavalent impurity is $N_{AS} = 5 \times 10^{22}\ \text{m}^{-3}$

The number of holes introduced by trivalent impurity added is $N_I = 5 \times 10^{20}\ \text{m}^{-3}$

So, net number of electrons added is

$$n_e = N_{AS} - N_I = 5 \times 10^{22} - 5 \times 10^{20}$$
$$= 4.95 \times 10^{22}\ \text{m}^{-3}$$

[1]

Now, by the law of mass action,

$$n_e n_h = n_i^2$$

So, $$n_h = \frac{n_i^2}{n_e} = \frac{(1.5 \times 10^{16})^2}{4.95 \times 10^{22}}$$ [1]

$$\Rightarrow \quad n_h = 4.54 \times 10^9 \text{ m}^{-3}$$

As, $n_e > n_h$ (number of holes). So, the material is *n*-type semiconductor. [1]

p-n Junction

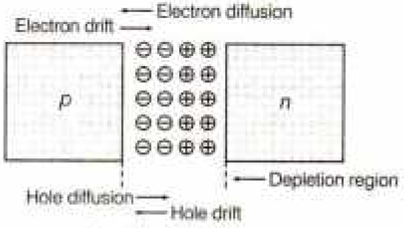
A *p-n* junction is an arrangement made by a close contact of *n*-type semiconductor and *p*-type semiconductor. There are various methods of forming *p-n* junction diode. In one method, an *n*-type germanium crystal is cut into thin slices called wafers. An aluminium film is laid on an *n*-type wafer, which is then heated in an oven at a temperature of about 600°C. Aluminium then diffuses into the surface of wafer. In this way, a *p-n* junction is formed.

Formation of Depletion Region in *p-n* Junction

In an *n*-type semiconductor, the concentration of electrons is more than concentration of holes. Similarly, in a *p*-type semiconductor, the concentration of holes is more than that of concentration of electrons. During formation of *p-n* junction and due to the concentration gradient across *p* and *n*-sides, holes diffuse from *p*-side to *n*-side $(p \to n)$ and electrons diffuse from *n*-side to *p*-side $(n \to p)$.

The diffused charge carriers combine with their counterparts in the immediate vicinity of the junction and neutralise each other.

Thus, near the junction positive charge is built on *n*-side and negative charge on *p*-side.



p-n junction formation process

This set up potential difference across the junction and an internal electric field E_i directed from *n*-side to *p*-side. The equilibrium is established when the field E_i becomes strong enough to stop further diffusion of the majority charge carriers (however it helps the minority charge carriers to diffuse across the junction).

The region on either side of the junction which becomes depleted (free) from the mobile charge carriers is called depletion region or **depletion layer.** The width of depletion region is of the order of 10^{-6} m.

The potential difference developed across the depletion region is called the potential barrier. Potential barrier depends on dopant concentration in the semiconductor and temperature of the junction.

Semiconductor Diode or *p-n* Junction Diode

A semiconductor diode is basically a *p-n* junction with metallic contacts provided at the ends for the application of an external voltage. It is a two terminal device.

A *p-n* junction diode is represented by $\overset{p \quad n}{-\!\!\triangleright\!\!|\!-}$.The direction of arrow indicates the conventional direction of current.

Forward Biasing and Reverse Biasing of Junction Diode

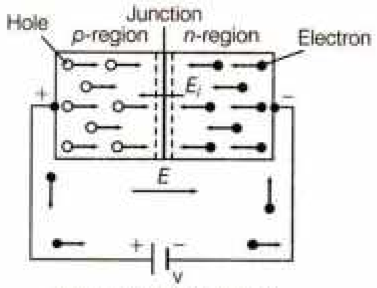
The junction diode can be connected to an external battery in two ways, called forward biasing and reverse biasing of the junction.

Forward Biasing

A junction is said to be forward biased when the positive terminal of the external battery is connected to the *p*-side and negative terminal to the *n*-side of the diode.

Flow of Current in Forward Biasing

In this situation, the forward voltage opposes the potential barrier, due to which the potential barrier decreases and depletion layer decreases. Under the effect of external electric field holes in the *p*-region and electrons in *n*-region, both move towards the junction.



Battery (Forward biased)

These holes and electrons mutually combine just near the junction and cease to exist. For each electron-hole combination, a covalent bond breaks up in the *p*-region near the positive terminal of the battery. Of the hole and electron so produced, the hole moves towards the junction, while the electron enters the positive terminal of the battery through the connecting wire.

Just at this moment, an electron is released from the negative terminal of the battery which enters the *n*-region to replace the electron lost by combining with a hole at the junction.

Thus, a current called **forward current**, is constituted by the motion of majority charge carriers across the junction. In forward bias, the junction diode offers low resistance.

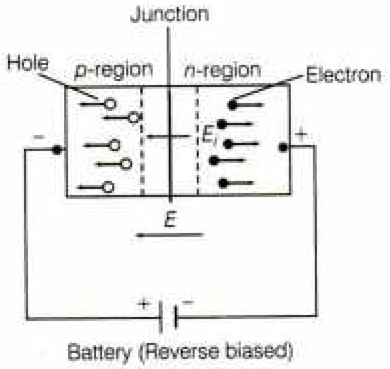
Reverse Biasing

A junction diode is said to be reverse biased when the positive terminal of the external battery is connected to the *n*-side and negative terminal to the *p*-side of the diode.

Flow of Current in Reverse Biasing

In this situation, the reverse voltage supports the potential barrier, due to which the potential barrier increases and depletion layer increases.

Under the effect of external electric field, holes in the *p*-region and electrons in the *n*-region are pushed away from the junction i.e. they cannot be combined at the junction. So, there is almost no flow of current due to majority charge carriers.



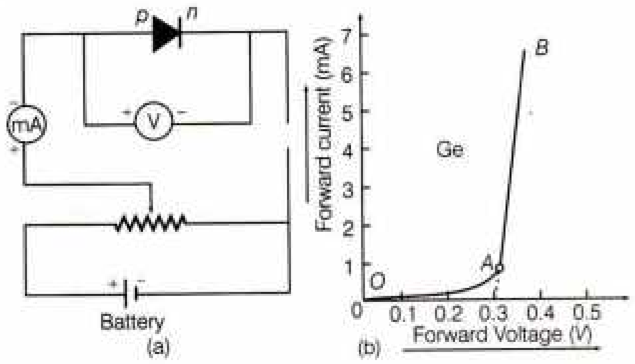
However, a very small current due to minority charge carriers, flows through across the junction. This current is called **reverse current.**

I-V (Current-Voltage) Characteristics of *p-n* Junction Diode

The graphical relations between voltage applied across *p-n* junction and current flowing through the junction are called ***I-V*** **characteristics of junction diode.**

Forward Biased Characteristics

The circuit diagram for studying forward biased characteristics is shown in the figure. Starting from a low value, forward bias voltage is increased step by step (measured by voltmeter) and forward current is noted (by ammeter). A graph is plotted between voltage and current. The curve so obtained is the forward characteristic of the diode.

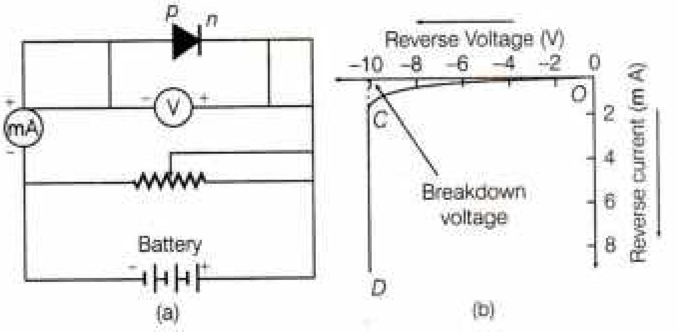


At the start when applied voltage is low, the current through the diode is almost zero. It is because of the potential barrier, which opposes the applied voltage. Till the applied voltage exceeds the potential barrier, the current increases very slowly with increase in applied voltage (*OA* portion of the graph).

With further increase in applied voltage, the current increases very rapidly (*AB* portion of the graph), in this situation the diode behaves like a conductor. The forward voltage beyond which the current through the junction starts increasing rapidly with voltage is called knee voltage. If line *AB* is extended back, it cuts the voltage axis at potential barrier voltage.

