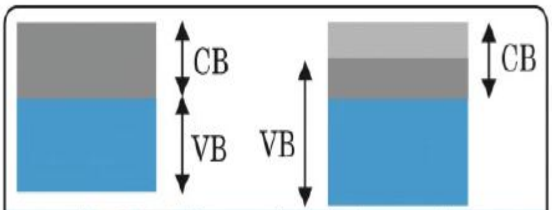
CHAPTER - 0

DIFFERENCE BETWEEN METALS, INSULATORS AND SEMICONDUCTORS ON THE BASIS OF ENERGY BANDS

Metals (Conductors)

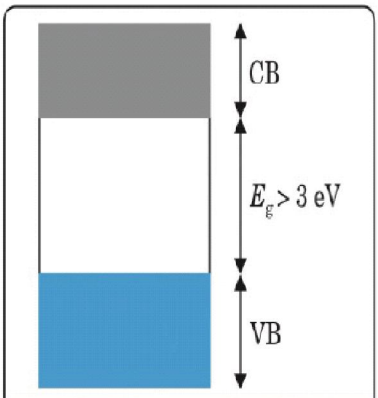
Energy band in a metal or conductor is formed in such a manner that there is almost no forbidden gap between valence band and conduction band or in some cases valence band considerably overlaps the conduction band (refer to Fig.). Hence, in case of conductors many electrons are available in conduction band, hence they are good conductor of electricity.



. Energy bands in metals.

2.1.2. Insulators

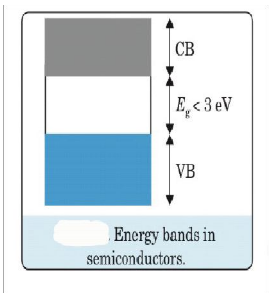
In case of insulators valence band is totally filled but conduction band is completely empty (Fig.2.3). The forbidden gap between the two bands is large and usually more than 3 eV. In case of diamond the forbidden gap is 6 eV. In normal temperature range it is nearly impossible for the electrons to cross to the conduction band. Hence, electrical conduction in these materials is nearly impossible.



. Energy bands in insulators.

2.1.3. Semiconductors

In case of semiconductors valence band is filled and conduction band is empty at absolute zero temperature (Fig) But energy gap between the two bands is very small and usually less than 3 eV. At absolute zero temperature electrons are unable to gain this small amount of energy also and hence semiconductor behaves like insulator at absolute zero temperature. But at room temperature some of the electrons of valence band are to acquire sufficient energy to cross the small energy gap between the bands. So, there are some electrons in conduction band. Hence, at room temperature semiconductors acquire some conductivity.



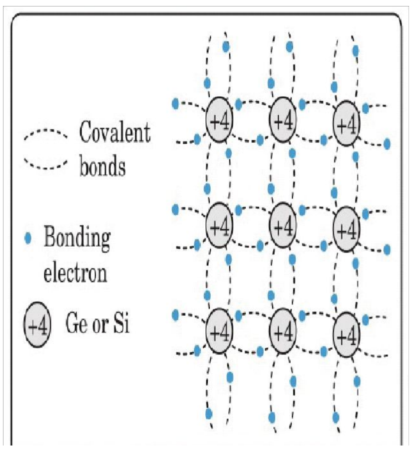
Energy bands in semiconductors.

TYPES OF SEMICONDUCTORS

Intrinsic Semiconductor

Semiconductors in their pure states are called intrinsic semiconductors. Silicon and germanium in their pure states are two examples of intrinsic semiconductors. There are four electrons in the outermost orbit of silicon as well as of germanium. In crystal of silicon and germanium, each atom shares one of its four valence electrons with each of its four nearest neighbours. Thus, after sharing electrons with neighbours, each of the atom of the crystal gets eight electrons in outermost orbit to achieve stability. The kind of bonding achieved through the sharing of electrons between atoms is called covalent bond or we can also call it valence bond.

Electrons of outermost orbits participating in covalent bonds are said to be in valence band. At low temperature all the electrons remain in valence band and hence all covalent bonds remain intact. But when temperature is increased then some of the electrons in covalent bonds acquire extra energy and are freed. These free electrons are said to be in conduction band. Electrons in conduction band participate in conduction of electricity when electric field is applied



We cell broken covalent bond as a hole and assume that it carries a positive charge that is equal in magnitude to the charge of electron. Flow of electrons in in a direction can be equivalently assumed as flow of positive charge in opposite direction.

When electric field is applied then electrons in valence band keep moving opposite to the field in order to fill adjacent vacancies or holes and thus we get equivalent flow of holes in the direction of field.

Now we can say that when electric field is applied across the semiconductor then negatively charged electrons in the conduction band start moving in the direction opposite to the applied electric field and holes in the valence band start moving in the direction of electric field. This way we get two streams of current in the same direction as we know that direction of electric current is assumed in the direction of moving positive charge and opposite to the direction of negative charge. Let I_e be the electronic current and I_h be the hole current then total current flowing in the semiconductor can be written as follows:

$I + I_e + I_h$

Although there are two streams of current flowing in the semiconductor, but still overall current remains small.

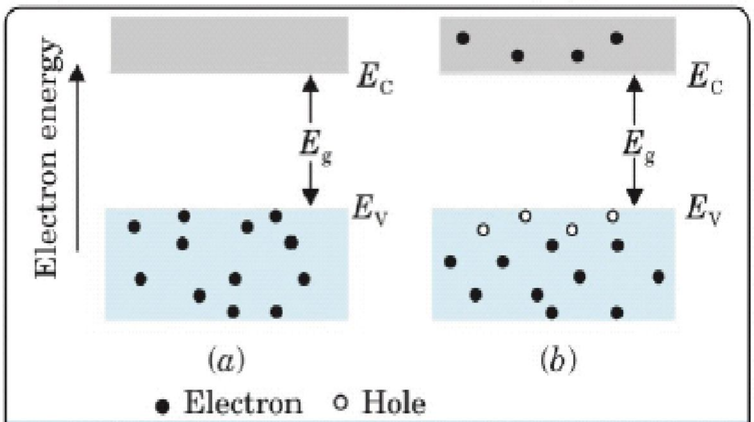
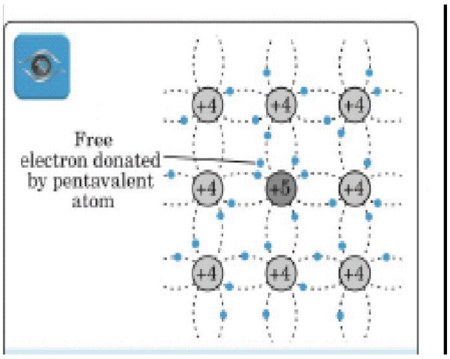


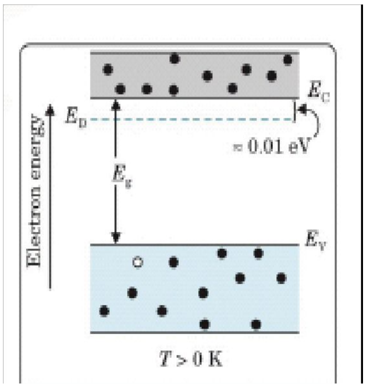
Fig. 3.3. (*a*) Energy bands of an intrinsic semiconductor at $T = 0$ K, (*b*) Energy bands of an intrinsic semiconductor at $T > 0$ K.

