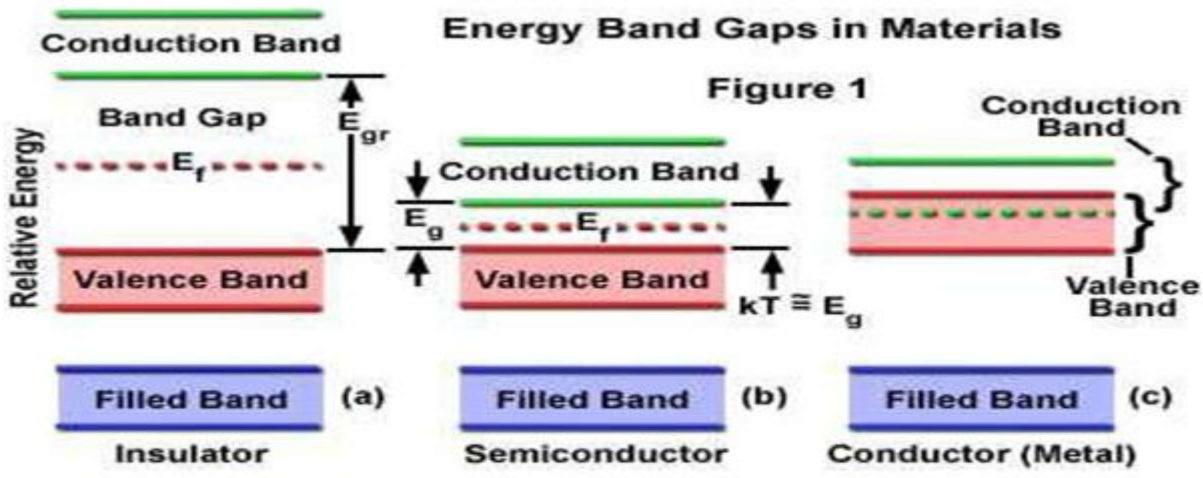
UNIT IV
SEMICONDUCTOR DIODE AND APPLICATIONS

4.1 INTRODUCTION:

We start our study of nonlinear circuit elements. These elements (diodes and transistors) are made of semiconductors. A brief description of how semiconductor devices work is rst given to understand their i v characteristics. You will see a rigorous analysis of semiconductors in the breadth courses.

4.1.1 Energy Bands in Solids:

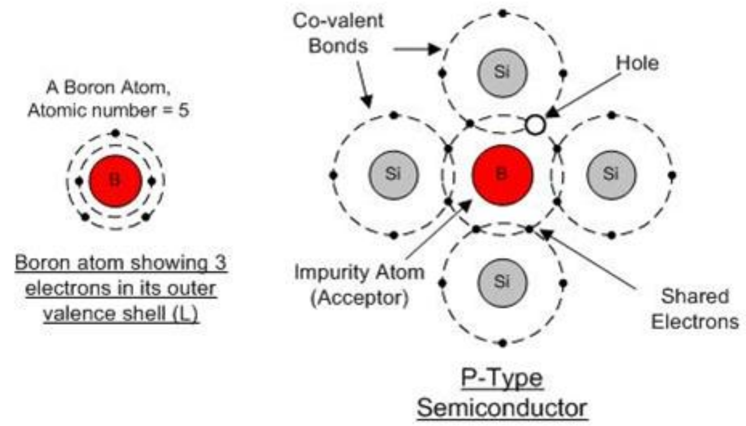


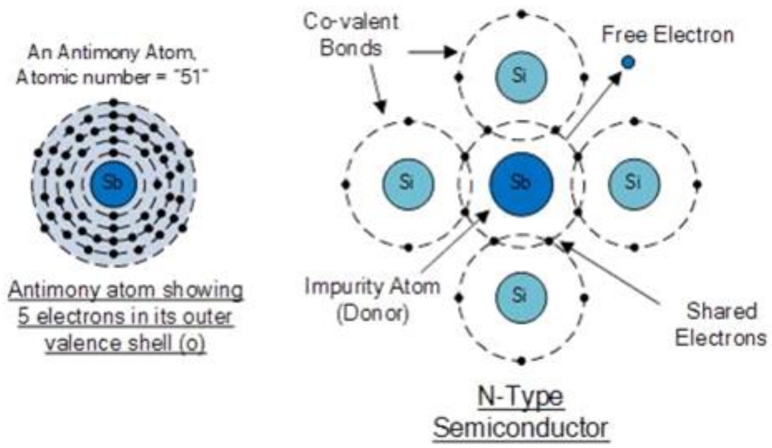
4.1.2 Semiconductors:

Semiconductor material are mainly made of elements from group IVB of the periodic table like C (diamond), Si, Ge, SiC. These material have 4 electrons in their outer most electronic shell. Each atom can form a \covalent" bond with four of its neighbors sharing one electron with that atom. In this manner, each atom \sees" eight electrons in its outer most electronic shell (4 of its own, and one from each neighbor), completely lling that shell. It is also possible to form this type of covalent bond by combining elements from group IIIB (sharing three electrons) with element from group VB (sharing ve electrons). Examples of these semiconductors are GaAs or AlGaAs and are usually called \3-5" semiconductors. We focus mostly on Si semiconductors in this class. Figure below shows this covalent

bond structure for Si. A pair of electrons and holes are slow shown. Note that Si form a tetrahedron structure and an atom in the center of the tetrahedron share electrons with atoms on the each vertex. Figure below is a two-dimensional representation of such a structure. The leftgure is for a pure Si semiconductor and an electron-hole pair is depicted. Both electrons and holes are called \mobile" carriers as they are responsible for carrying electric current.

If we add a small amount of an element from group VB, such as P, to the semiconductor, we create a n-type semiconductor and the impurity dopant is called a n-type dopant. Each of these new atoms also form a covalent bond with four of its neighbors. However, as a n-type dopant has 5 valance electron, the extra electron will be located in the \empty" energy band. As can be seen, there is no hole associated with this electron. In addition to electrons from the n-type dopant, there are electron-hair pair in the solid from the base semiconductor (Si in he above gure) which are generated due to temperature e ects. In a n-type semiconductor, the number of free electrons from the dopant is much larger than the number of electrons from electron-hole pairs. As such, a n-type semiconductor is considerably more conductive than the base semiconductor (in this respect, a n-type semiconductor is more like a \resistive" metal than a semiconductor).





In summary, in a n-type semiconductor there are two charge carriers: \holes" from the base semiconductor (called the \minority" carriers) and electrons from both the n-type dopant and electron-hole pairs (called the \majority" carrier).

Similarly, we can create a p-type semiconductor by adding an element from group IIIB, such as B, to the semiconductor. In this case, the p-type dopant generate holes. We will have two charge carriers: majority carriers are \holes" from the p-type dopant and electron-hole pairs and minority carriers are electrons from the base semiconductor (from electron-hole pairs).

The charge carriers (electrons and holes) move in a semiconductor through two mechanisms: First, charge carriers would move from regions of higher concentration to lower concentration in order to achieve a uniform distribution throughout the semiconductor. This process is called **Diff usion**" and is characterized by the diffusion coefficient, D. Second, charge carriers move under the influence of an electricfield. This motion is called the drift and is characterized by the mobility.

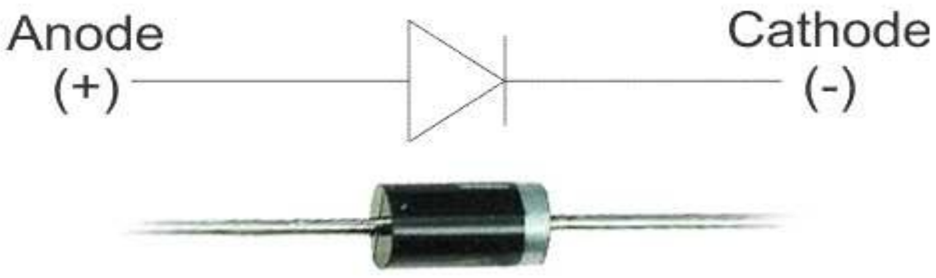
4.2 DIODE | WORKING PRINCIPLE AND TYPES OF DIODE

What is a Diode?
A diode is a device which only allows unidirectional flow of current if operated within a rated specified voltage level. A diode only blocks current in the reverse direction while the reverse voltage is within a limited range otherwise reverse barrier breaks and the voltage at which this breakdown occurs is called reverse breakdown voltage. The diode acts as a valve in the electronic and electrical circuit. A P-N junction is the simplest form of the diode which behaves as ideally short circuit when it is in forward biased and behaves as ideally open circuit when it is in the reverse biased. Beside simple PN junction diodes, there are different types of diodes although the fundamental principle is more or less same. So a particular arrangement of diodes can convert AC to pulsating DC, and hence, it is

sometimes also called as a rectifier. The name diode is derived from "di-ode" which means a device having two electrodes.

4.2.1 Symbol of Diode

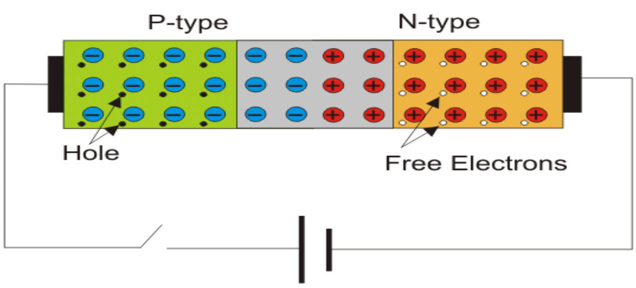
The symbol of a diode is shown below, the arrowhead points in the direction of conventional current flow.



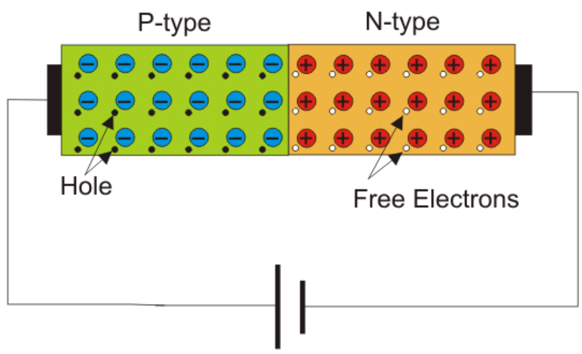
A simple **PN junction diode** can be created by doping donor impurity in one portion and acceptor impurity in other portion of a silicon or germanium crystal block. These make a p n junction at the middle portion of the block beside which one portion is p type (which is doped by trivalent or acceptor impurity) and other portion is n type (which is doped by pentavalent or donor impurity). It can also be formed by joining a p-type (intrinsic semiconductor doped with a trivalent impurity) and n-type semiconductor (intrinsic semiconductor doped with a pentavalent impurity) together with a special fabrication technique such that a p-n junction is formed. Hence, it is a device with two elements, the p-type forms anode and the n-type forms the cathode. These terminals are brought out to make the external connections.

4.2.3 Working Principle of Diode

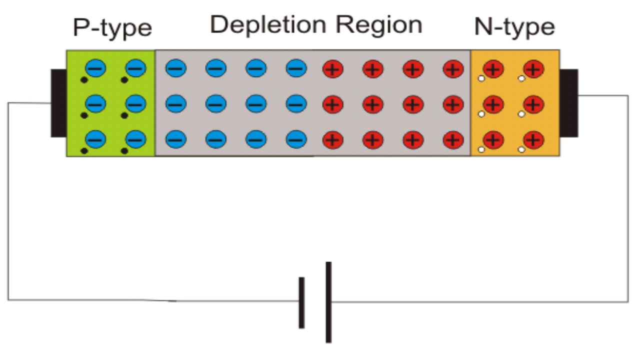
The n side will have a large number of electrons and very few holes (due to thermal excitation) whereas the p side will have a high concentration of holes and very few electrons. Due to this, a process called diffusion takes place. In this process free electrons from the n side will diffuse (spread) into the p side and combine with holes present there, leaving a positive immobile (not moveable) ion in the n side. Hence, few atoms on the p side are converted into negative ions. Similarly, few atoms on the n-side will get converted to positive ions. Due to this large number of positive ions and negative ions will accumulate on the n-side and p-side respectively. This region so formed is called as depletion region. Due to the presence of these positive and negative ions a static electric field called as "barrier potential" is created across the p-n junction of the diode. It is called as "barrier potential" because it acts as a barrier and opposes the further migration of holes and electrons across the junction.