Reverse Biased Characteristics

The circuit diagram for studying reverse biased characteristics is shown in the figure.



In reverse biased, the applied voltage supports the flow of minority charge carriers across the junction. So, a very small current flows across the junction due to minority charge carriers. Motion of minority charge carriers is also supported by internal potential barrier, so all the minority carriers cross over the junction.

Therefore, the small reverse current remains almost constant over a sufficiently long range of reverse bias, increasing very little with increasing voltage (OC portion of the graph). This reverse current is voltage independent upto certain voltage known as **breakdown voltage** and this voltage independent current is called **reverse saturation current**.

> ***Avalanche Breakdown*** *If the reverse bias is equal to the breakdown voltage, then the reverse current through the junction increases very rapidly (CD portion of the graph), this situation is called avalanche breakdown and the junction may get damaged due to excessive heating if this current exceeds the rated value of p-n junction.*

Diode as Rectifier

The process of converting alternating voltage/current into direct voltage/current is called rectification. Diode is used as a rectifier for converting alternating current/voltage into direct current/voltage.

Principle

From the V-I characteristic of a junction diode, we see that it allows current to pass only when it is forward biased. So, if an alternating voltage is applied across a diode, the current flows only in that part of the cycle when the diode is forward biased. This property is used to rectify the current/voltage.

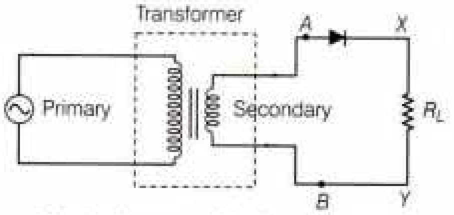
There are two ways of using a diode as a rectifier, i.e.

(*i*) Diode as a half wave rectifier

(*ii*) Diode as a full wave rectifier

(i) Diode as a Half-Wave Rectifier

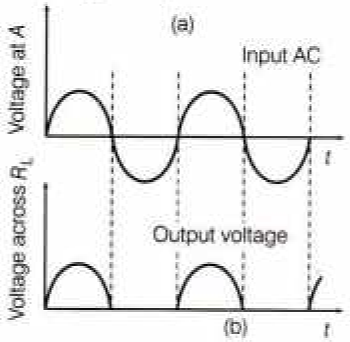
If the AC voltage to be rectified is connected to the primary coil of a step-down transformer. Secondary coil is connected to the diode through resistors R_L across which, output is obtained.



Circuit diagram of half-wave rectifier

Working

During positive half cycle of the input AC, the p-n junction is forward biased. Thus, the resistance in p-n junction becomes low and current flows. Hence, we get output in the load.

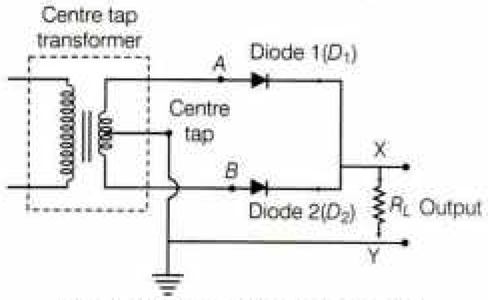


Input and output waveform

During negative half cycle of the input AC, the p-n junction is reverse biased. Thus, the resistance of p-n junction is high and current does not flow. Hence, no output is in the load.

(ii) Diode as a Full Wave Rectifier

In the full wave rectifier, two p-n junction diodes, D_1 and D_2 are used. This arrangement is shown in the diagram below.



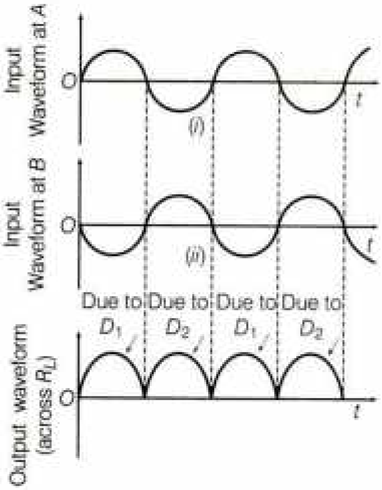
Circuit diagram of full wave rectifier

Working

During the positive half cycle of the input AC, the diode D_1 is forward biased and the diode D_2 is reverse biased. The forward current flows through diode D_1.

During the negative half cycle, the diode D_1 is reverse biased and diode D_2 is forward biased. Thus, current flows through diode D_2.

Thus, we find that during both the halves, current flows in the same direction.



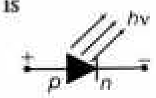
Optoelectronic Devices

Semiconductor diodes in which carriers are generated by photons i.e. photo excitation, such devices are known as optoelectronic devices. These are as follows:

1. Light Emitting Diode (LED)

It is a heavily doped *p-n* junction diode which converts electrical energy into light energy. This diode emits spontaneous radiation, under forward biasing. The diode is covered with a transparent cover, so that the emitted light may come out.

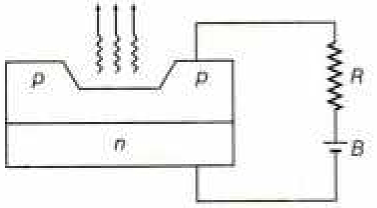
Its symbol is



Working

When *p-n* junction is forward biased, electrons and holes moves towards opposite sides of junction through it. Therefore, there are excess minority carriers on the either side of the junction boundary, which recombines with majority carriers near the junction.

On recombination of electron and hole, the energy is given out in the form of heat and light.

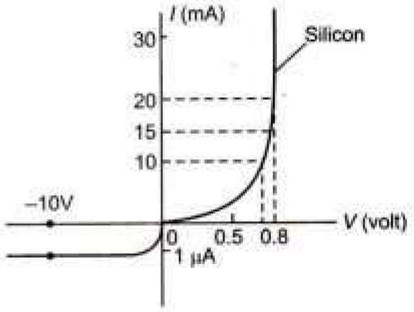


V-I Characteristics

V-I characteristics of LED are given below, which is similar to that of a simple junction diode. But the threshold voltages are much higher and slightly different for each colour. The reverse breakdown voltages of LEDs are very low.

The colour of light emitted by a given LED, depends on its band gap energy. The photon emitted by an LED is of energy equal to or slightly less than the band gap energy. Forward current conducted by the junction determines the intensity of light emitted by LED.

A low voltage DC supply is required to operate an LED. Current drawn by LED's is of the order of milliampere. So, in practice, a resistor of suitable value is joined in series with the LED to limit the current upto the safe value required.



LEDs Advantages over Incandescent low power lamps

It has the following advantages over conventional incandescent low power lamps.

(*i*) Fast action and no warm up time required.

(*ii*) The bandwidth of emitted light is 100 Å to 500 Å. So, its nearly (not exactly) monochromatic.

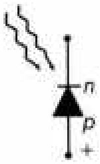
(*iii*) Long-life and ruggedness.

(*iv*) Low operational voltage and less power consumed.

(*v*) Fast on-off switching capability.

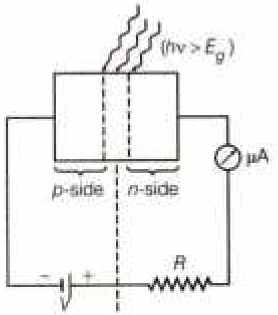
2. Photodiode

A photodiode is a special type of junction diode used for detecting optical signals. It is a reverse biased *p-n* junction made from a photosensitive material. In photodiode, current carriers are generated by photons through photo excitation. Its symbol is



Construction

A photodiode fabricated with a transparent cover to allow light to fall on the diode and operated under reverse bias.

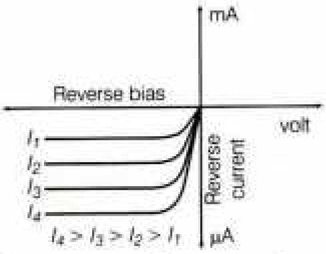


Working

When the photodiode is illuminated with light (photons), with energy greater than the energy gap of the semiconductor, then electron hole pairs are generated due to the absorption of photons. These charge carriers contribute to the reverse current.