Extrinsic Semiconductor

As we have discussed earlier that semiconductors can conduct electricity but their conductivity is very small at room temperature. Conductivity of semiconducting materials can be drastically improved with the addition of controlled amount of impurities in pure crystal of semiconductor material. Suitable impurity addition of one atom per million original atoms can change the conductivity of semiconductor manifold.

When pentavalent impurity is added to the crystal of tetravalent Si or Ge then we obtain n-type semiconductor. There are four electrons in outermost orbit of Si and Ge each one of which is shared with four neighbouring atoms to form covalent bonds. Pentavalent atom contains five electrons in its outermost orbit. When pentavalent atom occupies position of Si or Ge atom in the crystal then four of its electrons are used to form the covalent bond with four neighbouring Si or Ge atoms but fifth electron is extra. This fifth electron remains loosely bounded to the parent atom. Energy level of this fifth electron is found to be very close to the conduction band. Hence, this electron can be easily freed to become free electron. As the electron gets freed, the depand becomes positively charged but overall material remains neutral.





So in a semiconductor doped with suitable amount of pentavalent impurity, electrons are majority charge carriers and holes are minority charge carrier. Since in this type of doped semiconductor, the electrons are majority charge carriers, so it is known as n-type semiconductor. Here n stands for negative because electrons are majority charge carrier.

following condition: $$n_e n_h = n_i^2 \quad \text{.... (1)}$$

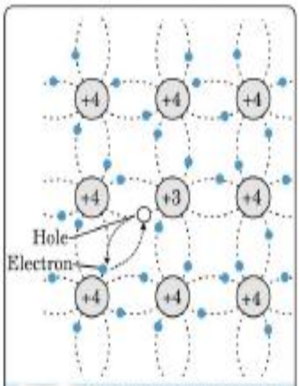
If N_D is the number of dopants atoms added to the intrinsic semiconductor then we can approximately assume it to be equal to number of majority charge carriers which is equal to n_e in n-type semiconductor.

$$n_e \approx N_D$$

(ii) p-type semiconductor

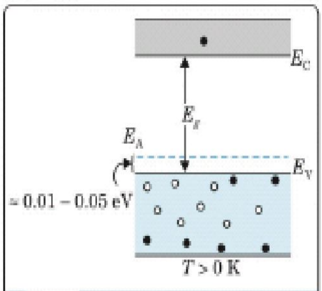
When trivalent impurity is added to tetravalent Si or Ge crystal then we obtain p-type semiconductor.

There are four electrons in the outer most orbit of Si and Ge atoms, each of which is shared with four neighbouring atoms to form covalent bonds. Trivalent atom contains three electrons in its outer most orbit. When trivalent atom occupies position of Si or Ge atom in the crystal lattice then it forms covalent bond with only three of its neighbouring Si or Ge atoms but does not have any electron to offer to complete covalent bond with the fourth Si or Ge atom . Its covalent bond with the impurity atom, in place of tetravalent Si or Ge, one incomplete covalent bond is created. This incomplete bond has a tendency to accept electron from its neighbouring complete bond just like a hole can do. Hence this incomplete bond created by impurity atom acts like a hole inside semiconductor. Trivalent impurity is referred to as acceptor impurity. Energy required by valence electrons to shift to this vacancy created by acceptor impurity is called acceptor energy level. From fig. we can observe that acceptor energy level is only slightly above the valence band. Hence, slight variation of energy is sufficient for valence electrons to shift to this vacancy created by impurity atom. We can say that vacancy in vovalent bonds created by trivalent impurity is same as hole.



Trivalent acceptor atom doped in tetravalent semiconductor forming p-type semiconductor.

Hence, in a semiconductor doped with trivalent impurity, number of holes (n_h) comprises of the holes provided by the acceptor impurity and those which are generated instrinsically due to transfer of valence electrons into conduction band. But the number of electrons (n_c) are generated only instrinsically. Hence, in this semiconductor the number of holes becomes greater than number of electrons. Moreover, when the number of holes inside a material increases, the probability of electrons combining with the holes also increases and this further reduces the number of electrons in the crystal. Hence, by controlling the concentration of impurity, number of holes can be made much larger than the number of free electrons in the semiconductor. So in a semiconductor doped with suitable amount of trivalent impurity, holes become majority charge



. Energy bands in *p*-type semicondutors at $T > 0$ K.

carriers and electrons become minority charge carriers. Since in the extrinsic semiconductor doped with the acceptor type of impurity, holes are majority charge carriers, it is known as p-type semiconductor. Here 'p' stands for positive because holes are majority charge carriers.

$$n_e n_h = n_i^2$$

If N_D is number of trivalent dopant atoms added then we can approximately assume it to be equal to the number of majority charge carriers which is n_h in p-type semiconductor.

$$n_e \approx N_D$$

Electrical conductivity of Semiconductors

In semiconductors at normal temperature range electrons are there in the conduction band and holes are also there in the valence band.

$$i_e = n_e eA\nu_e$$

$$i_h = n_h eA\nu_h$$

Substituting the values i_e and in i_n in equation (6) we get the following :

$$i = n_e eA\nu_e + n_h eA\nu_h = eA(n_e\nu_e + n_h\nu_h)$$

$$\Rightarrow \frac{i}{A} = e(n_e\nu_e + n_h\nu_h)$$

Using Ohm's law we can write the following:

$$V = iR = i\rho\frac{\ell}{A}$$

Here R is the resistance of semiconductor block and ρ is its resistivity.