In a PN junction diode when the forward voltage is applied i.e. positive terminal of a source is connected to the p-type side, and the negative terminal of the source is connected to the n-type side, the diode is said to be in forward biased condition. We know that there is a barrier potential across the junction. This barrier potential is directed in the opposite of the forward applied voltage. So a diode can only allow current to flow in the forward direction when forward applied voltage is more than barrier potential of the junction. This voltage is called forward biased voltage. For silicon diode, it is 0.7 volts. For germanium diode, it is 0.3 volts. When forward applied voltage is more than this forward biased voltage, there will be forward current in the diode, and the diode will become short circuited. Hence, there will be no more voltage drop across the diode beyond this forward biased voltage, and forward current is only limited by the external resistance">resistance connected in series with the diode. Thus, if forward applied voltage increases from zero, the diode will start conducting only after this voltage reaches just above the barrier potential or forward biased voltage of the junction. The time taken by this input voltage to reach that value or in other words the time taken by this input voltage to overcome the forward biased voltage is called recovery time.



Now if the diode is reverse biased i.e. positive terminal of the source is connected to the n-type end, and the negative terminal of the source is connected to the p-type end of the diode, there will be no current through the diode except reverse saturation current. This is because at the reverse biased condition the depilation layer of the junction becomes wider with increasing reverse biased voltage. Although there is a tiny current flowing from n-type end to p-type end in the diode due to minority carriers. This tiny current is called reverse saturation current. Minority carriers are mainly thermally generated electrons and holes in p-type semiconductor and n-type semiconductor respectively. Now if reverse applied voltage across the diode is continually increased, then after certain applied voltage the depletion layer will destroy which will cause a huge reverse current to flow through the diode. If this current is not externally limited and it reaches beyond the safe value, the **diode** may be permanently destroyed. This is because, as the magnitude of the reverse voltage increases, the kinetic energy of the minority charge carriers also increase. These fast moving electrons collide with the other atoms in the device to knock-off some more electrons from them. The electrons so released further release much more electrons from the atoms by breaking the covalent bonds. This process is termed as carrier multiplication and leads to a considerable increase in the flow of current through the p-n junction. The associated phenomenon is called Avalanche Breakdown.



4.3 Types of Diode

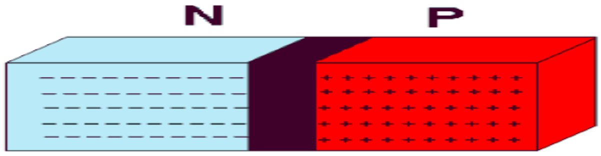
Types of diodes:

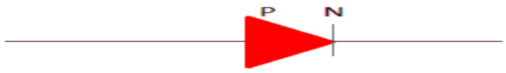
1) Zener diode
2) P-N junction diode

3) Tunnel diode
4) Varractor diode
5) Schottky diode
6) Photo diode
7) PIN diode
8) Laser diode
9) Avalanche diode
10) Light emitting diode

4.4 DIODE CHARACTERISTICS

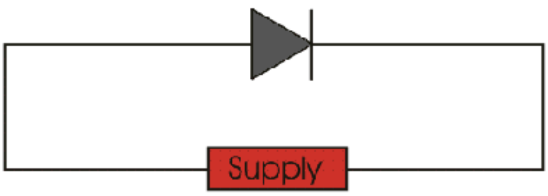
Semiconductor materials (Si, Ge) are used to form variety of electronic devices. The most basic device is diode. Diode is a two terminal P-N junction device. P-N junction is formed by bringing a P type material in contact with N type material.When a P-type material is brought in contact with N- type material electrons and holes start recombining near the junction. This result in lack of charge carriers at the junction and thus the junction is called depletion region. Symbol of P-N junction is given as:





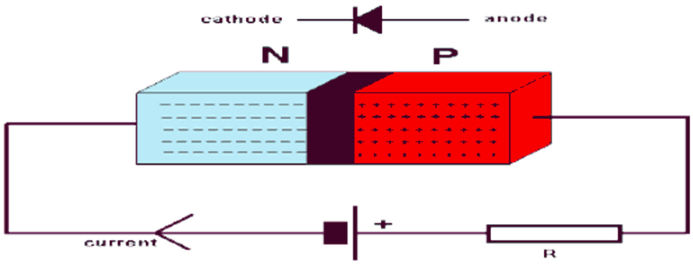
Biased i.e. when voltage is applied across the terminals of P-N junction, it is called diode.

Diode is unidirectional device that allows the flow of current in one direction only depending on the biasing.



4.4.1 Forward Biasing Characteristic of Diode

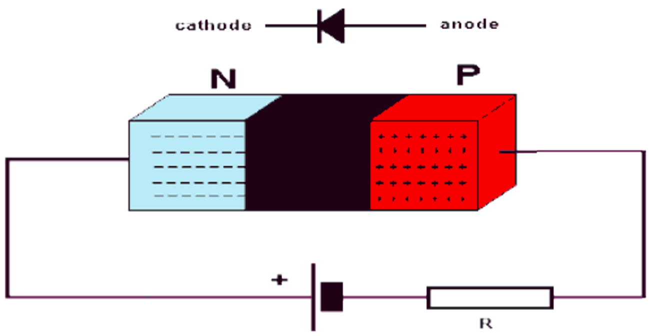
When, P terminal is more positive as compared to N terminal i.e. P- terminal connected to positive terminal of battery and N-terminal connected to negative terminal of battery, it is said to be forward biased.



Positive terminal of the battery repels majority carriers, holes, in P-region and negative terminal repels electrons in the N-region and push them towards the junction. This result in increase in concentration of charge carriers near junction, recombination takes place and width of depletion region decreases. As forward bias voltage is raised depletion region continues to reduce in width, and more and more carriers recombine. This results in exponential rise of current.

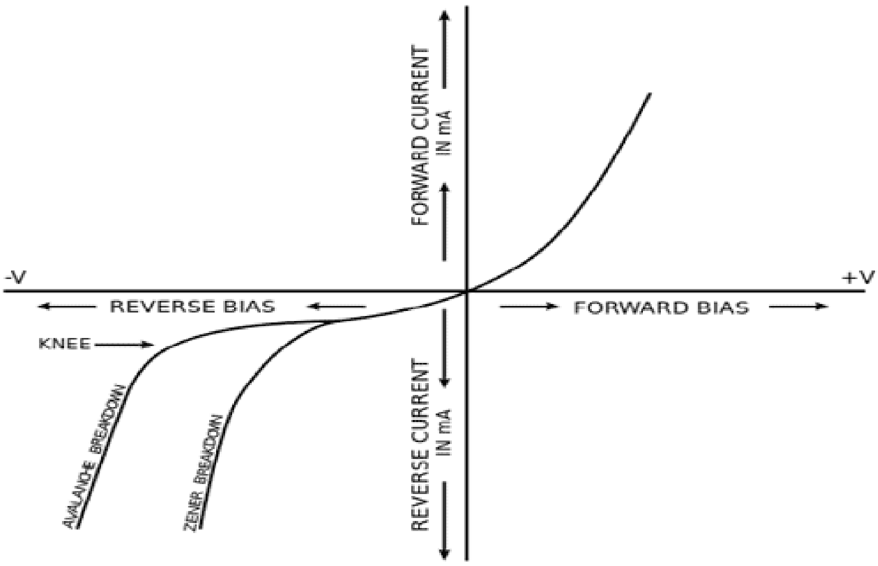
4.4.2 Reverse Biasing Characteristic of Diode

In reverse biasing P- terminal is connected to negative terminal of the battery and N- terminal to positive terminal of battery. Thus applied voltage makes N-side more positive than P-side.



Negative terminal of the battery attracts majority carriers, holes, in P-region and positive terminal attracts electrons in the N-region and pull them away from the junction. This result in decrease in concentration of charge carriers near junction and width of depletion region increases. A small amount of current flow due to minority carriers, called as reverse bias current or leakage current. As reverse bias voltage is raised depletion region continues to increase in width and no current flows. It can be concluded that diode acts only when forward biased. Operation of diode can be summarized in form of I-V **diode characteristics** graph. For reverse bias diode, V<0, $I_D = I_S$ Where, V = supply voltage I_D = diode current I_S = reverse saturation current For forward bias, V > 0, $I_D = I_S(e^{V/NV}{}_T - 1)$

Where,
V_T = volt's equivalent of temperature = KT/Q = T/11600
Q = electronic charge = 1.632 X 10^{-19} C
K = Boltzmann's constant = 1.38 X 10^{-23}
N = 1, for Ge
= 2, for Si



As reverse bias voltage is further raised, depletion region width increases and a point comes when junction breaks down. This results in large flow of current. Breakdown is the knee of **diode characteristics** curve. Junction breakdown takes place due to two phenomena

4.4.3 Avalanche Breakdown(for V> 5V)

Under very high reverse bias voltage kinetic energy of minority carriers become so large that they knock out electrons from covalent bonds, which in turn knock more electrons and this cycle continues until and unless junction breakdowns.

4.4.4 Zener Effect (for V<5V)

Under reverse bias voltage junction barrier tends to increase with increase in bias voltage. This results in very high static electric field at the junction. This static electric field breaks covalent bond and set minority carriers free which contributes to reverse current. Current increases abruptly and junction breaks down.

4.5 P-N JUNCTION DIODE AND CHARACTERISTICS OF P-N JUNCTION

The volt-ampere characteristics of a diode explained by the following equations:

$$I = I_S(e^{V_D/(\eta V_T)} - 1)$$

Where

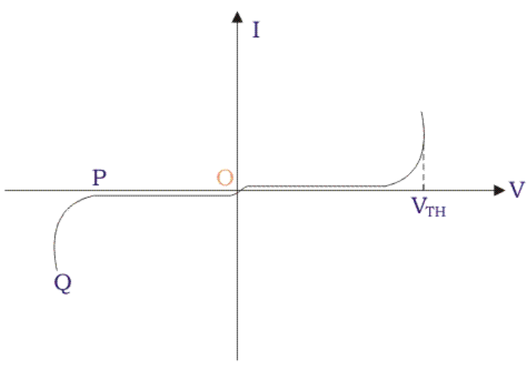
I = current flowing in the diode, I0 = reverse saturation current

VD = Voltage applied to the diode

VT = volt- equivalent of temperature = k T/q = T/ 11,600 = 26mV (@ room temp)

η = 1(for Ge) and 2 (for Si)

It is observed that **Ge** diodes has smaller cut-in-voltage when compared to **Si** diode. The reverse saturation current in **Ge** diode is larger in magnitude when compared to silicon diode.

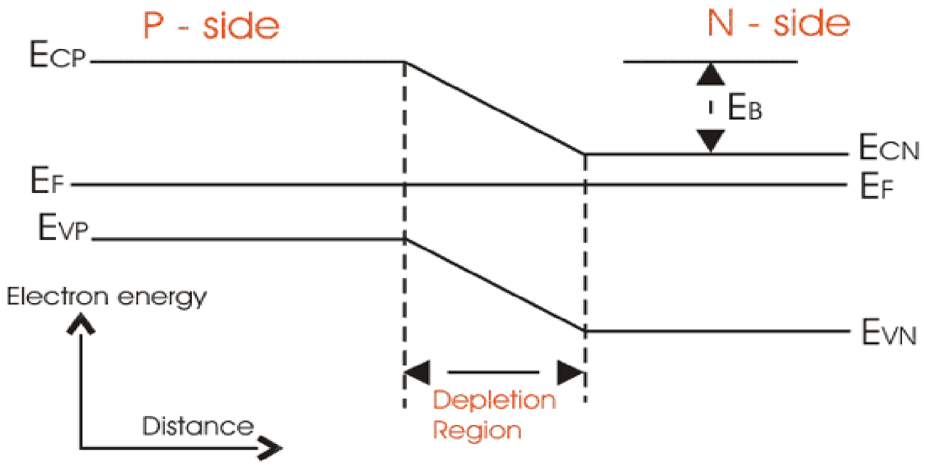


When, V is positive the junction is forward biased and when V is negative, the junction is reversing biased. When V is negative and less than VTH, the current is very small. But when V exceeds VTH, the current suddenly becomes very high. The voltage VTH is known as threshold or cut in voltage. For Silicon diode VTH = 0.6 V. At a reverse voltage corresponding to the point P, there is abrupt increment in reverse current. The PQ portion of the characteristics is known as breakdown region.