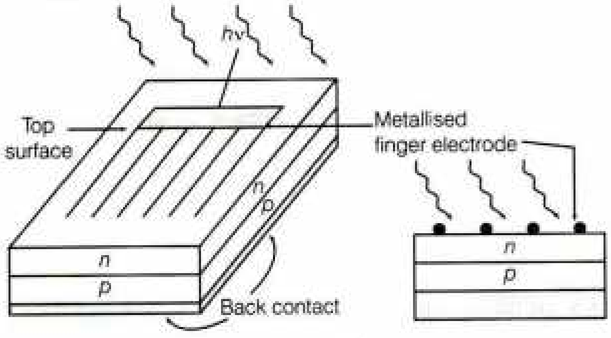
V-I Characteristics

Its *V-I* characteristics are shown in the figure, given below. We observe from the figure that current in photodiode changes with the change in light intensity (I) when reverse bias is applied.

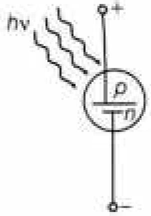


3. Solar Cell

Solar cell is a *p-n* junction diode, which converts solar energy into electrical energy.

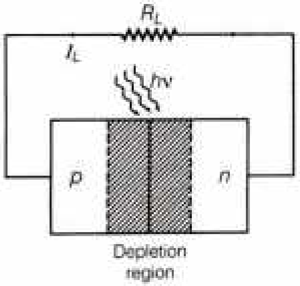


Its symbol is



Construction

It consists of a silicon or gallium-arsenide *p-n* junction diode packed in a can with glass window on the top.

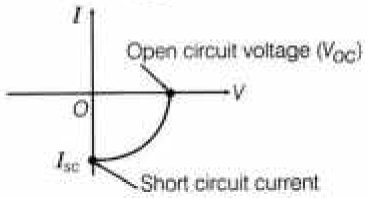


Working

When photons of light (of energy $hv > E_g$) falls at the junction, electron hole pair are generated near the junction and they move in opposite directions due to junction field. They will be collected at the two sides of the junction, giving rise to a photovoltage between the top and bottom metal electrodes. The top metal contact acts as positive electrode and bottom metal contact acts as negative electrode. When an external load is connected across metal electrodes, a photo current flows.

I-V Characteristics

The *I-V* characteristics of solar cell are shown in the figure. We can see in the figure, that it is drawn in the fourth quadrant of the coordinate axes, because a solar cell does not draw current but supplies the same to the load.



4. Zener Diode

Zener diode is a reverse biased heavily doped *p-n* junction diode. It is operated in breakdown region.

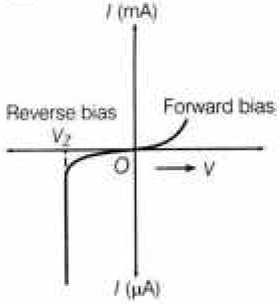
Zener diode is designed to operate in the reverse breakdown voltage continuously without being damaged.

This can be achieved by changing the thickness of the depletion layer to which the voltage is applied. Current through the zener diode is controlled by an external resistance. Zener diode is represented by the symbol.

Symbol of zener diode

V-I Characteristics

The *V-I* characteristics of zener diode is shown below and we observe that when the applied reverse voltage (V) reaches the breakdown voltage (V_Z) of the zener diode, there is a large change in the current.



But after the breakdown voltage V_Z, a large change in the current can be produced by almost insignificant change in the reverse bias voltage.

Zener Diode as a Voltage Regulator

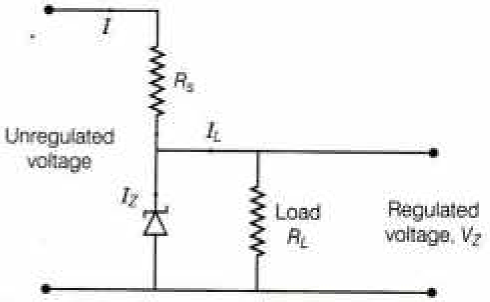
This is the most important application of a zener diode.

Principle

When the applied reverse voltage (V) reaches the breakdown voltage (V_Z) of the zener diode, there is a large change in the current. So, after the breakdown voltage V_Z, a large change in the current can be produced by almost insignificant change in the reverse bias voltage i.e. zener voltage remains constant even though the current through the zener diode varies over a wide range.

Zener diode is joined in reverse bias to the fluctuating. DC input voltage through a resistance R.

The constant output voltage is taken across a load resistance connected in parallel with zener diode.



Circuit diagram of zener diode as voltage regulator

Working

Here, when input DC voltage increases beyond a certain limit, the current through the circuit rises sharply, causing a sufficient increase in the voltage drop across the resistor R_s. Thus, the voltage across the zener diode remains constant and also the output voltage remains constant at V_Z.

When the input DC voltage decreases, the current through the circuit goes down sharply causing sufficient decrease in the voltage drop across the resistance. Thus, the voltage across the zener diode remains constant and also the output voltage across R_L remains constant at V_Z.

Hence, the output voltage remains constant in both conditions.

Analytical treatment

Let V_i and V_o be the unregulated input *dc* voltage and output voltage across R_L respectively. Let V_Z be the Zener voltage of the diode. The value of the series dropper resistor R is so chosen that the diode operates in the breakdown region under Zener voltage V_Z across it. If I be the current drawn from the supply, I_Z the current through the diode and I_L the current through the load, then

$$I = I_Z + I_L \qquad \text{(Kirchhoff's current law)}$$

or $$I_Z = I - I_L$$

If R_Z is the resistance of Zener diode, then

$$V_o = V_Z = I_Z R_Z = I_L R_L$$

Applying Kirchhoff's voltage law,

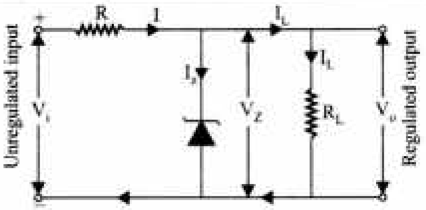
$$RI + V_Z = V_i \quad \text{or} \quad V_Z = V_i - RI$$

When $V_i < V_Z$, then $I_Z = 0$, $V_o = V_i$.

When V_i increases beyond V_Z, the voltage drop across R changes in such a way that $V_o = V_Z$ = constant.

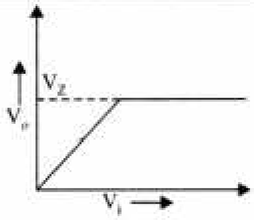
When V_i is fixed but I_L changes (say increases), then I_Z changes (decreases) in such a way that I is constant. So, drop IR is constant. Thus, V_o remains unchanged.

Fig. shows a plot of V_o versus V_i. It is clear from the graph that the output voltage remains constant in the Zener region.



Below V_Z, I is negligibly small. So, RI can be neglected.

For getting constant regulated output, operate the diode in Zener region and do not allow current to exceed a safe value. The series dropping resistance has to be chosen appropriately.



Plot of V_o versus V_i

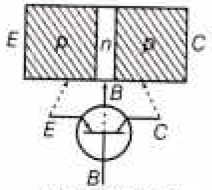
Junction Transistor

A junction transistor is three terminal semiconductor device consisting of two *p-n* junctions formed by placing a thin layer of doped semiconductor (*p*-type or *n*-type) between two thick similar layers of opposite type.

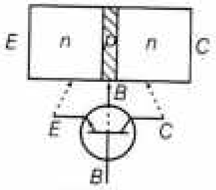
A transistor has three doped regions forming two *p-n* junctions between them.

There are two types of transistors.

1. ***n-p-n* transistor** Here, two segments of *n*-type semiconductor are separated by a segment of *p*-type semiconductor.
2. ***p-n-p* transistor** Here, two segments of *p*-type semiconductor are separated by a segment of *n*-type semiconductor.



p-n-p transistor



n-p-n transistor

Three segments of a transistor are called emitter (*E*), base (*B*) and collector (*C*).