$$\Rightarrow \frac{V}{I} = \rho\frac{i}{A}$$

From equation (5) we can substitute $V/I = E$. Hence, the above relation can be written as follows :

$$\Rightarrow \quad E = \rho \frac{i}{A}$$

$$\Rightarrow \quad \frac{i}{A} = \frac{E}{\rho}$$

Since reciprocal of resistivity (ρ) is defined as conductivity (σ); hence we can rewrite the above relation as follows:

$$\Rightarrow \quad \frac{i}{A} = E\sigma$$

Here i/A is the current per unit area and is known as current density (j) . The relation given in equation $(8)\, j = \sigma E$ is known as microscopic form of Ohm's law. Equating the expressions for $\frac{i}{A}$ in equation (8) and equation (7) we get the following:

$$\Rightarrow \quad E\sigma = e\left(n_e \nu_e + n_h \nu_h\right)$$

Let us rewrite the above relation as follows:

$$\Rightarrow \quad \sigma = e\left(n_e \frac{\nu_e}{E} + n_h \frac{\nu_h}{E}\right)$$

Mobility (μ) of the charge carriers is defined as the drift speed acquired by the charge carrier per unit electric field applied. We can write mobility of electrons and holes as follows:

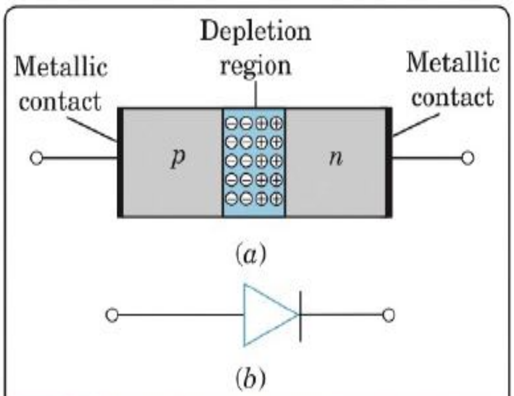
$$\mu_e = \frac{\nu_e}{E} \text{ and } \mu_h = \frac{\nu_h}{E}$$

Now in terms of mobility of electrons and holes equation (9) can be written as follows:

$$\Rightarrow \quad \sigma = e\left(n_e \mu_e + n_h \mu_h\right)$$

p-n JUNCTION

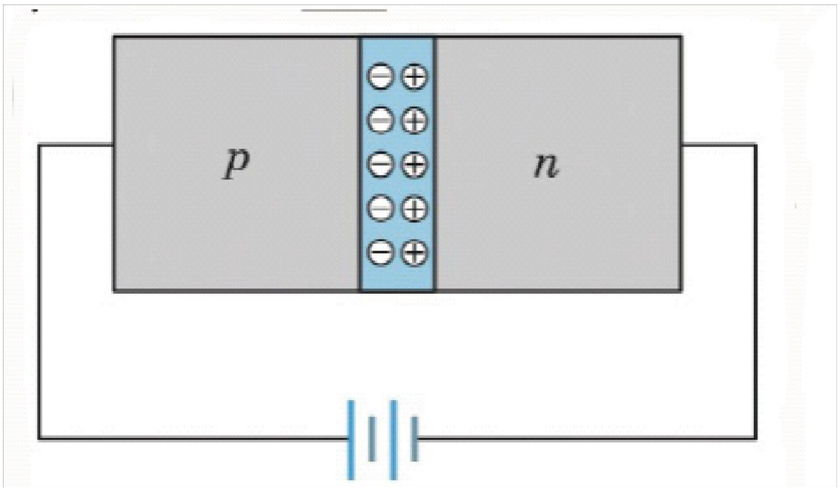
p-n juction is an important aspect of semiconductor devices like diodes and transistors. So it is important to understand first what a p-n junction is Basically when p-type semiconductor is brought in contact with n-type semiconductor then p-n junction is formed



(a) p-n junction as semiconductor diode, (b) symbolic representation of semiconductor diode.

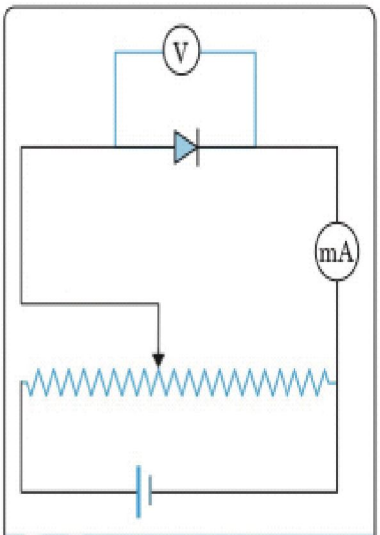
Forward Biased

When positive terminal of the battery is connected to the p-side and negative terminal is connected to the n-side of a p-n juction diode then it is said to be forward biased.

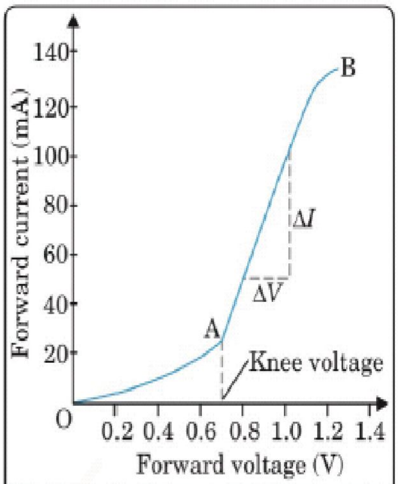


1. **Forward characteristics**

Graph between forward bias voltage across the p-n junction and the corresponding forward current (diffusion current) through the p-n junction is called forward characteristics



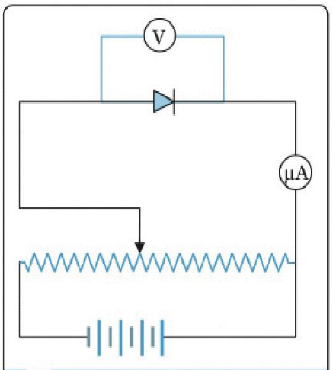
Circuit arrangement of *p-n* junction diode to study *V-I* characteristics in forward bias.