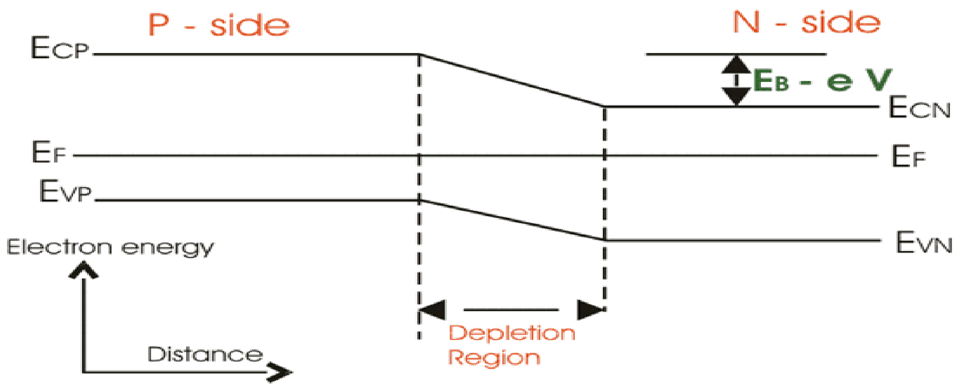
4.6 P-N Junction Band Diagram

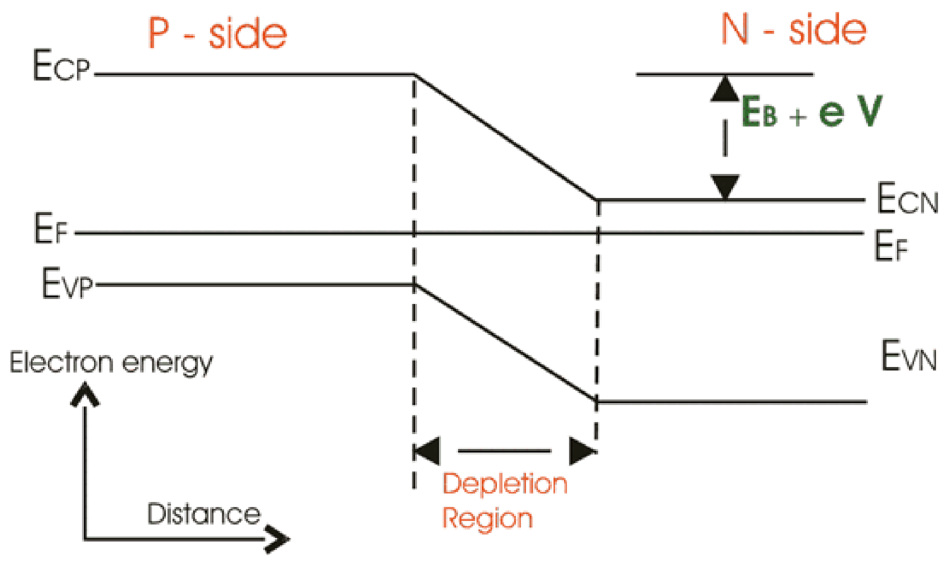
For an n-type semiconductor, the Fermi level E_F lies near the conduction band edge. E_C but for an p - type semiconductor, E_F lies near the valance band edge E_V.

Now, when a p-n junction is built, the Fermi energy E_F attains a constant value. In this scenario the p-sides conduction band edge. Similarly n–side valance band edge will be at higher level than E_{cn}, n-sides conduction band edge of p - side. This energy difference is known as barrier energy. The barrier energy is $E_B = E_{cp} - E_{cn} = E_{vp} - E_{vn}$



If we apply forward bias voltage V, across junction then the barrier energy decreases by an amount of eV and if V is reverse bias is applied the barrier energy increases by eV.





4.6.1 P-N Junction Diode Equation

The p-n junction diode equation for an ideal diode is given below

$I = I_S[\exp(eV/K_BT) - 1]$

Here,

I_S = reverse saturation current

e = charge of electron

K_B = Boltzmann constant

T = temperature For a normal p-n junction diode, the equation becomes

$I = I_S[\exp(eV/\eta K_BT) - 1]$

Here,

η = emission co-efficient, which is a number between 1 and 2, which typically increases as the current increases.

4.6.2 APPLICATIONS OF DIODES

- Rectifying a voltage, such as turning AC into DC voltages
- Isolating signals from a supply
- Voltage Reference
- Controlling the size of a signal
- Mixing signals
- Detection signals
- Lighting
- Lasers diodes

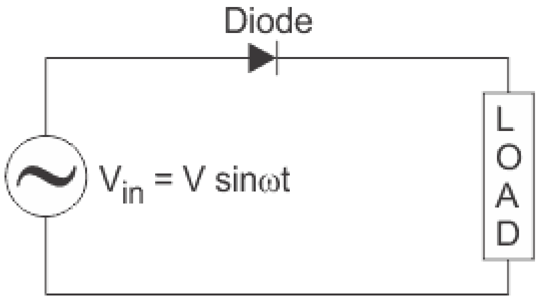
4.7 HALF WAVE DIODE RECTIFIER

Electric current flows through a p - n junction diode when it is forward biased and we get output current through the load. Let, we supply a sinusoidal voltage $V_{in} = V\sin\omega t$ as a source voltage. Now, if the input voltage is positive, the diode is forward biased and when that is negative, the diode is in reverse bias condition. When the input voltage is positive, i.e, for the positive cycle of the input voltage, the current flows through the diode.

So, the current will flow through the load also and we obtain output voltage across the load. But for the negative half cycle of the input, the p-n junction get reverse biased and no current flows through the diode as a result we obtain zero current and zero voltage across the load.

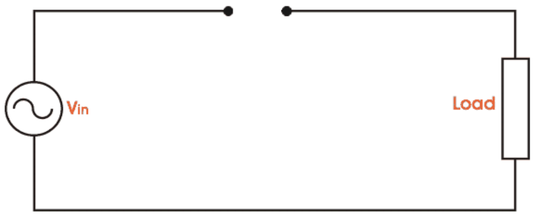
4.7.1 Circuit Diagram of Half Wave Rectifier

The basic diagram of **half wave diode rectifier** is given below,

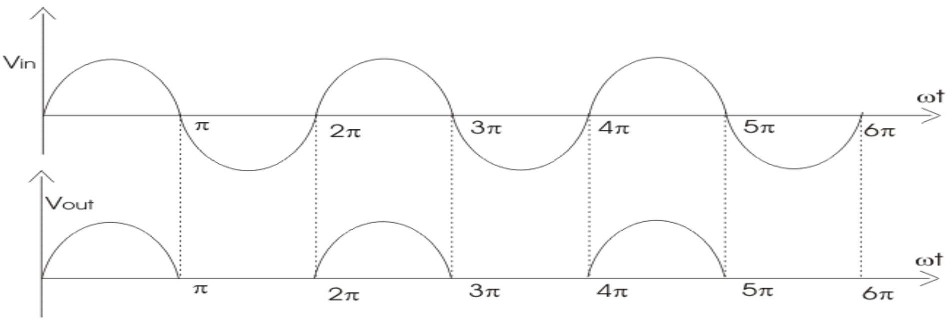


For positive half cycle

For negative half cycle



4.7.2 Input voltage and Output Voltage Waveforms



Now, different parameters for **half wave rectifier** is given below

The average of load current (I_{DC}) :
Let, the load current be $i_L = I_m \sin\omega t$,

$$I_{dc} = \frac{1}{2\pi}\int_0^{\pi} I_m\, sin\omega t = \frac{I_m}{\pi}$$

Ripple factor of half wave rectifier,

$$Ripple\ factor(r) = \frac{(I_{rms}^2 - I_{dc}^2)}{I_{dc}} = 1.21$$

The rms value of the load current (I_{rms}),

$$I_{rms} = \frac{I_m}{4}$$

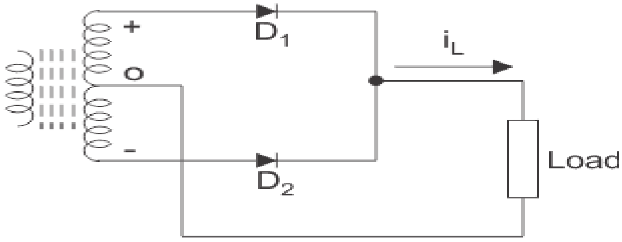
4.8 FULL WAVE DIODE RECTIFIER

The diode works only when it is in forward bias, only the current flows through p-n junction diode and output current across the load is found. If two diodes are connected in such a way that one diode conducts during one half of the input voltage and the other one conducts during the next half of the cycle, in a unidirectional can flow through the load during the full cycle of the impact voltage. This is known as **full wave rectifier.**

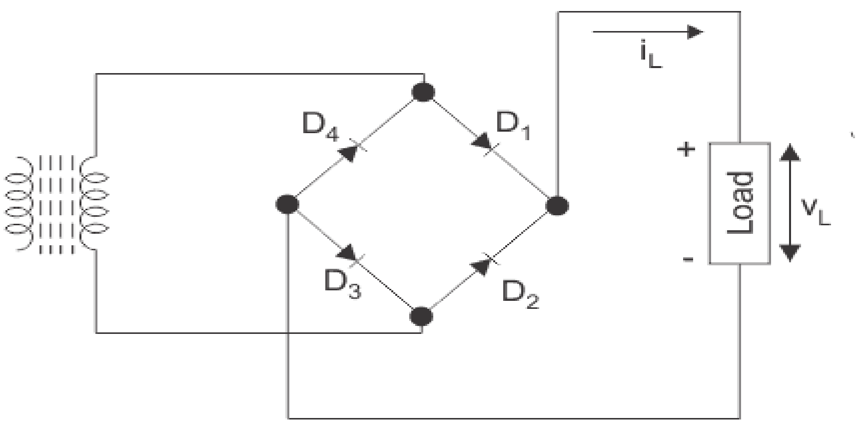
According to the diagram given below a center tapped transformer D_1, and D_2 are two p-n junction diodes with similar characteristics D_1 conducts for negative half of the output voltage. Thus we get output voltage and the output current for the entire input cycle.

4.8.1 Circuit Diagram of Full Wave Diode Rectifier

The circuit diagram of the **full wave diode rectifier** given below,

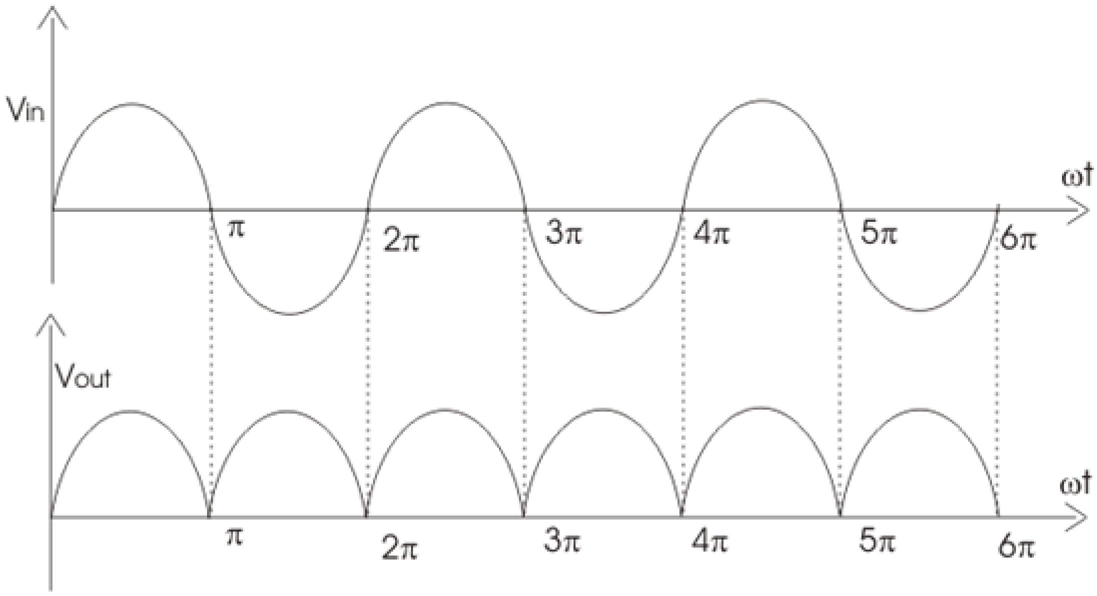


Full wave rectification can also be achieved using a bridge rectifier which is made of four diodes.