A junction transistor is a transformer of resistance, which can be achieved by interchanging the biasing across the junction triode. Thus, it is called a junction **transistor.**

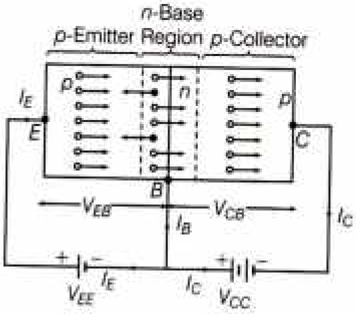
Biasing of Transistor

The emitter in *p-n-p* transistor is given a positive potential, while the collector is given a negative potential with respect to base in *n-p-n* transistor, connectors are reversed. Thus, the emitter-base junction on the left is forward biased (low resistance) and base-collector junction on the right is reverse biased (high resistance). A transistor is a current driven device, in which collector current is controlled by base current.

Transistor Action or Working of Transistor

p-n-p Transistor

From figure, we can see that the emitter-base junction is forward biased. Collector-base junction is reverse biased.



Flow of charge carrier in *p-n-p* transistor

The resistance of emitter-base junction is very low. So, the voltage of V_{EE} (V_{EB}) is quite small (i.e. 1.5 V).

The resistance of collector-base junction is very high. So, the voltage of V_{CC} (V_{CB}) is very high (i.e. 45 V).

Thus, holes which are majority carriers in emitter are repelled towards base resulting in emitter current (I_E).

The base being thin and lightly doped (*n*-type) has low density of electrons, thus when holes enter the base region, then only a few holes gets neutralised by the electron hole combination which results in base current (I_B).

The remaining holes pass over to the collector due to high negative potential of collector, resulting in collector current (I_C).

As one hole reaches to collector, it gets neutralised by the flow of one electron from the negative terminal of the battery V_{CC} to collector through connecting wire. At the same time, a covalent bond is broken in the emitter, the electron goes to the positive terminal of the battery V_{EE} through connecting wire and hole produced begins to move towards base to repeat the process again.

When the hole coming from emitter combines with the electrons in base, the deficiency of electron in the base is compensated by the flow of electron from negative terminal of battery V_{EE} to the base through connecting wire.

Thus, the current in *p-n-p* transistor is carried by holes and at the same time, their concentration is maintained.

But in external circuit, the current is due to the flow of electrons.

Thus in this case,

$$I_E = I_B + I_C \quad \text{[Using Kirchhoff's law]}$$

In the base, I_E and I_C flow in opposite directions.

n-p-n Transistor

In this transistor, the emitter-base junction is forward biased and its resistance is very low. So, the voltage of V_{EE} is quite small.

The collector-base junction is reverse biased. The resistance of this junction is very high. So, the voltage of V_{CC} (V_{CB}) is quite large (≈ 45 V). Electrons in emitter are repelled towards base by negative potential of V_{EE} on emitter, resulting emitter current I_E.

The base being thin and lightly doped has low density of holes, thus when electrons enter the base region, then only a few holes get neutralised by electron hole combination, resulting in base current (I_B). The remaining electrons pass over to the collector, due to high positive potential of collector, resulting in collector current (I_C).

As, one electron reaches to collector, it gets neutralised by the flow of one electron from the negative terminal of the battery V_{CC} to collector through connecting wire. Then, one electron flow from negative terminal of battery V_{CC} to positive terminal of battery V_{EE} and one electron flow from negative terminal of V_{EE} to emitter.

When the electron coming from emitter combines with the holes in base, the deficiency of hole in the base is compensated by the breaking of covalent bond there.

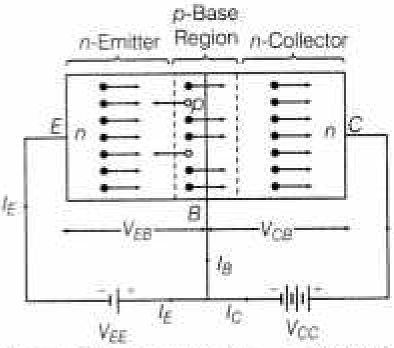
The electron, so released flows to the positive terminal of battery V_{EE}, through connecting wire.

Thus, in *n-p-n* transistor, the current is carried inside as well as in external circuit by the electrons.

Thus in this case also,

$$I_E = I_B + I_C \quad \text{[Kirchhoff's 1st law]}$$

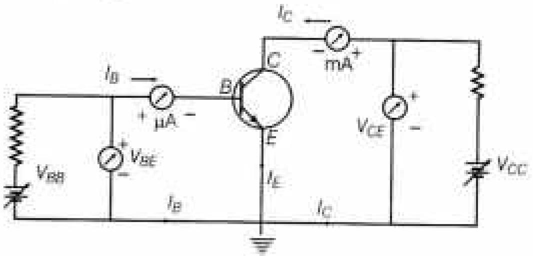
In the base, I_E and I_C flow in opposite direction.



Flow of charge carries in *n* - *p* - *n* transistor

Common-Emitter Transistor Characteristics

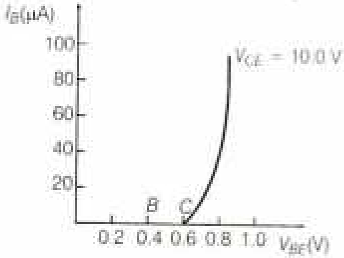
To study the characteristics of a *n-p-n* transistor in common-emitter mode, required circuit is shown in the figure. Here, base-emitter circuit is forward biased with battery V_{BE} and emitter-collector circuit is reverse biased with battery V_{CC}.



From circuit diagram, we come across to know that it is made up of two sections i.e. input and output.

These two characteristics can be studied as,

(i) Emitter or Input Characteristics



It is a graphical relation between the emitter voltage and the emitter current by keeping collector voltage constant is called **input characteristics** of the transistor. Adjust collector-emitter voltage at a suitable high value V_{CE} (say = +10 V). It is necessary so as to make the base-collector junction reverse biased. Now, with the help of rheostat, gradually increase the value of base-emitter voltage V_{BE} in small steps and note the corresponding values of base current I_B.

Input resistance It is defined as the ratio of change in base-emitter voltage (ΔV_{BE}) to the resulting change in the base current (ΔI_B) at constant collector-emitter voltage (V_{CE}). It is reciprocal of slope of I_B-V_{BE} curve.

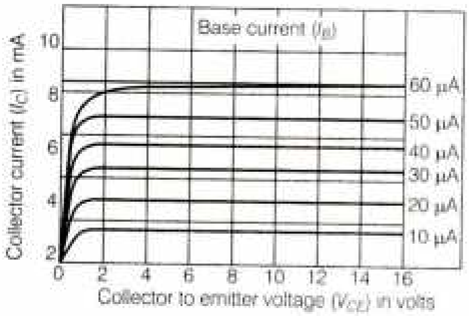
$$\text{Input resistance, } R_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE} = \text{constant}}$$

(ii) Collector or Output Characteristics

A graphical relation between the collector voltage and collector current by keeping base current constant is called **output characteristics** of the transistor. To study the output characteristics of transistor, we keep value of base current I_B fixed (say at 10 μA) with the help of V_{BE}. Now, gradually change the value of V_{CE} and note the values of collector current I_C.

Plot I_C-V_{CE} graph. Repeat the process for different constant values of I_B.

The output characteristics are shown as,



Output Resistance From the output characteristics, we define output resistance of transistor as the ratio of change in collector-emitter voltage to the resulting change in collector current at constant base current. Thus,

$$\text{Output resistance, } r_0 = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B = \text{constant}}$$

$$= \text{Reciprocal of slope of } I_C\text{-}V_{CE} \text{ curve}$$

Current Amplification Factor The current amplification factor (β) of a transistor in *CE* configuration is defined as the ratio of change in collector current to the change in base current at a constant collector-emitter voltage when the transistor is in active state.

$$\therefore \qquad \beta_{AC} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE} = \text{constant}}$$

Its value is very large ($\beta_{AC} >> 1$).

Transistor as an Amplifier

(Common-Emitter Configuration)

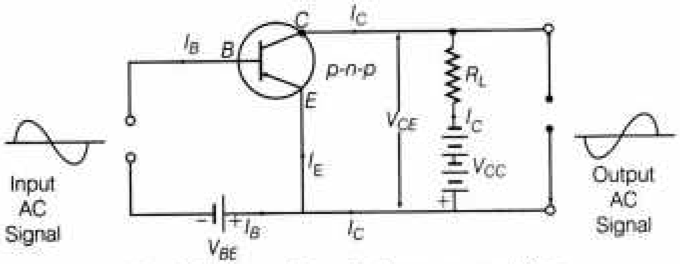
An amplifier is a device which is used for increasing the amplitude of input signal.