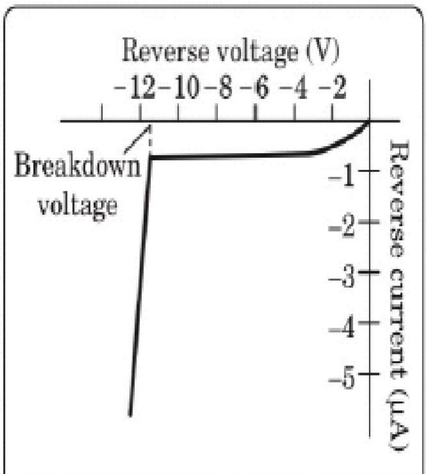
V-I characteristics of forward bias *p-n* junction.

2. **Reverse characteristics**

Graph between reverse bias voltage across the p-n junction and the corresponding reverse current (drift current) through the p-n junction is called reverse characteristics.



Circuit arrangement of *p-n* junction diode to study *V-I* characteristics in reverse bias.

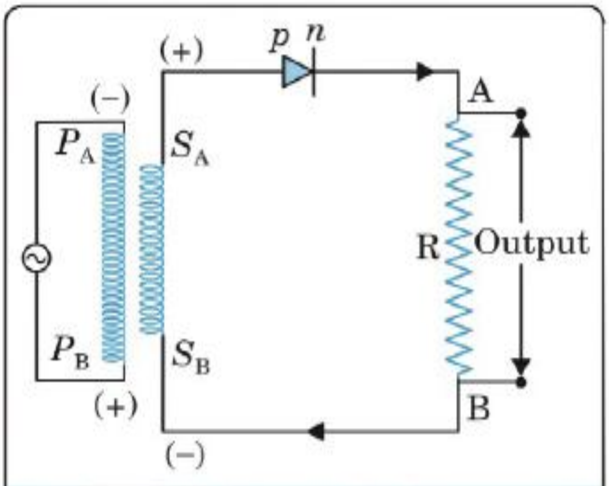


V-I characteristics for *p-n* junction in reverse bias.

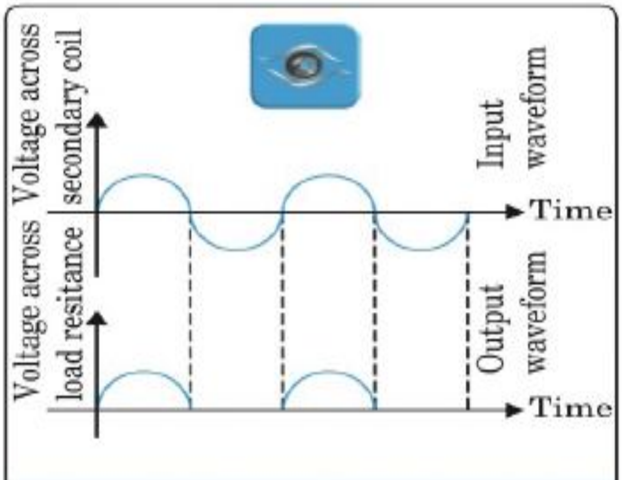
p-n Junction as Rectifier

A rectifier is a circuit which converts alternating current or voltage into direct current or voltage

Half wave Rectifier

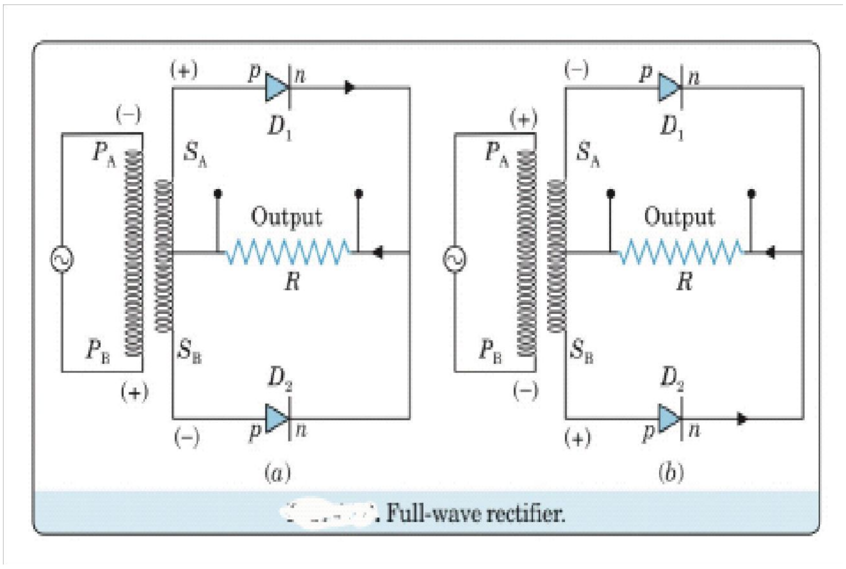


. Circuit of half-wave rectifier.

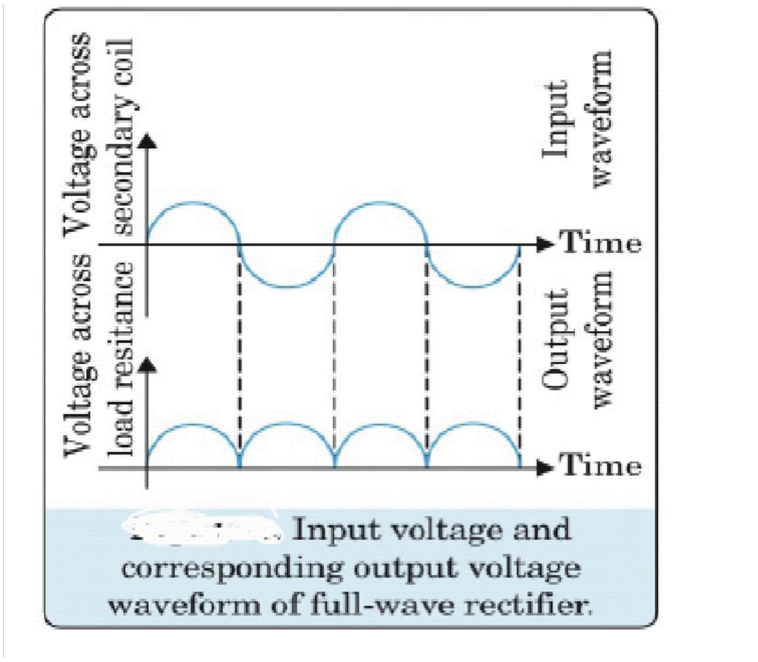


. Input and corresponding output voltage wave form from half-wave rectifier.

Full wave rectifier



. Full-wave rectifier.