According to the figure, when D_1 and D_3 are forward biased, they conduct but D_2 and D_4 and on D_1 and D_3 are reverse biased in both cases load current in the same direction.

Bridge rectifier has several advantages over simple full wave rectifier. It performance and efficiency is better than that of the simple full time rectifier.



Now, different parameters for **half wave rectifier** is given below
The average of load current (I_{dc}) : Let, the load current be $i_L = I_m \sin\omega t$

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_m \sin\omega t = \frac{2I_m}{\pi}$$

Ripple factor of half wave rectifier,

$$Ripple\ factor(r) = \frac{(I_{rms}^2 - I_{dc}^2)^{\frac{1}{2}}}{I_{dc}} = 0.482$$

$$Here,\ I_{rms} = \frac{I_m}{\sqrt{2}}$$

4.9 HALF WAVE RECTIFIERS

Rectifiers are the circuits used to convert alternating current (AC) into direct current (DC). Half-Wave Rectifiers are designed using a diode (D) and a load resistor (R_L) as shown in Figure 1. In these rectifiers, only one-half of the input waveform is obtained at the output i.e. the output will comprise of either positive pulses or the negative pulses only. The polarity of the output voltage so obtained (across R_L) depends on the direction of the diode used in the circuit of half-wave rectifier. This is evident from the figure as Figure 1a shows the output waveform consisting of only positive pulses while the Figure 1b has only negative pulses in its output waveform.

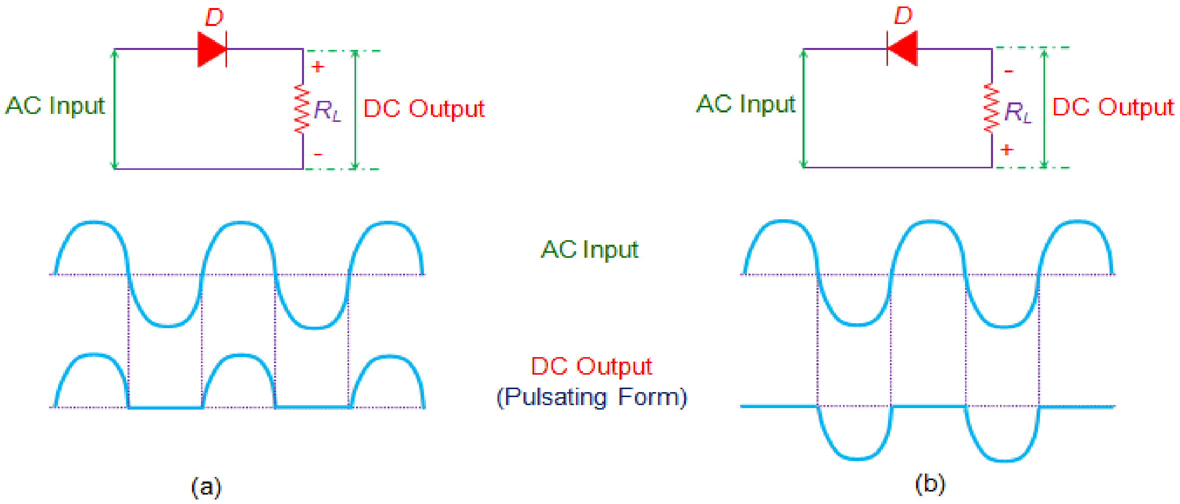


Figure 1 Half Wave Rectifier with Input and Output Waveforms

This is because, in Figure 1a the diode gets forward biased only during the positive pulse of the input which causes the current to flow across R_L, producing the output voltage.

Further for the same case, if the input pulse becomes negative, then the diode will be reverse biased and hence there will be no current flow and no output voltage. Similarly for the circuit shown in Figure 1b, the diode will be forward biased only when the input pulse is negative, and thus the output voltage will contain only the negative pulses. Further it is to be noted that the input to the half-wave rectifier can be supplied even via the transformer. This is advantageous as the transformer provides isolation from the power line as well as helps in obtaining the desired level of DC voltage. Next, one can connect a capacitor across the resistor in the circuit of half wave rectifier to obtain a smoother DC output (Figure 2). Here the capacitor charges through the diode D during the positive pulse of the input while it discharges through the load resistor R_L when the input pulse will be negative. Thus the output waveform of such a rectifier will have ripples in it as shown in the figure.

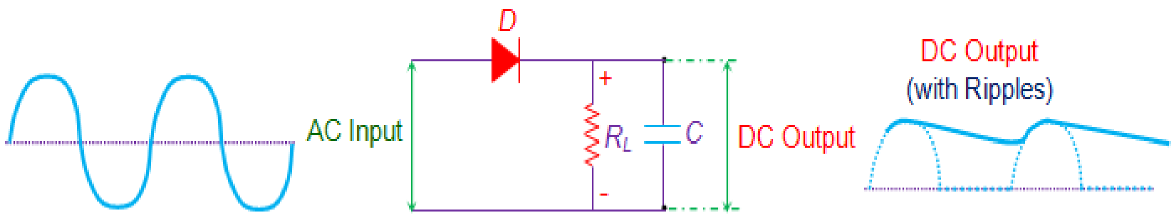


Figure 2 Half-Wave Rectifier with a RC Filter

Different parameters associated with the half wave rectifiers are

1. **Peak Inverse Voltage (PIV):** This is the maximum voltage which should be withstood by the diode under reverse biased condition and is equal to the peak of the input voltage, Vm.
2. **Average Voltage:** This is the DC content of the voltage across the load and is given by Vm/π. Similarly DC current is given as Im/π, where Im is the maximum value of the current.
3. **Ripple Factor (r):** It is the ratio of root mean square (rms) value of AC component to the DC component in the output and is given by

$$r = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

   Further, for half-wave rectifier, rms voltage is given as Vm/2 which results in the ripple factor of 1.21.
4. **Efficiency:** It is the ratio of DC output power to the AC input power and is equal to 40.6 %.
5. **Transformer Utilization Factor:** It is the ratio of DC power delivered to the load to the AC rating of the transformer secondary and is equal to 0.287.

6. **Form Factor:** This is the ratio of rms value to the average value and is thus equal to 1.57 for half-wave rectifier.
7. **Peak Factor:** It is the ratio of peak value to the rms value and is equal to 2.

Half wave rectifiers are advantageous as they are cheap, simple and easy to construct. These are quite rarely used as they have high ripple content in their output. However they can be used in non-critical applications like those of charging the battery. They are also less preferred when compared to other rectifiers as they have low output power, low rectification efficiency and low transformer utilization factor. In addition, if AC input is fed via the transformer, then it might get saturated which inturn results in magnetizing current, hysteresis loss and/or result in the generation of harmonics. Lastly it is important to note that the explanation provided here applies only for the case where the diode is ideal. Although for a practical diode, the basic working remains the same, one will have to consider the voltage drop across the diode as well as its reverse saturation current into consideration during the analysis.

4.10 FULL WAVE RECTIFIERS

The circuits which convert the input alternating current (AC) into direct current (DC) are referred to as rectifiers. If such rectifiers rectify both the positive as well as negative pulses of the input waveform, then they are called Full-Wave Rectifiers. Figure 1 shows such a rectifier designed using a multiple winding transformer whose secondary winding is equally divided into two parts with a provision for the connection at its central point (and thus referred to as the centre-tapped transformer), two diodes (D_1 and D_2) and a load resistor (R_L). Here the AC input is fed to the primary winding of the transformer while an arrangement of diodes and the load resistor which yields the DC output, is made across its secondary terminals.

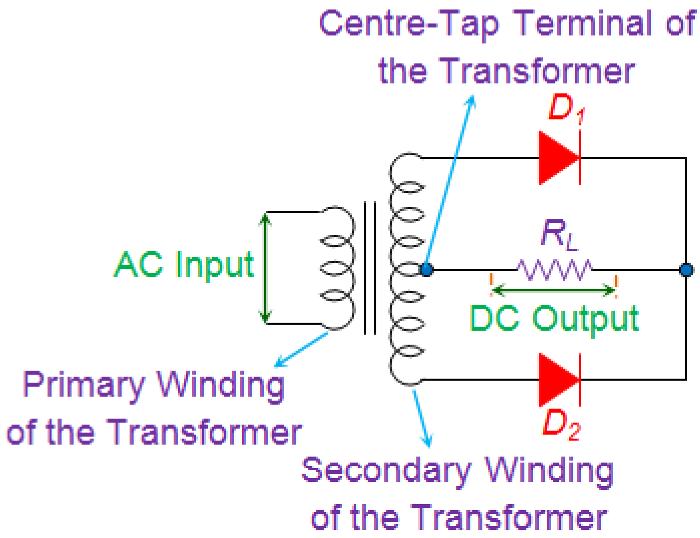


Figure 1 Full Wave Rectifier

The circuit can be analyzed by considering its working during the positive and the negative input pulses separately.

Figure 2a shows the case where the AC pulse is positive in nature i.e. the polarity at the top of the primary winding is positive while its bottom will be negative in polarity. This causes the top part of the secondary winding to acquire a positive charge while the common centre-tap terminal of the transformer will become negative.

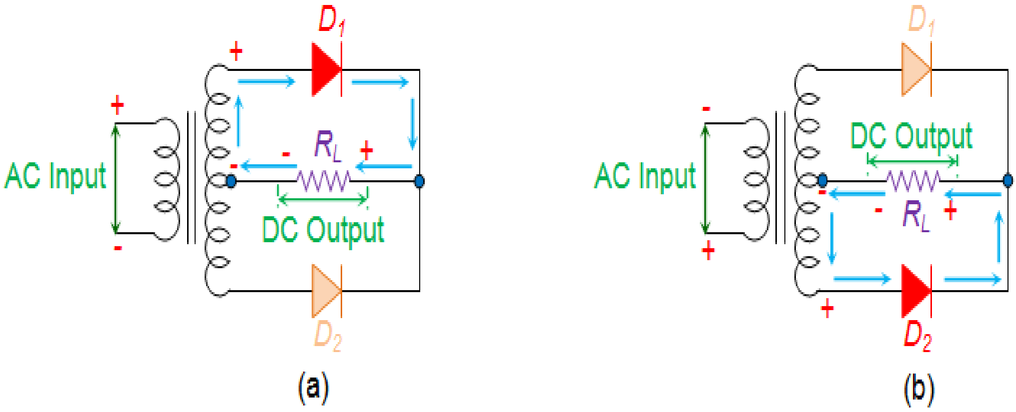


Figure 2 Conduction Path of Full Wave Rectifier for (a) Positive Input Pulse (b) Negative Input Pulse

This causes the diode D_1 to be forward biased which inturn causes the flow of current through R_L along the direction shown in Figure 2a. However at the same time, diode D_2 will be reverse biased and hence acts like an open circuit. This causes the appearance of positive pulse across the R_L, which will be the DC output. Next, if the input pulse becomes negative in nature, then the top and the bottom of the primary winding will acquire the negative and the positive polarities respectively. This causes the bottom of the secondary winding to become positive while its centre-tapped terminal will become negative. Thus the diode D_2 gets forward biased while the D_1 will get reverse biased which allows the flow of current as shown in the Figure 2b. Here the most important thing to note is the fact that the direction in which the current flows via R_L will be identical in either case (both for positive as well as for negative input pulses). Thus we get the positive output pulse even for the case of negative input pulse (Figure 3), which indicates that both the half cycles of the input AC are rectified.