Principle

In a transistor, there are two *p-n* junctions, one is forward biased (low resistance) and other is reverse biased (high resistance). The weak input signal is applied across the forward biased junction and output signal is taken across the reverse biased junction. Since, the input and output currents are almost equal, the output signal appears with a much higher voltage, because of high output resistance.

Working

The circuit diagram for *p-n-p* transistor as an amplifier is shown in the figure given below:



Circuit diagram of transistor as an amplifier

The emitter-base circuit is forward biased by a low voltage battery V_{BE}, that means the resistance of input circuit is small.

The collector-emitter circuit is reverse biased by a high voltage battery V_{CC}, that means the resistance of output circuit is high. R_L is a load resistance connected in collector-emitter circuit. The weak input AC signal is applied across the base-emitter circuit and amplified output signal is obtained across collector-emitter circuit. When no AC voltage is applied to the input circuit, we have

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

Due to collector current I_C, the voltage drop across load resistance (R_L) is $I_C R_L$. Therefore, the collector-emitter voltage V_{CE} is given by

$$V_{CE} = V_{CC} - I_C R_L \qquad \ldots\text{(ii)}$$

When the input AC voltage signal is applied across base-emitter circuit, it changes base-emitter voltage and hence, emitter current I_E changes which in turn changes the collector current I_C. So, the collector-emitter voltage V_{CE} varies in accordance with Eq. (ii). This variation in V_{CE} appears as an amplified output.

Gains in Common-Emitter Amplifier

α and β parameters of a transistor are defined as $\alpha = \frac{I_C}{I_E}$ and $\beta = \frac{I_C}{I_B}$. α is about 0.95 to 0.99 and β is about 20 to 100.

The various gains in a common-emitter amplifier are as follows:

(i) DC Current Gain

It is defined as the ratio of the collector current to the base current and is denoted by β_{DC}. Thus,

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{I_C/I_E}{1 - I_C/I_E} \qquad [\because I_E = I_B + I_C]$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad [\because \alpha = I_C/I_E]$$

(ii) AC Current Gain

It is defined as the ratio of the change in the collector current to the change in the base current at a constant collector-to-emitter voltage and is denoted by β_{AC}.

Thus, $$\beta_{AC} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

The value of β is from 15 to 100, for a transistor.

Transconductance (g_m) It is defined as the ratio of the change in the collector current to the change in the base-to-emitter voltage at constant collector-to-emitter voltage and is denoted by g_m.

Thus, $$g_m = \left(\frac{\Delta I_C}{\Delta V_i}\right)_{V_{CE}}$$

We can express it in terms of β_{AC}, $g_m = \frac{\Delta I_C}{\Delta I_B} \times \frac{\Delta I_B}{\Delta V_i}$

Now, $$\frac{\Delta I_C}{\Delta I_B} = \beta_{AC} \quad \text{and} \quad \frac{\Delta V_i}{\Delta I_B} = R_B$$

[a resistance of the input circuit]

$$\therefore \quad g_m = \frac{\beta_{AC}}{R_{in}}$$

The unit if g_m is Ω^{-1} (Ohm $^{-1}$) or S (siemen).

(iii) AC Voltage Gain

It is defined as the ratio of the change in the output voltage to the change in the input voltage and is denoted by A_V. Suppose, on applying an AC input voltage signal, the input base current changes by ΔI_B and correspondingly to the output collector current changes by ΔI_C. If R_{in} and R_{out} are the resistances of the input and the output circuits respectively, then

$$A_V = \frac{\Delta I_C \times R_{out}}{\Delta I_B \times R_{in}} = \frac{\Delta I_C}{\Delta I_B} \times \frac{R_{out}}{R_{in}}$$

Now, $\Delta I_C / \Delta I_B$ is the AC current gain β_{AC} and R_{out} / R_{in} is the resistance gain.

$$\therefore \quad A_V = \beta_{AC} \times \text{Resistance gain}$$

Since $\beta_{AC} >> \alpha_{AC}$, the AC voltage gain in common-emitter amplifier is larger as compared to that in common-base amplifier, although the resistance gain is smaller.

(iv) AC Power Gain

It is defined as the ratio of the change in the output power to the change in the input power. Since,

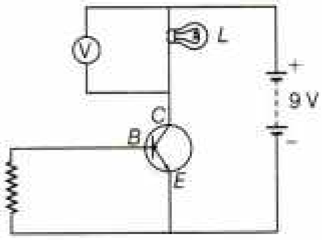
Power = Current × Voltage

We have, AC power gain = AC current gain × AC voltage gain

$$= \beta_{AC} \times A_V = \beta_{AC} \times (\beta_{AC} \times \text{Resistance gain})$$
$$= \beta_{AC} \times \text{Resistance gain}$$

Since $\beta_{AC} >> \alpha_{AC}$, the AC power gain in common-emitter amplifier is extremely large as compared to that in common-base amplifier.

In the given circuit diagram, a voltmeter V is connected across a lamp L. How would



(i) the brightness of the lamp and

(ii) voltmeter reading V be affected,

if the value of resistance R_B is decreased? Justify your answer. **Delhi 2013**

Sol. The given figure in question is common-Emitter (CE) configuration of an n-p-n transistor. The base-emitter junction is forward biased and collector base junction is reverse biased. **[1]**

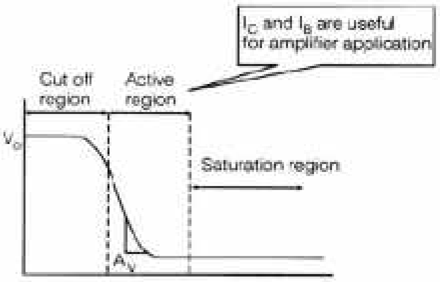
As, the base resistance R_B decreases, the input circuit will become more forward biased thus decreasing the base current (I_B) (i.e. less number of recombination in base due to reduction in area of base) and increasing the emitter current (I_E). This will increase the collector current (I_C) as $I_E = I_B + I_C$.

When I_C increases which flows through the lamp, the voltage across the bulb will also increase thus making the lamp brighter and as the voltmeter is connected in parallel with the lamp, the reading in the voltmeter will also increase. **[1]**

Draw the general shape of the transfer characteristics of a transistor in its CE configuration. Which regions of this characteristic of a transistor are used when, it works

(i) as a switch? (ii) as an amplifier? **All India 2010C**

Sol.

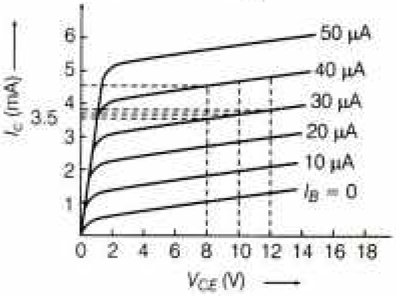


Transfer characteristic of base biased transistor **[1]**

(i) The transfer characteristics of a transistor in CE configuration is used as a switch in cut-off and saturation region. **[1]**

(ii) The active region of transfer characteristic curve is used as an amplifier. **[1]**

Output characteristics of an n-p-n transistor in CE configuration is shown in the figure.



Determine,

(i) dynamic output resistance *(ii) DC current gain*

(iii) AC current gain at an operating point $V_{CE} = 10$ V, when, $I_B = 30\,\mu$A. **Delhi 2013**

Sol. (i) Dynamic output resistance is given as,

$$R_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B = \text{constant}}$$

$$= \frac{12-8}{(3.6-3.4)\times 10^{-3}} = \frac{4}{0.2\times 10^{-3}}$$

$$= 20\ \text{k}\Omega$$

(ii) DC current gain,

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.5\,\text{mA}}{30\,\mu\text{A}}$$

$$= \frac{3.5\times 10^{-3}}{30\times 10^{-6}}$$

$$= \frac{350}{3} = 116.67$$

(iii) AC current gain,

$$\beta_{DC} = \frac{\Delta I_C}{\Delta I_B} = \frac{(4.7-3.5)\,\text{mA}}{(40-30)\ \mu\text{A}} = \frac{1.2\times 10^{-3}}{10\times 10^{-6}} = 120$$

A potential barrier of 0.4 V exists across p-n junction.