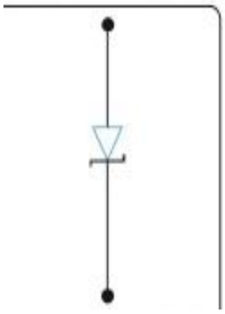
Input voltage and corresponding output voltage waveform of full-wave rectifier.

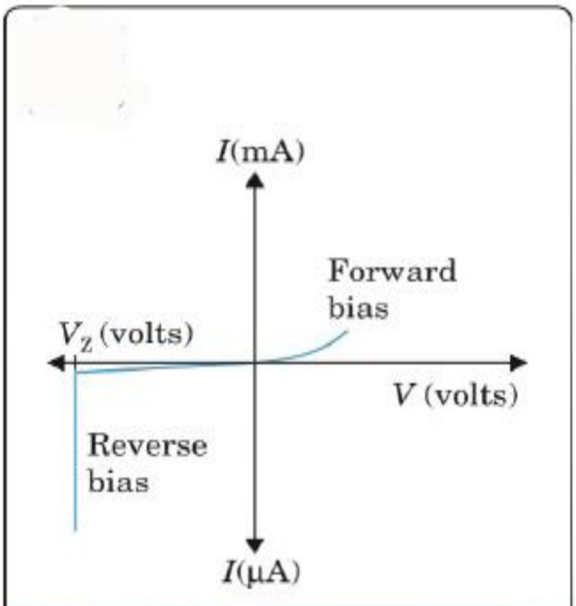
4.9 Special Purpose p-n Junction Diodes

We have already studied about the basic construction of p-n junction diode and also studied about one of its applications which is rectification of alternating voltage. There are general multipurpose diodes but some of the diodes are developed with some special purpose. We shall now discuss about such diodes which are developed for different applications.

Zener diode

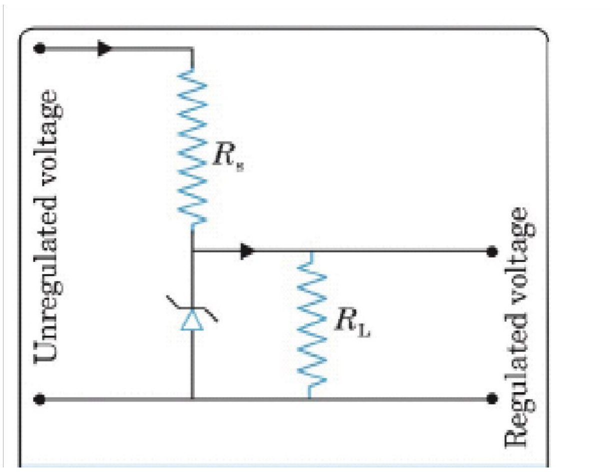
C.Zener is the name of the inventor who developed this diode and hence is the name Zener diode. It is specially designed to operate under breakdown region when connected in reverse biased mode. This diode is used as a voltage regulator because when it is in reverse biased breakdown state then voltage across its terminal does not change apprectiably inspite of large variations in the current flowing through it. If we want to see it in the perspective of Ohm's law V = IR then we can say that the device has ability to change the resistance across its junction so that the product of current and the resistance. IR, remains almost constant. Symbol that we use to denote Zener diodes in schematic circuit diagrams is as shown in Fig.





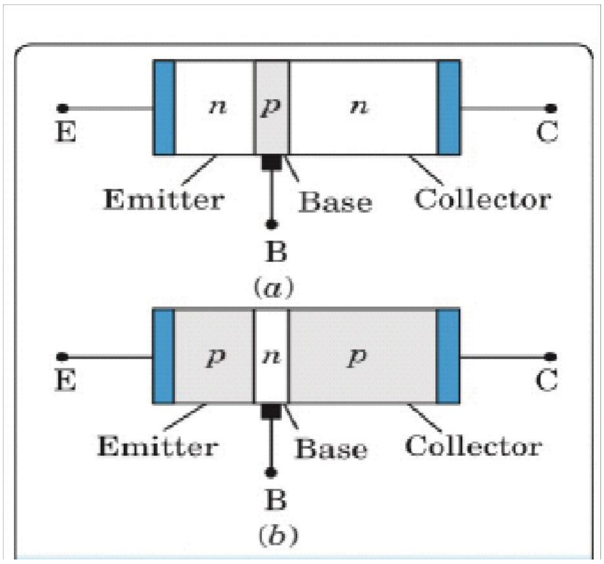
V-I Characteristics of Zener Diode.

R_s in series. Load resistance R_l across which output is to be observed is connected across the terminals of Zener diode. Zener diode is selected according to operation voltage and it operates in breakdown region for this voltage. When operating voltage increases then it increases the current throug diode and series resistance R_S. Increase in applied voltage is compensated by increase in voltage across series resistor without affecting voltage across the Zener diode even though current through the Zener diode has increased. And the reason behind this we

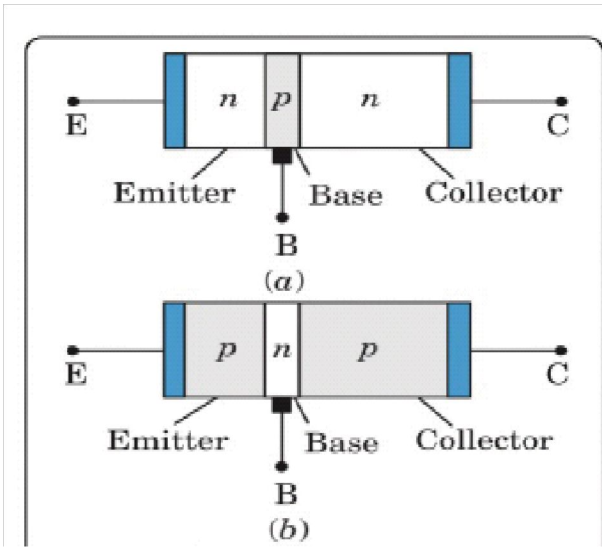


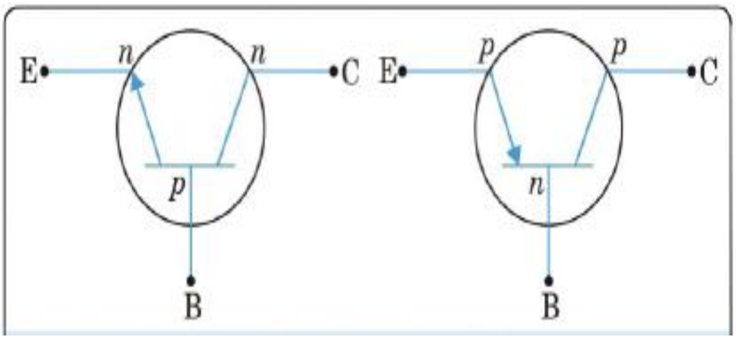
JUNCTION TRANSISTOR

We can make a transistor by sandwiching one n-type crystal between two p-type crystals or we can sandwich one p-type crystal between two n-type crystals. Two types of transistors thus formed are known as p-n-p transistor and n-p-n transistor and they are shown in Fig.