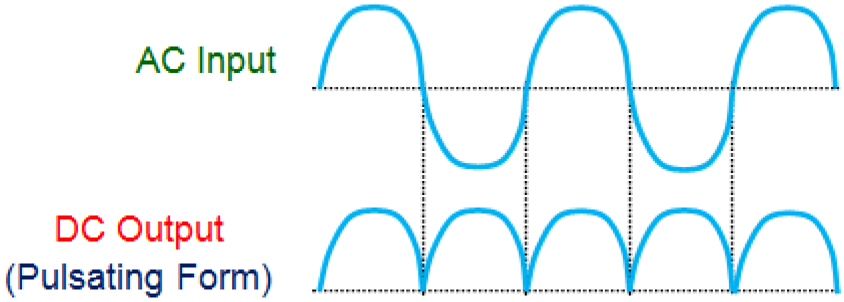


Figure 3 Input and Output Waveforms of Full Wave Rectifier

Such circuits are referred to as (i) Centre-Tapped **Full Wave Rectifiers** as they use a centre-tapped transformer, (ii) Two-Diode Full-Wave Rectifiers because of the use of two diodes and/or (iii) Bi-Phase Circuits due to the fact that in these circuits, the output voltage will be the phasor addition of the voltages developed across the load resistor due to two individual diodes, where each of them conducts only for a particular half-cycle. However as evident from Figure 3, the output of the rectifier is not pure DC but pulsating in nature, where the frequency of the output waveform is seen to be double of that at the input. In order to smoothen this, one can connect a capacitor across the load resistor as shown by the Figure 4. This causes the capacitor to charge via the diode D_1 as long as the input positive pulse increases in its magnitude. By the time the input pulse reaches the positive maxima, the capacitor would have charged to the same magnitude. Next, as long as the input positive pulse keeps decreasing, the capacitor tries to hold the charge acquired (being an energy-storage element).

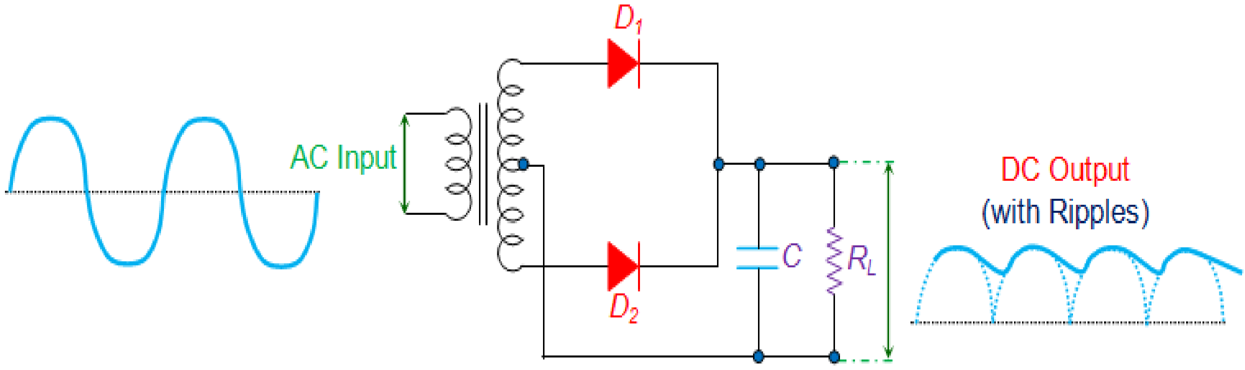


Figure 4 Full-Wave Rectifier with a RC Filter

However there will be voltage-loss as some amount of charge gets lost through the path provided by the load resistor (nothing but discharging phenomenon). Further, as the input pulse starts to go low to reach the negative maxima, the capacitor again starts to charge via the path provided by the diode D_2 and acquires an almost equal voltage but with opposite polarity. Next, as the input voltage starts to move towards 0V, the capacitor slightly discharges via R_L. This charge-discharge cycle of the capacitor causes the ripples to appear in the output waveform of the full-wave rectifier with RC filter as shown in Figure 4.

Different parameters and their values for the centre-tapped full-wave rectifiers are

1. **Peak Inverse Voltage (PIV):** This is the maximum voltage which occurs across the diodes when they are reverse biased. Here it will be equal to twice the peak of the input voltage, $2V_m$.
2. **Average Voltage:** It is the DC voltage available across the load and is equal to $2V_m/\pi$. The corresponding DC current will be $2I_m/\pi$, where Im is the maximum value of the current.
3. **Ripple Factor (r):** This is the ratio of the root mean square (rms) value of AC component to the dc component at the output. It is given by

$$r = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

and will be equal to 0.482 as the rms voltage for a full-wave rectifier is given as

$$V_m / \sqrt{2}$$

4. **Efficiency:** This is the ratio of DC output power to the AC input power and is equal to 81.2 %.
5. **Transformer Utilization Factor (TUF):** This factor is expressed as the ratio of DC power delivered to the load to the AC rating of the transformer secondary. For the full-wave rectifier this will be 0.693.
6. **Form Factor:** This is the ratio of rms value to the average value and is equal to 1.11.
7. **Peak Factor:** It is the ratio of peak value to the rms value and is equal to √2 for the full-wave rectifiers.

Further it is to be noted that the two-diode full-wave rectifier shown in Figure 1 is costly and bulky in size as it uses the complex centre-tapped transformer in its design. Thus one may resort to another type of full-wave rectifier called Full-Wave Bridge Rectifier (identical to Bridge Rectifier) which might or might not involve the transformer (even if used, will not be as complicated as a centre-tap one). It also offers higher TUF and higher PIV which makes it ideal for high power applications. However it is to be noted that the full wave bridge rectifier uses four diodes instead of two, which in turn increases the magnitude of voltage drop across the diodes, increasing the heating loss. **Full wave rectifiers** are used in general power supplies, to charge a battery and to provide power to the devices like motors, LEDs, etc. However due to the ripple content in the output waveform, they are not preferred for audio applications. Further these are advantageous when compared to half-wave rectifiers as they have higher DC output power, higher transformer utilization factor and lower ripple content, which can be made more smoother by using π-filters. All these merits mask-up its demerit of being costly in comparison to the half-wave rectifiers due to the use of increased circuit elements. At last, it is to be noted that the explanation provided here considers the diodes to be ideal in nature. So, incase of practical diodes, one will have to consider the voltage drop across the diode, its reverse saturation current and other diode characteristics into account and reanalyze the circuit. Nevertheless the basic working remains the same.

4.10 BRIDGE RECTIFIERS

Bridge Rectifiers are the circuits which convert alternating current (AC) into direct current (DC) using the diodes arranged in the bridge circuit configuration. They usually comprise of four or more number of diodes which cause the output generated to be of the same polarity irrespective of the polarity at the input. Figure 1 shows such a bridge rectifier composed of four diodes D_1, D_2, D_3 and D_4 in which the input is supplied across two terminals A and B in the figure while the output is collected across the load resistor R_L connected between the terminals C and D.

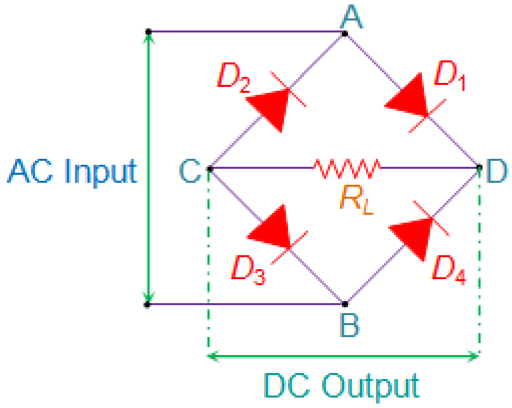


Figure 1 Bridge Rectifier

Now consider the case wherein the positive pulse appears at the AC input i.e. the terminal A is positive while the terminal B is negative. This causes the diodes D_1 and D_3 to get forward biased and at the same time, the diodes D_2 and D_4 will be reverse biased.

As a result, the current flows along the short-circuited path created by the diodes D_1 and D_3 (considering the diodes to be ideal), as shown by Figure 2a. Thus the voltage developed across the load resistor R_L will be positive towards the end connected to terminal D and negative at the end connected to the terminal C.

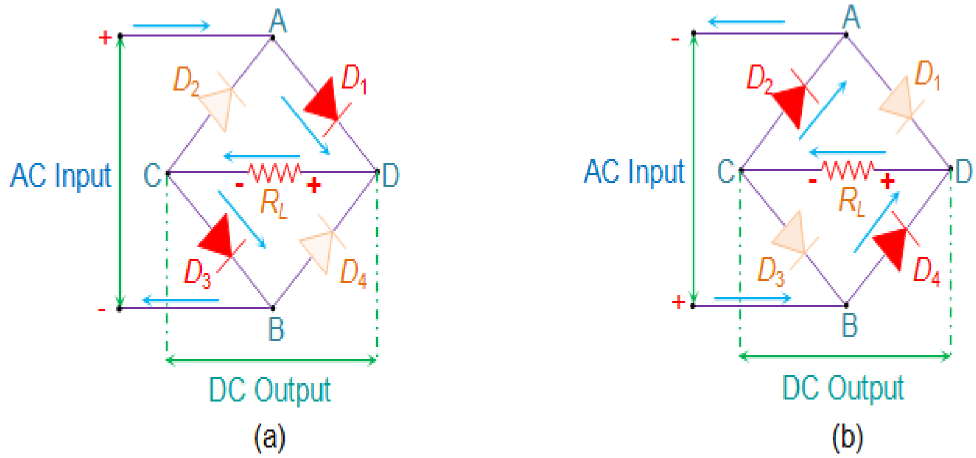


Figure 2 Current Path Through the Bridge Rectifier for (a) Positive half-cycle (b) Negative Half-Cycle

Next if the negative pulse appears at the AC input, then the terminals A and B are negative and positive respectively. This forward biases the diodes D_2 and D_4, while reverse biasing D_1 and D_3 which causes the current to flow in the direction shown by Figure 2b. At this instant, one has to note that the polarity of the voltage developed across R_L is identical to that produced when the incoming AC pulse was positive in nature. This means that for both positive and negative pulse, the output of the bridge rectifier will be identical in polarity as shown by the wave forms in Figure 3.

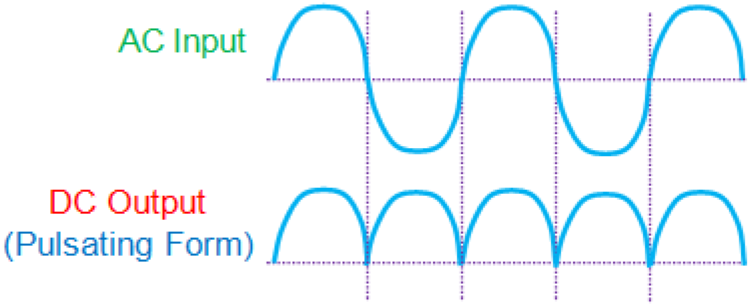


Figure 3 Input-Output Waveforms of a Bridge Rectifier

However it is to be noted that the bridge rectifier's DC will be pulsating in nature. In order to obtain pure form of DC, one has to use capacitor in conjunction with the bridge circuit (Figure 4).

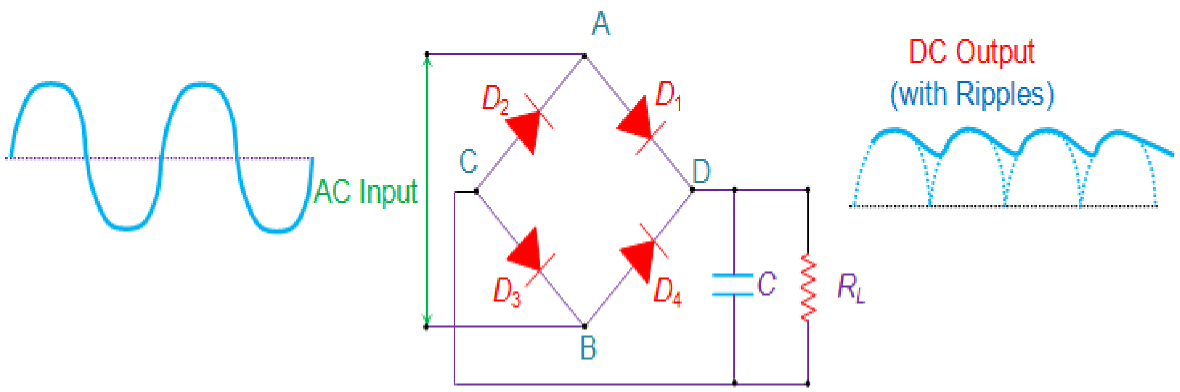


Figure 4 Bridge Rectifier with a RC Filter

In this design, the positive pulse at the input causes the capacitor to charge through the diodes D_1 and D_3. However as the negative pulse arrives at the input, the charging action of the capacitor ceases and it starts to discharge via R_L. This results in the generation of DC output which will have ripples in it as shown in the figure. This ripple factor is defined as the ratio of AC component to the DC component in the output voltage. In addition, the mathematical expression for the ripple voltage is given by the equation

$$V_r = \frac{I_l}{fC}$$

Where, V_r represents the ripple voltage.