(i) If the depletion region is 4.0×10^{-7} m wide, what is the intensity of the electric field in this region?

(ii) If an electron with speed 4×10^5 m/s approaches the p-n junction from the n-side, find the speed with which it will the p-side.

Sol. Given $V = 0.4$ V

(a) $d = 4\times 10^{-7}$m, $E = ?$

(b) $V_1 = 4\times 10^5$ m/s, $V_2 = ?$

(i) Electric field, $E = \dfrac{V}{d} = \dfrac{0.4}{4\times 10^{-7}} = 1\times 10^6$ V/m

(ii) Suppose V_1 be the speed of electron when it enters the depletion layer and V_2 be the speed when it comes out of the depletion layer.

According to principle of conservation of energy,

KE before entering the depletion layer = Gain in PE + KE after crossing the depletion layer

$$\Rightarrow \quad \frac{1}{2}mV_1^2 = e\times V + \frac{1}{2}mV_2^2$$

$$\Rightarrow \frac{1}{2}\times 9.1\times 10^{-31}\times (4\times 10^5)^2$$

$$= 1.6\times 10^{-19}\times 0.4 + \frac{1}{2}\times 9.1\times 10^{-31}\times V_2^2$$

$$\Rightarrow \quad V_2 = 1.39\times 10^5\,\text{m/s}$$

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

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

$$n' = n + \Delta n \qquad p' = p + \Delta p.$$

Here n' and p' are the electron and hole concentrations at any particular illumination and n and p are carrier concentrations when there is no illumination. Remember $\Delta n = \Delta p$ and $n >> p$. Hence, the fractional change in the majority carriers (*i.e.*, $\Delta n/n$) would be much less than that in the minority carriers (*i.e.*, $\Delta p/p$). In general, we can state that the fractional change due to the photo-effects on the minority carrier dominated reverse bias current is more easily measurable than the fractional change in the forward bias current. Hence, photodiodes are preferably used in the reverse bias condition for measuring light intensity.

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

Sol. Energy of the incident photon with a wavelength of 6000 nm

$$E = \frac{hc}{\lambda} = \frac{6.63\times 10^{-34}\times 3\times 10^8}{6\times 10^{-6}} = 0.207\ \text{eV}$$

The photodiode need an energy of 2.8 eV to give response to incident light. As $E < E_g$, the given photodiode cannot detect the radiation of wavelength 6000 nm.

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

Sol. For n-type silicon, statement c is true.

2. **Which of the statements given in previous question is true for p-type semiconductors?**

Sol. For p-type semiconductors, statement (d) is true.

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

Sol. The energy band gap is largest for carbon, less for silicon and least for germanium.

So, the correct statement is (c).

$(E_g)_C > (E_g)_{Si} > (E_g)_{Ge}$

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

Sol. In the unbiased p-n junction, holes diffuse from the p-region to n-region because holes concentration in the p-region is high as compared to n-region.

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

Sol. Under forward biasing the movement of majority charge carriers across the junction reduces the width of depletion layer or lowers the potential barrier.

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

Sol. We know that for each atom doped of Arsenic one free electron is received. Similarly for each atom doped of indium a vacancy is created.

So, the number of free electrons introduced by pentavalent impurity added $n_e = N_{As} = 5 \times 10^{22}$ m^{-3}

The number of holes introduced by trivalent impurity added $n_h = N_{In} = 5 \times 10^{20}$ m^{-3}

We know the relation

$$n_e\, n_h = n_i^2 \qquad \text{...(i)}$$

Now $n_e - n_h = 5 \times 10^{22} - 5 \times 10^{20}$

$$= 4.95 \times 10^{22} \qquad \text{...(ii)}$$

So, $(n_e + n_h)^2 = (n_e - n_h)^2 + 4n_e\, n_h$

$(n_e + n_h)^2 = (n_e - n_h)^2 + 4\, n_i^2$

$$n_e + n_h = \sqrt{(4.95\times10^{22})^2 + 4\,(1.5\times10^{16})^2} \qquad \text{...(iii)}$$

Adding equation (iii) and (ii)

$$2n_e = 4.95\times10^{22} + \sqrt{(4.95\times10^{22})^2 + 4\,(1.5\times10^{16})^2}$$

$$n_e = \frac{1}{2}\left[4.95\times10^{22} + \sqrt{(4.95\times10^{22})^2}\ \right]$$

$n_e = 4.95 \times 10^{22}$ m^{-3}

Now using equation (i)

$$n_h = \frac{n_i^2}{n_e} = \frac{(1.5\times10^{16})^2}{4.95\times10^{22}} = 4.5\times10^{9}\ \text{m}^{-3}$$

So, $n_e >> n_h$, the material is of n-type.

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

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

where n_0 is a constant. $k_B = 8.62 \times 10^{-5}$ eV K^{-1}

Sol. Conductivity is given by $\sigma = e\,(n_e\,\mu_e + n_h\,\mu_h)$

For intrinsic semiconductor $n_e = n_h = n_i$

Also mobility of holes $(\mu_h) <<$ mobility of electrons (μ_e)

So, conductivity $\sigma = en_e\mu_e$

Temperature dependence of intrinsic carrier concentration

$$n_i = n_0 e^{-\frac{E_g}{2k_BT}}$$

So, conductivity

$$\sigma = en_i\mu_e = e\mu_e\,n_0 e^{-\frac{E_g}{2k_BT}}$$

where $e\mu_e n_0 = \sigma_0 =$ constant

hence $\sigma = \sigma_0 e^{-\frac{E_g}{2k_BT}}$

Conductivity at 600K

$$\sigma_1 = \sigma_0 e^{-\frac{1.2\text{ eV}}{2k_B(600)}} \quad \text{...(i)}$$

Conductivity at 300K

$$\sigma_2 = \sigma_0 e^{-\frac{1.2\text{ eV}}{2k_B(300)}} \quad \text{...(ii)}$$

Dividing (i) by (ii)

$$\frac{\sigma_1}{\sigma_2} = e^{-\left[\frac{0.6\text{ eV}}{600k_B} - \frac{0.6\text{ eV}}{300\,k_B}\right]} = e^{+\frac{0.6}{8.62\times10^{-5}}\left[\frac{1}{600}\right]}$$

$$\frac{\sigma_1}{\sigma_2} = e^{11.6} = 1\times10^5$$

So, $\sigma_{(600\text{K})} = 10^5\,\sigma_{(300\text{K})}$

Conductivity increases rapidly with the rise of temperature.

8. In a *p-n* junction diode, the current *I* can be expressed as

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

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

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

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

(c) What is the dynamic resistance?

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

Sol. The current *I* through a junction diode is given as

$$I = I_0\left[\exp\left(\frac{eV}{k_BT}\right) - 1\right]$$

where $I_0 = 5 \times 10^{-12}$ A, $T = 300$K,

$k_B = 8.6 \times 10^{-5}$ eVK^{-1}

$= 8.6 \times 10^{-5} \times 1.6 \times 10^{-19}$ JK^{-1}.

(a) When $V = 0.6$ V

$$\frac{eV}{k_BT} = \frac{1.6\times10^{-19}\times0.6}{8.6\times1.6\times10^{-24}\times300} = \frac{600}{8.6\times3} = 23.26$$

$$\therefore\ I = I_0\left[\exp\left(\frac{eV}{k_BT}\right) - 1\right]$$

$= 5 \times 10^{-12}$ [exp (23.26) −1] A

$= 5 \times 10^{-12}$ [1.2586×10^{10} − 1] A

$= 5 \times 10^{-12} \times 1.2586 \times 10^{10}$ A

= 0.06293 A.

(b) When $V = 0.7$ V,

$$\frac{eV}{k_BT} = \frac{1.6\times10^{-19}\times0.7}{8.6\times1.6\times10^{-24}\times300} = 27.13$$

$$\therefore\ I = I_0\left[\exp\left(\frac{\text{eV}}{k_BT}\right) - 1\right]$$

$= 5 \times 10^{-12}$ [exp (27.13) − 1] A

$= 5 \times 10^{-12} \times [6.07 \times 10^{11} - 1]$ A

$= 5 \times 10^{-12} \times 6.07 \times 10^{11}$ A = 3.035 A

Increase in current, $\Delta I = 3.035 - 0.06293 = 2.972$ A.