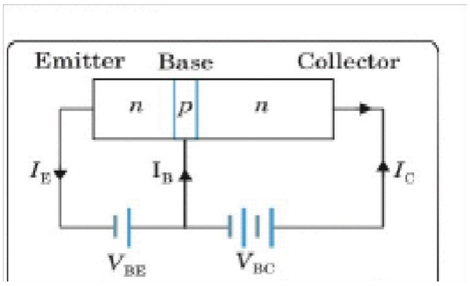
Thickness of the corresponding semiconductor in the middle of the two types of transistors is kept very small in comparison to the two on both sides. This middle region of transistor is called base. For appropriate working of the transistor thickness of the base should be kept small and also the level of doping is kept very light in the base region. Similar types of semiconductors on both sides of the base are kept smaller in comparison to base region but thickness of one is kept smaller in comparison to the other. Region with smaller thickness on one side of base is called emitter. This emitter region of transistor is heavily doped with suitable impurity. Region with greater thickness on the other side of base is called collector and this region is moderately doped. Contact area of base collector interface is kept larger than contact area between emitter and base region. Metal contacts are made with base, emitter and collector to connect the transistor in a circuit. Hence, transistor is a three terminal device.



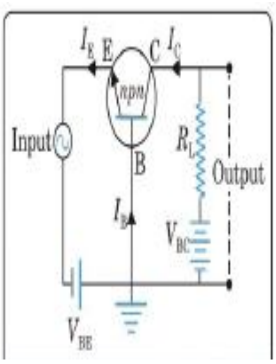


Working of n-p-n Transistor

Fig. illustrates the biasing of an n-p-n transistor. Here emitter is of n-type semiconductor and it is connected to the negative terminal and p-type base is connected to the positive terminal of the battery V_{BE}. Hence, the emitter-base junction is forward biased. Collector is of n-type semiconductor and it is connected to positive terminal of battery and p-type base is connected to the negative terminal of battery V_{BC}. Hence, collector base junction is reverse biased.

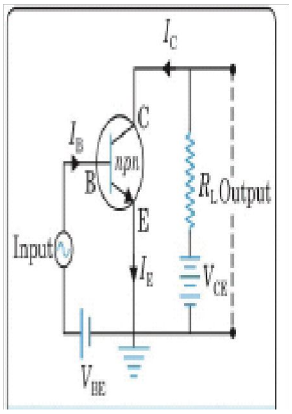


Emitter base junction is forward biased so majority charge carriers, which are electrons in n-type emitter region, start diffusing towards the p-type base region. Base region is lightly doped and very thin. So electrons diffusing towards base region come in contact with the collector region easily. And large reverse biased voltage applied to collector-base junction helps these electrons to diffuse towards the collector region. We can see that positive terminal of battery V_{BC} is connected to collector so it attracts electrons towards it. Most of the electrons diffusing from emitter towards base region are diverted towards the collector region and only a few of them combine with majority charge carrier holes present in p-type base region. If I_E is current flowing through the emitter then almost 95% of this current flows through collector as collector current I_C and remaining 5% of emitter current flows through the base as base current I_B.



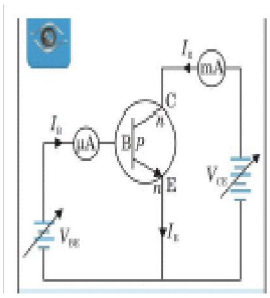
In Fig. the circuit diagram for common base configuration of a transistor is given. In this configuration, input circuit is connected between emitter and base and output circuit is connected between collector and base. Hence base is the common terminal for both input and output. Common terminal, i.e. the base is grounded in this configuration. We can say that imput is applied to emitter and output is collected at the collector.

5.5 Common Emitter Configuration



In Fig. the circuit diagram for common emitter configuration of a transistor is given. In this configuration input circuit is connected between emitter and base and output circuit is connected between collector and emitter. Hence, emitter is common terminal for both input and output. Common terminal emitter is grounded. We can say that input is applied to base and output is collected at the collector

5.9 Common Emitter Transistor Characteristic



Experimental set-up to draw the common emitter characteristic is shown in Fig. Variable potential differences V_{BE} and V_{CE} are applied to input and output sections of the circuit. Here base current I_B is called input current. Collector current I_C is called output current.

Input characteristic is graph between base current I_B and emitter voltage V_{BE} when collector voltage V_{CE} is kept constant.

Output characteristic is graph between collector current I_C and collector voltage V_{CE}, when input current I_B is kept constant.

(i) **Input characteristic:** To draw the input characteristic we fix the potential V_{CE} to a certain appropriate value and then note down base current corresponding to applied emitter voltage $V_{BE.}$