I_l represents the load current.

f represents the frequency of the ripple which will be twice the input frequency.

C is the Capacitance.

Further, the **bridge rectifiers** can be majorly of two types, viz., Single-Phase Rectifiers and Three-Phase Rectifiers. In addition, each of these can be either Uncontrolled or Half-Controlled or Full-Controlled. Bridge rectifiers for a particular application are selected by considering the load current requirements. These bridge rectifiers are quite advantageous as they can be constructed with or without a transformer and are suitable for high voltage applications. However here two diodes will be conducting for every half-cycle and thus the voltage drop across the diodes will be higher. Lastly one has to note that apart from converting AC to DC, **bridge rectifiers** are also used to detect the amplitude of modulated radio signals and to supply polarized voltage for welding applications.

UNIT V

BIPOLAR JUNCTION TRANSISTOR AND APPLICATIONS

5.1 INTRODUCTION

The transistor was invented in 1947 by John Bardeen, Walter Brattain and William Shockley at Bell Laboratory in America. A transistor is a semiconductor device, commonly used as an Amplifier or an electrically Controlled Switch.

There are two types of transistors:

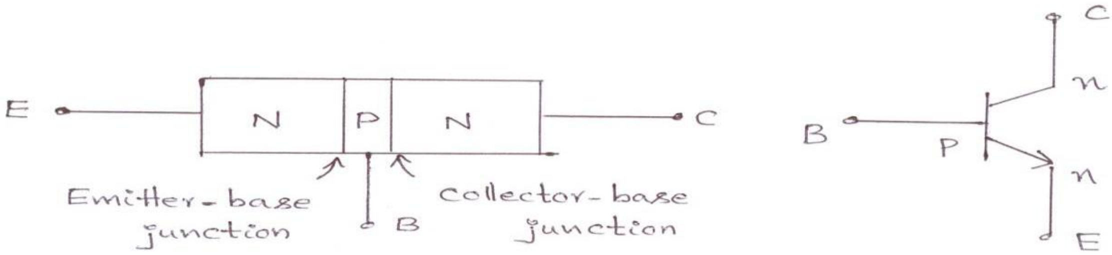
1) Unipolar Junction Transistor
2) Bipolar Junction Transistor

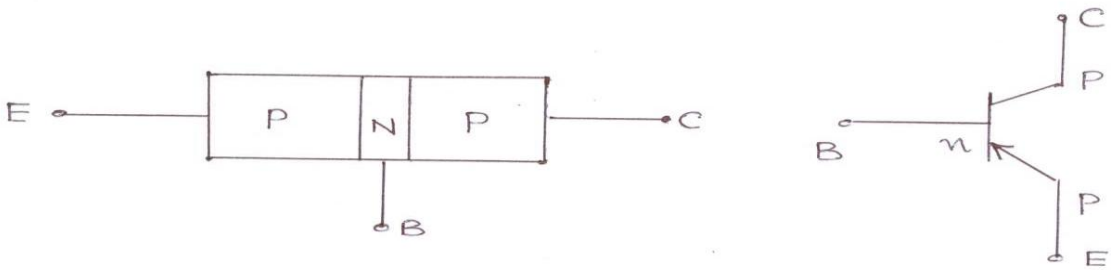
In Unipolar transistor, the current conduction is only due to one type of carriers i.e., majority charge carriers. The current conduction in bipolar transistor is because of both the types of charge carriers i.e., holes and electrons. Hence it is called as Bipolar Junction Transistor and it is referred to as BJT.

BJT is a semiconductor device in which one type of semiconductor material is sand witched between two opposite types of semiconductor i.e., an n-type semiconductor is sandwiched between two p-type semiconductors or a p-type semiconductor is sandwiched between two n-type semiconductor.
Hence the BJTs are of two types.They are:

1) n-p-n Transistor
2) p-n-p Transistor

The two types of BJTs are shown in the figure below.





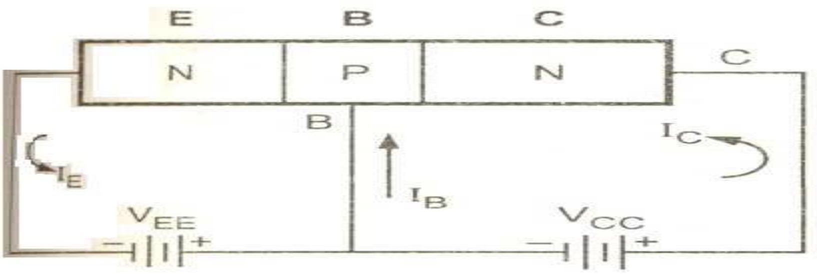
The arrow head represents the conventional current direction from p to n. Transistor has three terminals.
1) Emitter 2) Base 3) Collector

Transistor has two p-n junctions. They are:
1) Emitter-Base Junction
2) Collector-Base Junction
Emitter: Emitter is heavily doped because it is to emit the charge carriers.

Base: The charge carriers emitted by the emitter should reach collector passing through the base. Hence base should be very thin and to avoid recombination, and to provide more collector current base is lightly doped.
Collector: Collector has to collect the most of charge carriers emitted by the emitter. Hence the area of cross section of collector is more compared to emitter and it is moderately doped.
Transistor can be operated in three regions.
1) Active region.
2) Saturation region.
3) Cut-Off region.
Active Region: For the transistor to operate in active region base to emitter junction is forward biased and collector to base junction is reverse biased.
Saturation Region: Transistor to be operated in saturation region if both the junctions i.e., collector to base junction and base to emitter junction are forward biased.
Cut-Off Region: For the transistor to operate in cut-off region both the junctions i.e., base to emitter junction and collector to base junction are reverse biased.
Transistor can be used as
1) Amplifier 2) Switch
For the transistor to act as an amplifier, it should be operated in active region. For the transistor to act as a switch, it should be operated in saturation region for ON state, and cut-off region for OFF state.

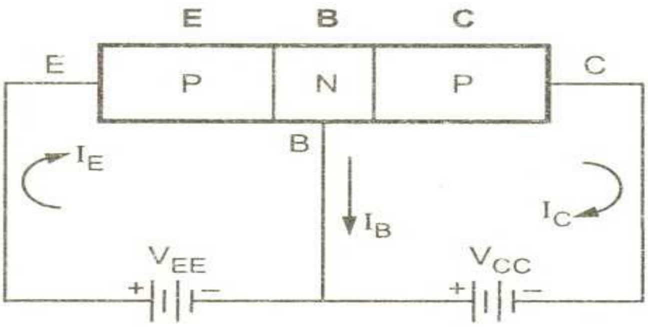
5.2 TRANSISTOR OPERATION:

Working of a n-p-n transistor:



The n-p-n transistor with base to emitter junction forward biased and collector base junction reverse biased is as shown in figure.
As the base to emitter junction is forward biased the majority carriers emitted by the n type emitter i.e., electrons have a tendency to flow towards the base which constitutes the emitter
Current IE As the base is p-type there is chance of recombination of electrons emitted by the emitter with the holes in the p-type base. But as the base is very thin and lightly doped only few electrons emitted by the n-type emitter less than 5% combines with the holes in the p-type base, the remaining more than 95% electrons emitted by the n-type emitter cross over into the collector region constitute the collector current. The current distributions are as shown in fig **IE = IB + IC**

Working of a p-n-p transistor:



The p-n-p transistor with base to emitter junction is forward biased and collector to base junction reverse biased is as show in figure. As the base to emitter junction is forward biased the majority carriers emitted by the type emitter i.e., holes have a tendency to flow towards the base which constitutes the emitter current IE. As the base is n-type there is a chance of recombination of holes emitted by the emitter with the electrons in the n-type base. But as the base us very thin and lightly doped only few electrons less than 5% combine with the holes emitted by the p-type emitter, the remaining 95% charge carriers cross over into the collector region to constitute the collector current. The current distributions are shown in figure.

IE = IB + IC

Current components in a transistor:

The figure below shows the various current components which flow across the forward biased emitter junction and reverse-biased collector junction in P-N-P transistor

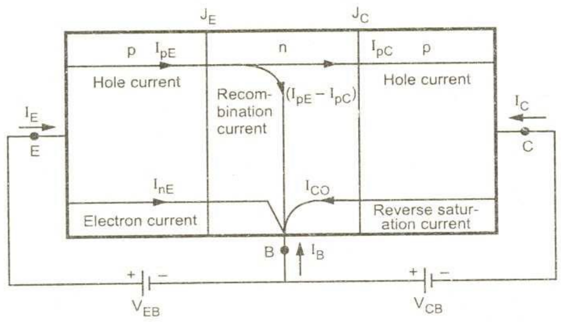


Figure. Current components in a transistor with forward-biased emitter and reverse-biased Collector junctions. The emitter current consists of the following two parts:

1) Hole current IpE constituted by holes (holes crossing from emitter into base).
2) Electron current InE constituted by electrons (electrons crossing from base into the emitter).

Therefore, Total emitter current IE = IpE (majority)+ InE (Minority)

The holes crossing the emitter base junction JE and reaching the collector base junction JC constitutes collector current IpC. Not all the holes crossing the emitter base junction JE reach collector base junction JC because some of them combine with the electrons in the n-type base Since base width is very small, most of the holes cross the collector base junction JC and very few recombine, constituting the base current (IpE – IpC).

When the emitter is open-circuited, IE=0, and hence IpC=0. Under this condition, the base and collector together current IC equals the reverse saturation current ICO, which consists of the following two parts: IPCO caused by holes moving across IC from N-region to P-region.

InCO caused by electrons moving across IC from P-region to N-region. ICO = InCO + IpCO

In general,

IC = InC + IpC

Thus for a P-N-P transistor,

IE = IB + IC

5.3 TRANSISTOR CIRCUIT CONFIGURATIONS:

Following are the three types of transistor circuit configurations:
1) Common-Base (CB)
2) Common-Emitter (CE)
3) Common-Collector (CC)

Here the term ‘Common’ is used to denote the transistor lead which is common to the input and output circuits. The common terminal is generally grounded.

It should be remembered that regardless the circuit configuration, the emitter is always forward-biased while the collector is always reverse-biased.