(c) For $\Delta V = 0.7 - 0.6 = 0.1$ V, $\Delta I = 2.972$ A

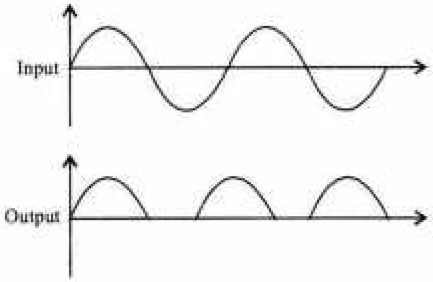
Dynamic resistance, $r_d = \dfrac{\Delta V}{\Delta I} = \dfrac{0.1}{2.972} = 0.0336\ \Omega$.

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

$$I \quad -I_0 = -5\times10^{-12}\text{ A.}$$

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

Sol. In half wave rectification, only one ripple is obtained per cycle of the output.

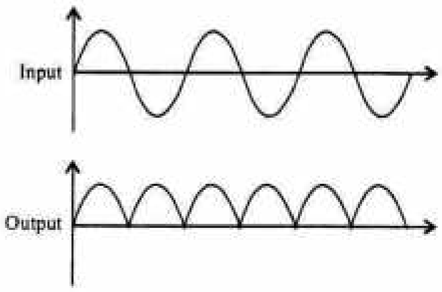


Output frequency of a half wave rectifier

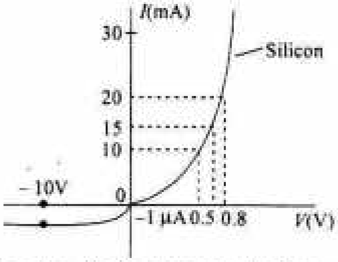
= input frequency = 50 Hz

In full wave rectification, two ripples are obtained per cycle of the output.

Output frequency = 2 × input frequency = 2 × 50 = 100 Hz



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



Sol. Considering the diode characteristics as a straight line between I = 10 mA to I = 20 mA.

Calculate the resistance using Ohm's law

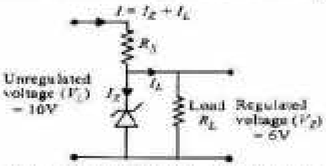
(a) From the curve, at I = 20 mA,
V = 0.8 V, I = 10 mA, V = 0.7 V
$r_{fb} = \Delta V/\Delta I$ = 0.1 V/10 mA = 10 Ω

(b) From the curve at V = – 10 V, I = – 1 μA,
Therefore slope of the graph
r_{rb} = 10 V/1μA = 1.0×10^7 Ω

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

Sol. The value of R_S should be such that the current through the Zener diode is much larger than the load current. This is to have good load regulation. Choose Zener current as five times the load current, *i.e.*, I_Z = 20 mA. The total current through R_s is, therefore, 24 mA. The voltage drop across R_S is 10.0 – 6.0 = 4.0 V. This gives

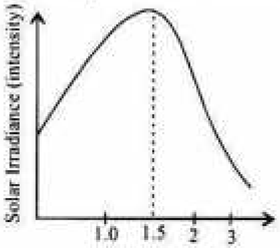
$R_S = \dfrac{4.0\text{ V}}{(24 \times 10^{-3})}$ A = 167 Ω. The nearest value of carbon resistor is 150 Ω. So, a series resistor of 150 Ω is appropriate. Note that slight variation in the value of the resistor does not matter, what is important is that the current I_Z should be sufficiently larger than I_L.



Zener diode as DC voltage regulator.

12. Why are Si and GaAs are preferred materials for solar cells?

Sol. The solar radiation spectrum is shown in figure.



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

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

13. From the output characteristic shown in figure, calculate the values of β_{ac} and β_{dc} of the transistor when V_{CE} is 10 V and I_C = 4.0 mA.

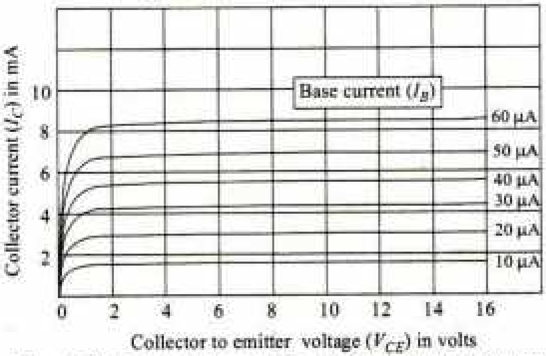


Fig.: (a) Typical input characteristics, (b) Typical output characteristics.

Sol. Consider two characteristics for two values of I_B which lie above and below the given value of I_C = 4.0 mA. So we choose the output characteristics for I_B = 30 μA and I_B = 20 μA. To determine ac current gain, we draw a vertical line corresponding to V_{CE} = 10 V. Then

$$\beta_{ac} = \left|\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}=10\text{ V}} = \frac{(4.5-3.0)\text{ mA}}{(30-20)\ \mu\text{A}} = \frac{1.5\times10^{-3}}{10\times10^{-6}} = 150$$

To determine β_{dc}, we calculate the two values of β_{dc} for the two characteristics chosen and find their mean.

For I_C = 4.5 mA and I_B = 30 μA,

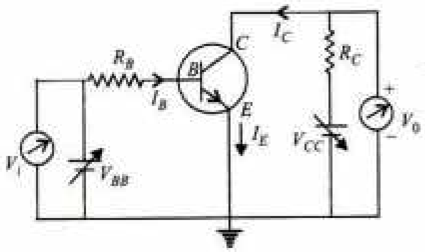
$$\beta_{dc} = \frac{I_C}{I_B} = \frac{4.5\text{ mA}}{30\ \mu\text{A}} = 150$$

For $I_C = 3.0$ mA and $I_B = 20\ \mu$A,

$$\beta_{dc} = \frac{3.0\text{ mA}}{20\ \mu\text{A}} = 150$$

Hence $\beta_{dc} = \dfrac{150+150}{2} = 150$

14. In figure the V_{BB} supply can be varied from 0V to 5.0V. The Si transistor has β_{dc} = 250 and R_B = 100 kΩ, R_C = 1 kΩ, V_{CC} = 5.0V. Assume that when the transistor is saturated, V_{CE} = 0V and V_{BE} = 0.8V. Calculate (a) the minimum base current, for which the transistor will reach saturation. Hence (b) determine V_1 when the transistor is 'switched on'. (c). Find the ranges of V_1 for which the transistor is 'switched off and 'switched on'.



Sol. Given at saturation V_{CE} = 0V, V_{BE} = 0.8V

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

$I_C = V_{CC}/R_C$ = 5.0V/1.0 kΩ = 5.0 mA

Therefore $I_B = I_C/\beta$ = 5.0 mA/250 = 20 μA

The input voltage at which the transistor will go into saturation is given by

$$V_{IH} = V_{BB} = I_B R_B + V_{BE}$$
$$= 20\ \mu\text{A} \times 100\text{ k}\Omega + 0.8\text{V} = 2.8\text{V}$$

The value of input voltage below which the transistor remains cutoff is given by

$$V_{IL} = 0.6\text{V},\ V_{IH} = 2.8\text{ V}$$

Between 0.0V and 0.6V, the transistor will be in the 'switched off' state. Between 2.8V and 5.0V, it will be in 'switched on' state.

Note that the transistor is in active state when I_B varies from 0.0 mA to 20 mA. In this range, $I_C = \beta I_B$ is valid. In the saturation range, $I_C \le \beta I_B$.

15. Two amplifiers are connected one after the other in series (cascaded). The first amplifier has a voltage gain of 10 and the second has a voltage gain of 20. If the input signal is 0.01 volt, calculate the output ac signal.