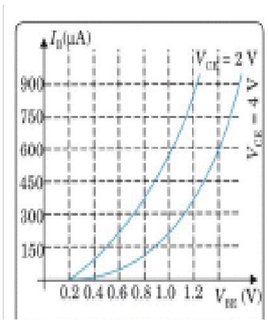
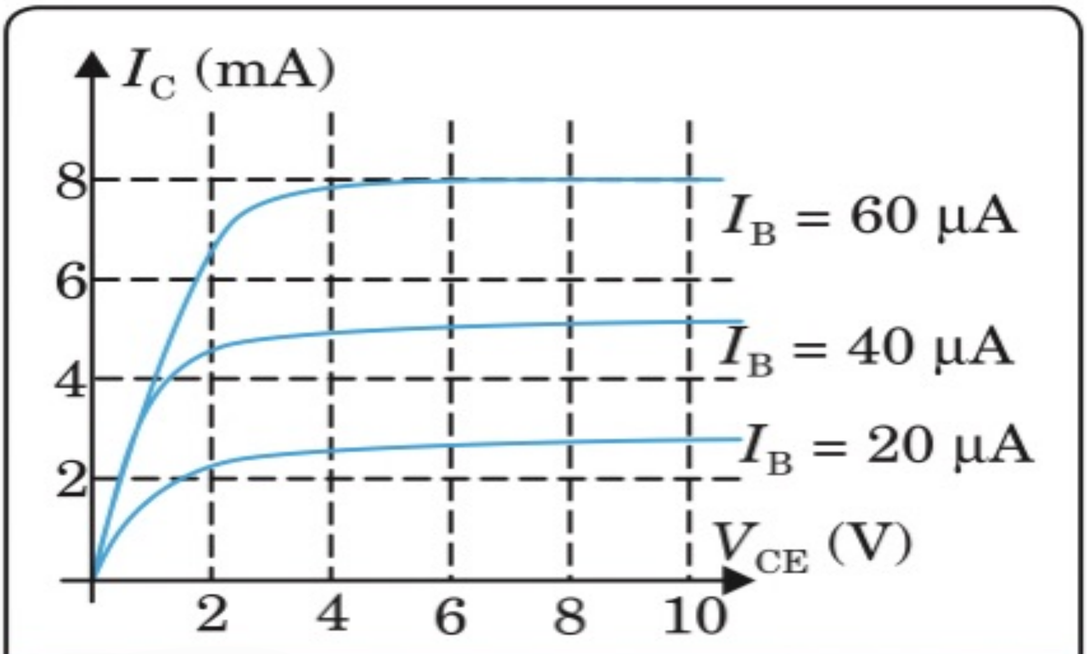


Fig. shows the input characteristic for n-p-n transistor in common emitter configuration. We can see that emitter current starts increasing rapidly with voltage V_{BE} when it is above a certain value. When the graph is redrawn for higher values of voltage V_{BE} then we get less steep curve. Hence for higher output voltage slope of input characteristic decreases. This is due to the fact that when output voltage increases then collector current increases and this reduces the growth of input current. Reverse of the slope of input characteristic is called input resistance (R_i).

ii) **Output characteristic:**

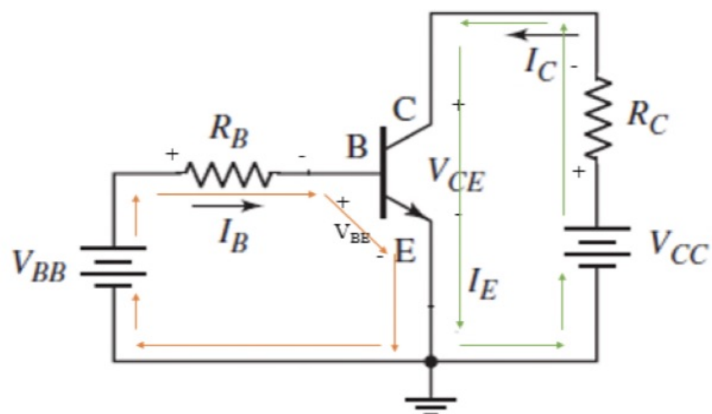
To draw the output characteristic we first fix input current I_B to a constant value. And then note down collector current through ammeter by changing potential difference between emitter and collector.



Output characteristics for *n-p-n* transistor in common emitter configuration.

Transistor as a Switch

- Transistor can be used as a switch either in Cut-off region or in Saturation region.
- Prerequisites: if potential across two terminals are maximum (battery given), then there is an open circuit (Similar to OFF Switch) between the terminals. If potential across two terminals are minimum (zero or nearly zero), then there is a short circuit (similar to ON Switch) between the terminals.
- For the better understanding of the transistor switch consider a Base biased Common Emitter configuration as shown in figure.



by writing Kirchhoff's voltage law at input side

$$+V_{BB} - I_B R_B - V_{BE} = 0$$

$$V_{BB} = I_B R_B + V_{BE} \rightarrow (1)$$

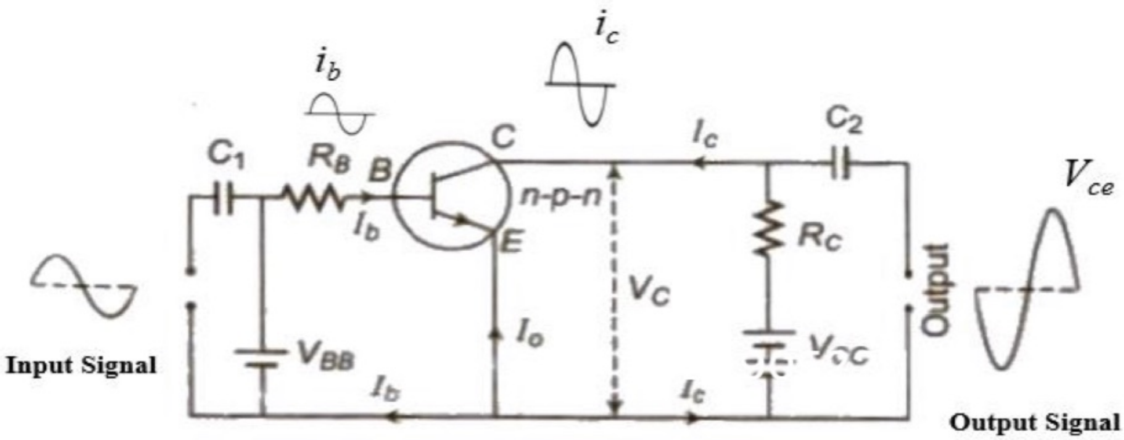
similarly, from the output side

$$+V_{CC} - I_C R_C - V_{CE} = 0$$

$$V_{CE} = V_{CC} - I_C R_C \rightarrow (2)$$

Transistor as an Amplifier

- Amplifier is an electronic device which produce large version of a very small input given at its input side.
- Transistor will work as an amplifier in the active region (*ie,* EB Junction FB & CB Junction RB).