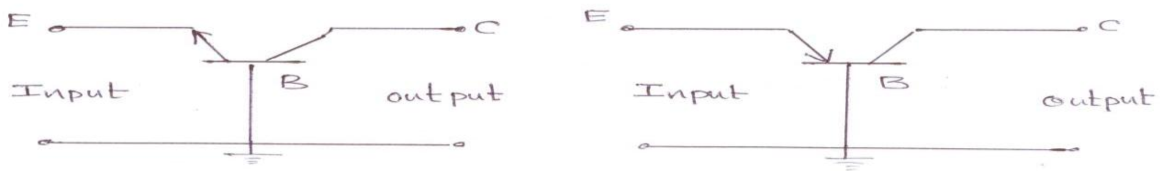


Fig. Common – Base configuration

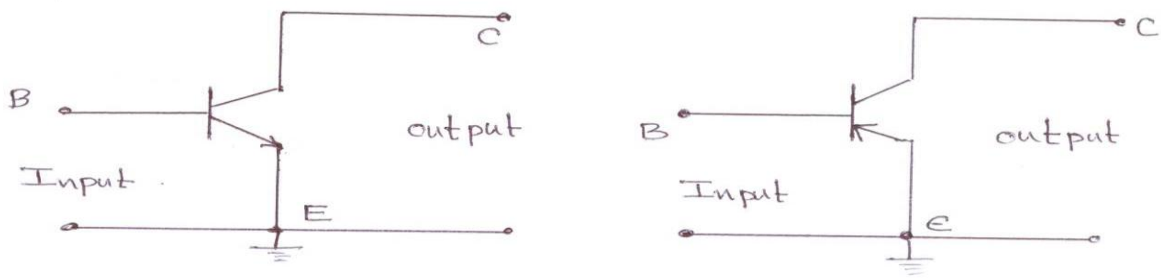


Fig. Common – emitter configuration

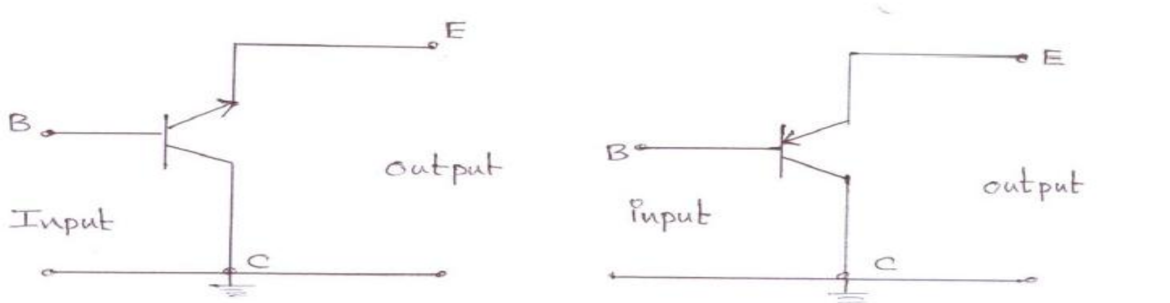


Fig. Common – Collector configuration

5.3.1 Common – Base (CB) configurations:

In this configuration, the input signal is applied between emitter and base while the output is taken from collector and base. As base is common to input and output circuits, hence the name common-base configuration. Figure show the common-base P-N-P transistor circuit.

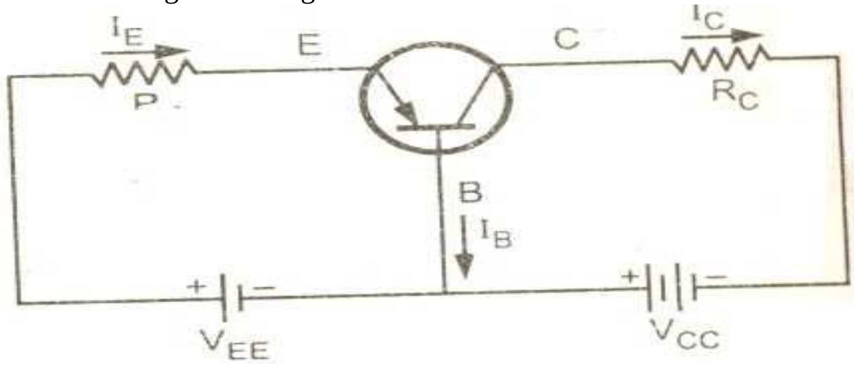


Fig. Common – base PNP transistor amplifier.

Current Amplification Factor (α) **:**

When no signal is applied, then the ratio of the collector current to the emitter current is called dc alpha (α dc) of a transistor.

$$\alpha_{dc} = \frac{-I_C}{I_E} \quad ,............... (1)$$

(Negative sign signifies that IE flows into transistor while IC flows out of it). ‘ α’ of a transistor is a measure of the quality of a transistor. Higher is the value of ‘α ’, better is the transistor in the sense that collector current approaches the emitter current. By considering only magnitudes of the currents, IC = a IE and hence IB = IE - IC
Therefore,

IB = IE -a IE = IE(1-a) ………… (2)

When signal is applied, the ratio of change in collector current to the change in emitter current at constant collector-base voltage is defined as current amplification factor,

$$\alpha_{dc} = -\frac{\Delta I_C}{\Delta I_E} \text{ .... } (3)$$

For all practical purposes, dc a =aac =a and practical values in commercial transistors range from 0.9 to 0.99.

Total Collector Current:

The total collector current consists of the following two parts
i) a IE , current due to majority carriers
ii) ICBO, current due to minority carriers
\ Total collector current IC = a IE + ICBO ………… (4)
The collector current can also be expressed as IC = a (IB+IC) + ICBO (Q IE = IB + IC)

$$\Rightarrow I_C(1-\alpha) = \alpha I_B + I_{CBO}$$

$$\Rightarrow I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO} \text{ .... } (5)$$

5.3.2 COMMON-EMITTER (CE) CONFIGURATION:

In this configuration, the input signal is applied between base and emitter and the output is taken from collector and emitter. As emitter is common to input and output circuits, hence the name common emitter configuration.
Figure shows the common-emitter P-N-P transistor circuit.

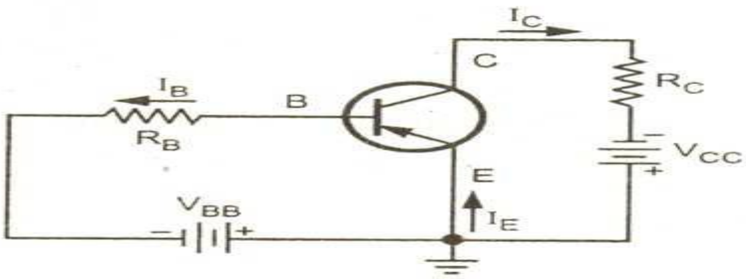


Fig. Common-Emitter PNP transistor amplifier.

Current Amplification Factor (β):
When no signal is applied, then the ratio of collector current to the base current is called dc beta (βdc) of a transistor.

$$\beta_{dc} = \beta = \frac{I_C}{I_B} \quad .... (1)$$

When signal is applied, the ratio of change in collector current to the change in base current is defined as base current amplification factor. Thus,

$$\beta_{dc} = \beta = \frac{\Delta I_C}{\Delta I_B} \quad ....(2)$$

From equation (1), $I_C = \beta I_B$

Almost in all transistors, the base current is less than 5% of the emitter current. Due to this fact, 'β' ranges from 20 to 500. Hence this configuration is frequently used when appreciable current gain as well as voltage gain is required.

Total Collector Current:

The Total collector current IC = β IB + ICEO ………… (3)

Where ICEO is the leakage current.

But, we have, $I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO}$ ....(4)

Comparing equations (3) and (4), we get

$$\beta = \frac{\alpha}{1-\alpha} \text{ and } I_{CEO} = \frac{1}{1-\alpha} I_{CBO} \quad ....(5)$$

Relation between α and β:

We know that $\alpha = \frac{I_C}{I_E}$ and $\beta = \frac{I_C}{I_B}$

$I_E = I_B + I_C$ (or) $I_B = I_E - I_C$

Now $$\beta = \frac{I_C}{I_E - I_C} = \frac{\frac{I_C}{I_E}}{1 - \frac{I_C}{I_E}} = \frac{\alpha}{1-\alpha} \quad .... (6)$$

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

$$\Rightarrow \alpha = \frac{\beta}{1+\beta} \quad .... (7)$$

It can be seen that $1 - \alpha = \frac{1}{1+\beta}$ .... (8)

5.3.3 COMMON – COLLECTOR (CC) CONFIGURATION:

In this configuration, the input signal is applied between base and collector and the output is taken from the emitter. As collector is common to input and output circuits, hence the name common collector configuration. Figure shows the common collector PNP transistor circuit.

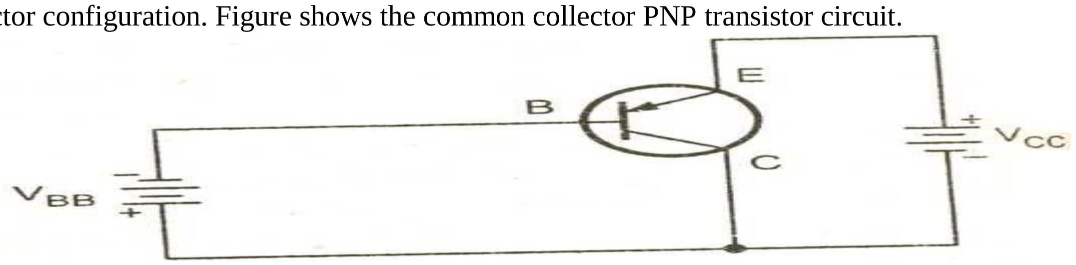


Fig. Common collector PNP transistor amplifier.

Current Amplification Factor γ):

When no signal is applied, then the ratio of emitter current to the base current is called as dc gamma (γdc) of the transistor.

$$\gamma_{dc} = \gamma = \frac{I_E}{I_B} \quad .... (1)$$

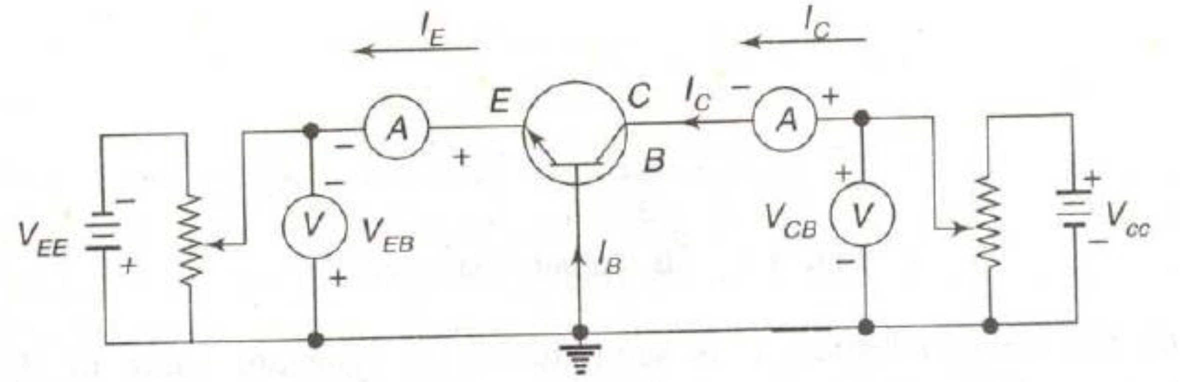


Fig. Circuit to determine CB static characteristics.

5.4 INPUT CHARACTERISTICS:

To determine the input characteristics, the collector-base voltage VCB is kept constant at zero volts and the emitter current IE is increased from zero in suitable equal steps by increasing VEB. This is repeated for higher fixed values of VCB. A curve is drawn between emitter current IE and emitter-base voltage VEB at constant collector-base voltage VCB.
The input characteristics thus obtained are shown in figure below.

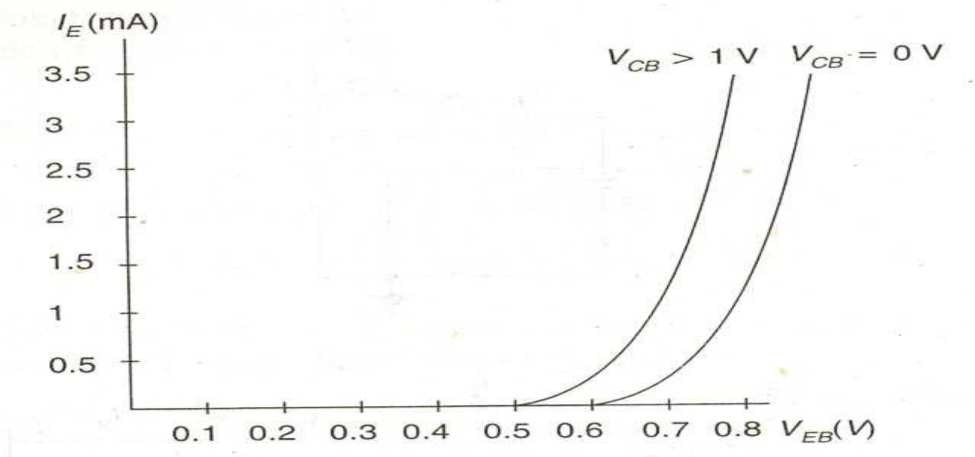
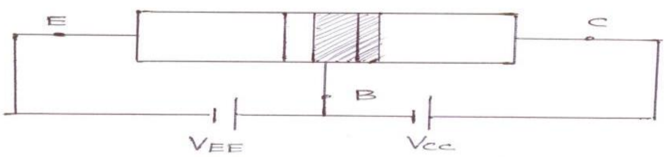


Fig. CB Input characteristics.