Sol. Total voltage gain can be calculated as

$$A_v = A_{v_1} \times A_{v_2}$$
$$A_v = 10 \times 20 = 200$$
$$A_v = \frac{V_{\text{output}}}{V_{\text{input}}}$$
$$200 = \frac{V_{\text{out}}}{0.01} \quad , \quad V_{\text{out}} = 2\text{ V}$$

16. For a *CE*-transistor amplifier, the audio signal voltage across the collector resistance of 2 kΩ is 2 V. Suppose the current amplification factor of the transistor is 100, find the input signal voltage and base current, if the base resistance is 1 kΩ.

Sol. Here R_C = 2 kΩ = 2000 Ω,

R_B = 1 kΩ = 1000 Ω, β = 100, V_0 = 2 V

(i) Voltage gain, $\dfrac{V_0}{V_i} = \dfrac{\beta R_0}{R_i}$ or $\dfrac{2}{V_i} = 100 \times \dfrac{2000}{1000}$

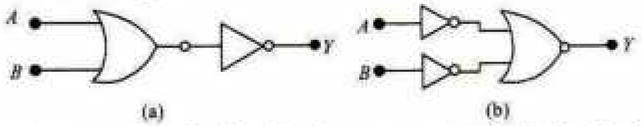
∴ Input signal voltage, V_i = 0.01 V.

(ii) $\beta = \dfrac{I_C}{I_B} = \dfrac{V_0 / R_C}{I_B}$

∴ Base current,

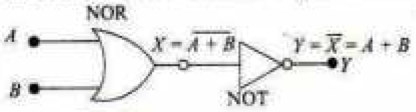
$$I_B = \frac{V_0}{\beta R_C} = \frac{2}{100 \times 2000} = 10^{-5}\text{ A} = 10\ \mu\text{A}$$

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



Sol. Let us first find the Boolean expression for logic circuit

(a)



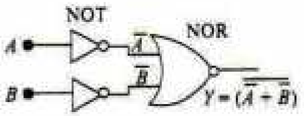
Here $X = \overline{A+B}$

and $Y = \overline{X} = \left(\overline{\overline{A+B}}\right) = A + B$

So, above logic circuit provide output as OR gate.

Now let us find the Boolean expression for logic circuit

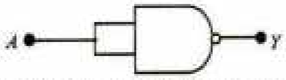
(b)



By De-morgan's theorem we know $\left(\overline{\overline{A} + \overline{B}}\right) = A \cdot B$

So, above logic circuit provide output as AND gate

18. Write the truth table for a NAND gate connected as given in figure.



Here the input *A* is connected at both points.

Sol. The Boolean expression for NAND gate will be

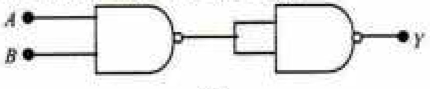
$$Y = (\overline{A \cdot A}) \quad \text{or} \quad Y = \overline{A}$$

Truth table

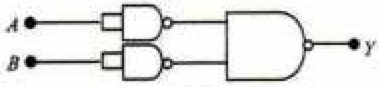
A	A	$A \cdot A$	$Y = \overline{A}$
0	0	0	1
1	1	1	0

The circuit operates like a NOT gate.

19. You are given two circuits as shown in figure which consist of NAND gates. Identify the logic operation carried out by the two circuits.

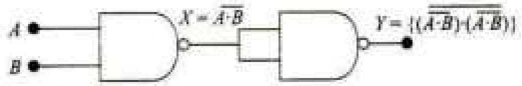


(a)



(b)

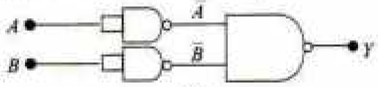
Sol. (a) Let us find Boolean expression for given logic circuit



so, output $Y = \left\{\overline{\overline{A \cdot B} \cdot \overline{A \cdot B}}\right\} = \overline{\overline{A \cdot B}} = A \cdot B$

Hence logic circuit operates as AND gate.

(b) Let us first find the Boolean expression for logic circuit



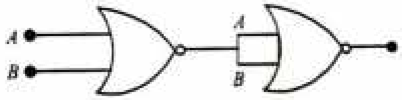
(b)

By De-Morgan's theorem

$$\left(\overline{\overline{A} \cdot \overline{B}}\right) = \overline{\overline{A}} + \overline{\overline{B}} = A + B$$

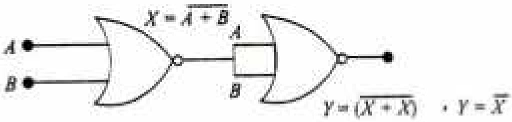
so, the given logic circuit function as OR gate.

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



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

Sol. Let us find the Boolean expression for the logic circuit.



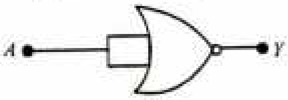
So, output $Y = \overline{X} = \left(\overline{\overline{A + B}}\right) = A + B$

Hence, the output of given logic circuit shows that logic circuit acts as OR gate.

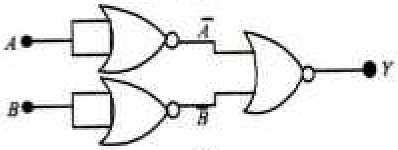
Truth Table

First NOR gate				Second NOR gate		
A	B	$A + B$	$X = \overline{A + B}$	$A = X$	$B = X$	$Y = \overline{X}$
0	0	0	1	1	1	0
0	1	1	0	0	0	1
1	0	1	0	0	0	1
1	1	1	0	0	0	1

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

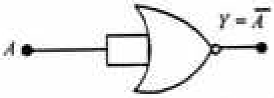


(a)



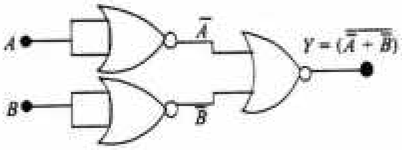
(b)

Sol. Boolean expression for logic circuit (a)



Here the given NOR gate with short circuit input is acting as NOT gate.

Boolean expression for logic circuit (b)



So, output by De-Morgan's theorem

$Y = \left(\overline{\overline{A} + \overline{B}}\right) = A \cdot B$

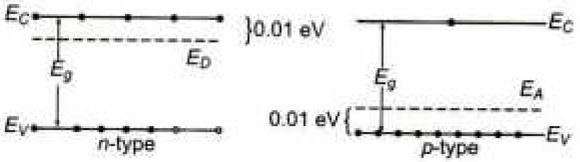
Hence the logic circuit act like AND gate.

A	B	$X = \overline{A} + \overline{B}$	$Y = \overline{X}$
0	0	1	0
0	1	1	0
1	0	1	0
1	1	0	1

Write two characteristic features to distinguish between n-type and p-type semiconductors.

Sol. (*i*) In *n*-type semiconductor, the semiconductor is doped with pentavalent impurity. The electrons are majority carriers and holes are minority carriers or $n_e >> n_h$, (n_e = number density of electrons, n_h = number density of holes).

In energy band diagram of *n*-type semiconductor, the donor energy level E_D is slightly below the bottom of conduction band E_C and thus, the electron can move to conduction band, even with small supply of energy.



(*ii*) In *p*-type semiconductor, the semiconductor is doped with trivalent impurity. The holes are the majority carriers and electrons are the minority carriers i.e. $n_h >> n_e$.

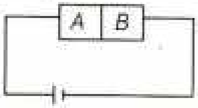
In energy band diagram of *p*-type, the acceptor energy level is slightly above the top of valence band E_V.

Thus, even with small supply of energy electron from valence band can jump to level, E_A and ionise the acceptor, negatively.

The current in the forward bias is known to be more (mA) *than the current in the reverse bias* (μA). *What is the reason, to operate the photodiode in reverse bias?*

Sol. When photodiode is illuminated with light due to breaking of covalent bonds, equal number of additional electrons and holes comes into existence whereas fractional change in minority charge carrier is much higher than fractional change in majority charge carrier. Since, the fractional change of minority carrier current is measurable significantly in reverse bias than that of forward bias. Therefore, photodiode are connected in reverse bias.

There are two semiconductor materials A and B is made by doping Germanium crystal with indium and arsenic respectively. As shown in the given figure, it is biased with a battery. Will the junction be forward bias and reverse bias?



Sol. As, semiconductor *A* is doped with indium, so it behaves as *p*-type semiconductor and *B* is doped with arsenic. It behaves as *n*-type semiconductor. So, figure shows that it is forward bias condition.