- A small fluctuating sinusoidal input voltage corresponding to voice signal is fed to the Base of the transistor through the input coupling capacitor C_{C1}.
- This small fluctuating voltage corresponding to voice signal will cause a small fluctuating Base current i_b to flow along with the biasing current I_B.
- This fluctuating i_b and constant I_B will be transformed to the fluctuating i_c and constant I_C by the transistor at the output side.
- That is, a fluctuating sinusoidal output current i_c is generated in corresponding to fluctuating sinusoidal input base current i_b. This i_c will be β times larger version of input current i_b.
- The output voltage v_{ce} and output current i_c has inverse relationship, hence a large version of input signal with 180° phase shift is obtained at the output side.
- This can also be proven mathematically as follows,

by considering Kirchhoff's Voltage Law at input side

$$V_{BB} - I_B R_B - V_{BE} = 0$$

$$V_{BB} = I_B R_B + V_{BE}$$

Accommodating the changes due to the sinusoidal input signal equation (1) becomes,

$$V_{BB} + v_{signal} = (I_B + i_b) R_B + V_{BE}$$

Since amplification is only required for the sinusoidal signal the terms with changes can only be considered, so the above equation will become

$$\Delta v_{in} = \Delta i_b R_B$$

Similarly, by considering Kirchhoff's Voltage Law at output side

$$V_{CC} - I_C R_C - V_{CE} = 0$$

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

Incorporating changes due to the sinusoidal signal

$$V_{CE} + v_{ce\text{-}ac} = V_{CC} - (I_C + i_c) R_C$$

the terms with only changes are considered here also

$$\Delta V_O = \Delta V_{CE} = - \Delta i_c R_C$$

the voltage gain of an amplifier (the ratio of output voltage to the input voltage)

$$A_V = \frac{\Delta V_O}{\Delta V_{in}} = \frac{\Delta i_C R_C}{-\Delta i_b R_B} = \frac{-\beta R_c}{R_B}$$

- The negative sign in the equation indicates 180° phase shift between input and output.
- The output voltage of the transistor amplifier is $-\left(\frac{\beta R_c}{R_B}\right)$ times of input voltage.

$$A_v = \frac{v_0}{v_{in}} = -\left(\frac{\beta R_c}{R_B}\right)$$

$$v_0 = -\left(\frac{\beta R_c}{R_B}\right) v_{in}$$

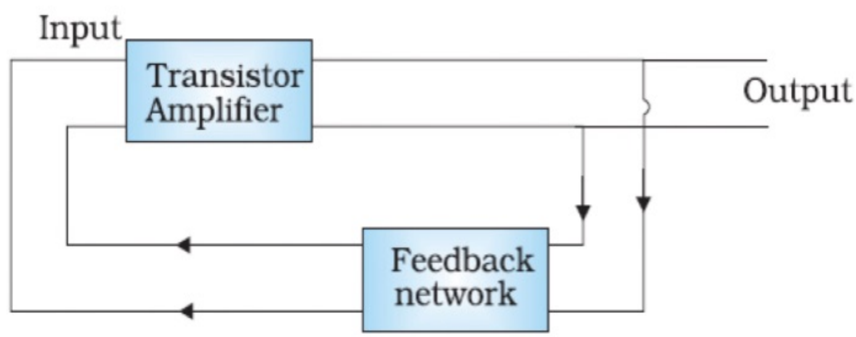
Power gain of the amplifier is given by

$$A_p = A_v \times A_I$$

$$A_p = \left(\frac{\beta R_C}{R_B}\right) \times \beta = \beta^2 \left(\frac{R_C}{R_B}\right)$$

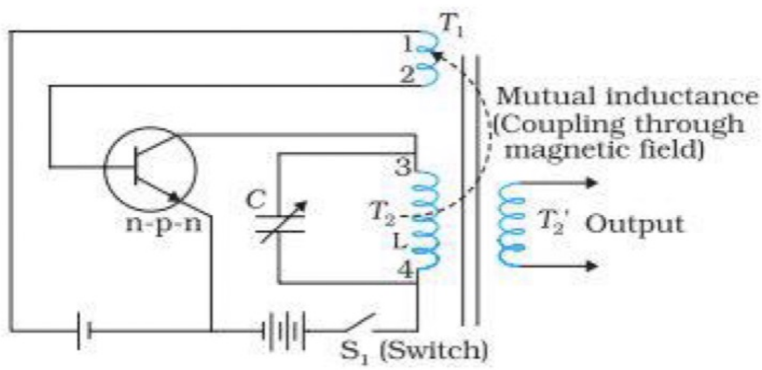
Transistor as an Oscillator

- Oscillator is an electronic device which produces continuous oscillation in its output without giving any oscillatory input.
- *That is,* oscillators generate oscillatory signals from the DC signal given to it.
- The frequency of oscillation of the oscillator is determined by type of feedback network connected.
- Logic of an oscillator is simple, feedback circuit / oscillator circuit will generate oscillations, which will be damped out due to the energy losses in the oscillator circuit. An additional part is added along with feedback to increase the energy, which has been lost in the feedback circuit (due to inductive and capacitive losses).
- *That is*, an oscillator is nothing but an amplifier connected with a feedback circuit.

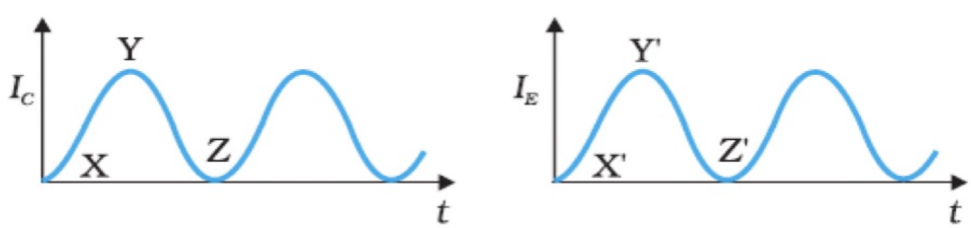


- Process of giving one portion of output to the input of a device called feedback.
- There are two types of feedback in electronics, one is positive feedback and other is negative feedback.
- An amplifier - feedback circuit satisfying Barkhausen's criteria is called as an oscillator.

- Oscillation is nothing but movement of operating point of the amplifier between cut-off and saturation.
- If LC circuit is used in the feedback, frequency is $f = \frac{1}{2\pi\sqrt{LC}}$
- If RC circuit is used in the feedback, frequency is $f = \frac{1}{2\pi RC}$
- The figure shown below is an example of a oscillator circuit, which has NPN transistor connected in tuned with LC circuit as feedback.



- In the circuit given below, if the switch S is closed, current starts flowing through Inductor coil T_2 to collector.
- Coil T_2 and T_1 are mutually coupled, induced current will be flowing through the Base of the transistor. Which will help to increase Collector current I_c and consequently I_E.
- At a particular point of time, the current through T_2 becomes maximum, hence I_B also becomes maximum. That is transistor moves to saturation.



- In this case, feedback current helped to increase output current. Then such feedback is called positive feedback. (if total phase shift is 0 or 360 then also called positive feedback)