Early effect (or) Base – Width modulation:

As the collector voltage VCC is made to increase the reverse bias, the space charge width between collector and base tends to increase, with the result that the effective width of the base decreases. This dependency of base-width on collector-to-emitter voltage is known as Early effect (or) Base-Width modulation.



Thus decrease in effective base width has following consequences:
i. Due to Early effect, the base width reduces, there is a less chance of recombination of holes with electrons in base region and hence base current IB decreases.
ii. As IB decreases, the collector current IC increases.
iii. As base width reduces the emitter current IE increases for small emitter to base voltage.
iv. As collector current increases, common base current gain (a) increases.

5.5 Punch Through (or) Reach Through:

When reverse bias voltage increases more, the depletion region moves towards emitter junction and effective base width reduces to zero. This causes breakdown in the transistor. This condition is called “Punch Through” condition.

Output Characteristics:

To determine the output characteristics, the emitter current IE is kept constant at a suitable value by adjusting the emitter-base voltage VEB. Then VCB is increased in suitable equal steps and the collector current IC is noted for each value of IE. Now the curves of IC versus VCB are plotted for constant values of IE and the output characteristics thus obtained is shown in figure below.

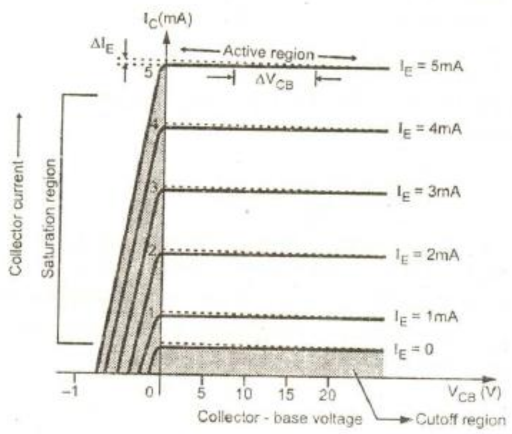


Fig. CB Output characteristics

From the characteristics, it is seen that for a constant value of IE, IC is independent of VCB and the curves are parallel to the axis of VCB. Further, IC flows even when VCB is equal to zero. As the emitter-base junction is forward biased, the majority carriers, i.e., electrons, from the emitter are injected into the base region. Due to the action of the internal potential barrier at the reverse biased collector-base junction, they flow to the collector region and give rise to IC even when VCB is equal to zero.

Transistor Parameters:

The slope of the CB characteristics will give the following four transistor parameters. Since these parameters have different dimensions, they are commonly known as common base hybrid parameters (or) h-parameters.

i) Input Impedance (hib):

It is defined as the ratio of change in (input) emitter to base voltage to the change in (input) emitter current with the (output) collector to base voltage kept constant. Therefore,

$$h_{ib} = \frac{\Delta V_{EB}}{\Delta I_E}, \; V_{CB} \text{ constant}$$

It is the slope of CB input characteristics curve.
The typical value of hib ranges from 20I to 50I.

ii) Output Admittance (hob):

It is defined as the ratio of change in the (output) collector current to the corresponding change in the (output) collector-base voltage, keeping the (input) emitter current IE constant. Therefore,

$$h_{ob} = \frac{\Delta I_C}{\Delta V_{CB}} \text{ , } I_E \text{ constant}$$

It is the slope of CB output characteristics IC versus VCB.
The typical value of this parameter is of the order of 0.1 to 10µmhos

iii) Forward Current Gain (hfb):

It is defined as a ratio of the change in the (output) collector current to the corresponding change in the (input) emitter current keeping the (output) collector voltage VCB constant. Hence,

$$h_{fb} = \frac{\Delta I_C}{\Delta I_E} \text{ , } V_{CB} \text{ constant}$$

It is the slope of IC versus IE curve. Its typical value varies from 0.9 to 1.0.

iv) Reverse Voltage Gain (hrb):
It is defined as a ratio of the change in the (input) emitter voltage and the corresponding change in (output) collector voltage with constant (input) emitter current, IE. Hence,

$$h_{rb} = \frac{\Delta V_{EB}}{\Delta V_{CB}} \text{ , } I_E \text{ constant.}$$

It is the slope of VEB versus VCB curve. Its typical value is of the order of 10^{-5} to 10^{-4}

CHARACTERISTICS OF COMMON-EMITTER CIRCUIT:

The circuit diagram for determining the static characteristic curves of the an N-P-N transistor in the common emitter configuration is shown in figure below.

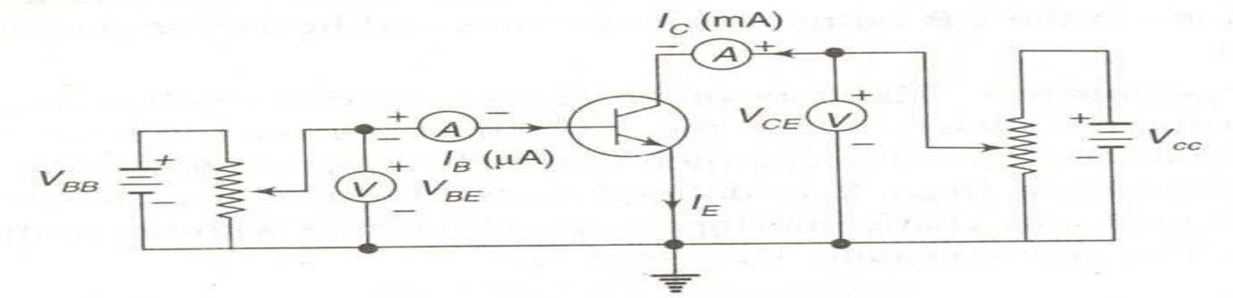


Fig. Circuit to determine CE Static characteristics.

Input Characteristics:
To determine the input characteristics, the collector to emitter voltage is kept constant at zero volts and base current is increased from zero in equal steps by increasing VBE in the circuit. The value of VBE is noted for each setting of IB. This procedure is repeated for higher fixed values of VCE, and the curves of IB versus VBE are drawn.
The input characteristics thus obtained are shown in figure below.

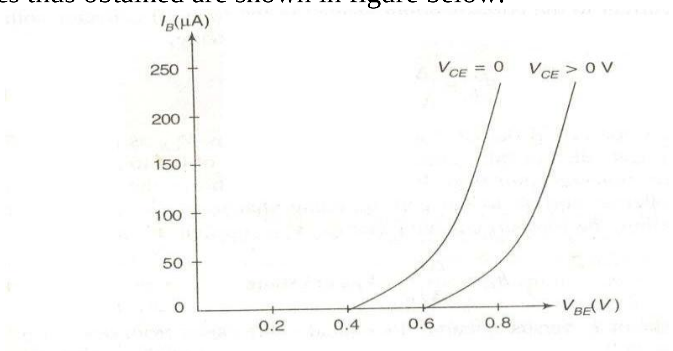


Fig. CE Input Characteristics.

When VCE=0 , the emitter-base junction is forward biased and he junction behaves as a forward biased diode. When VCE is increased, the width of the depletion region at the reverse biased collector-base junction will increase. Hence he effective width of the base will decrease. This effect causes a decrease in the base current IB. Hence, to get the same value of IB as that for VCE=0, VBE should be increased. Therefore, the curve shifts to the right as VCE increases.

Output Characteristics:

To determine the output characteristics, the base current IB is kept constant at a suitable value by adjusting base-emitter voltage, VBE. The magnitude of collector-emitter voltage VCE is increased in suitable equal steps from zero and the collector current IC is noted for each setting of VCE. Now the curves of IC versus VCE are plotted for different constant values of IB. The output characteristics thus obtained are shown in figure below.

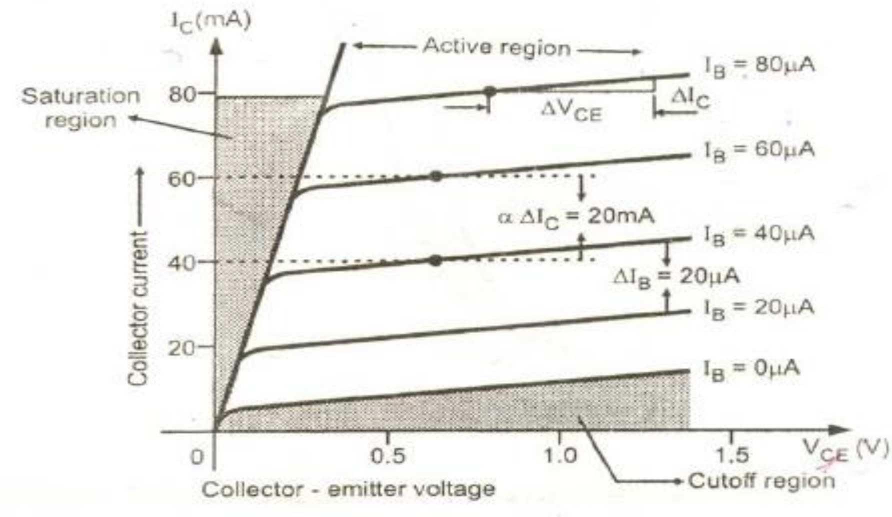


Fig. CE Output characteristics

The output characteristics of common emitter configuration consist of three regions: Active, Saturation and Cut-off regions.

Active Region:

The region where the curves are approximately horizontal is the “Active” region of the CE configuration. In the active region, the collector junction is reverse biased. As VCE is increased, reverse bias increase. This causes depletion region to spread more in base than in collector, reducing the changes of recombination in the base. This increase the value of a dc . This Early effect causes collector current to rise more sharply with increasing VCE in the active region of output characteristics of CE transistor.

Saturation Region:

If VCE is reduced to a small value such as 0.2V, then collector-base junction becomes forward biased, since the emitter-base junction is already forward biased by 0.7V. The input junction in CE configuration is base to emitter junction, which is always forward biased to operate transistor in active region. Thus input characteristics of CE configuration are similar to forward characteristics of p-n junction diode. When both the junctions are forwards

biased, the transistor operates in the saturation region, which is indicated on the output characteristics. The saturation value of VCE, designated VCE(Sat) , usually ranges between 0.1V to 0.3V.

Cut-Off Region:

When the input base current is made equal to zero, the collector current is the reverse leakage current ICEO. Accordingly, in order to cut off the transistor, it is not enough to reduce IB=0. Instead, it is necessary to reverse bias the emitter junction slightly. We shall define cut off as the condition where the collector current is equal to the reverse saturation current ICO and the emitter current is zero.

5.6 TRANSISTOR PARAMETERS:

The slope of the CE characteristics will give the following four transistor parameters. Since these parameters have different dimensions, they are commonly known as Common emitter hybrid parameters (or) h-parameters.

i) Input Impedance (hib):

It is defined as the ratio of change in (input) base voltage to the change in (input) base current with the (output) collector voltage (VCE), kept constant. Therefore,

$$h_{ie} = \frac{\Delta V_{BE}}{\Delta I_B} \text{ , } \Delta V_{CE} \text{ constant}$$

It is the slope of CB input characteristics IB versus VBE.
The typical value of hie ranges from 500Ωto 2000Ω.

ii) Output Admittance (hoe):

It is defined as the ratio of change in the (output) collector current to the corresponding change in the (output) collector voltage. With the (input) base current IB kept constant. Therefore,

$$h_{oe} = \frac{\Delta I_C}{\Delta V_{CE}} \text{ , } I_B \text{ constant}$$

It is the slope of CE output characteristics IC versus VCE.
The typical value of this parameter is of the order of 0.1 to 10μmhos.

iii) Forward Current Gain (hfe):

It is defined as a ratio of the change in the (output) collector current to the corresponding change in the (input) base current keeping the (output) collector voltage VCE constant. Hence,

$$h_{fe} = \frac{\Delta I_C}{\Delta I_B} \text{ , } V_{CE} \text{ constant}$$

It is the slope of IC versus IB curve.
It's typical value varies from 20 to 200.

iv) Reverse Voltage Gain (hre):

It is defined as a ratio of the change in the (input) base voltage and the corresponding change in (output) collector voltage with constant (input) base current, IB. Hence,

$$h_{re} = \frac{\Delta V_{BE}}{\Delta V_{CE}} \text{ , } I_E \text{ constant.}$$

It is the slope of VBE versus VCE curve.
It's typical value is of the order of 10-5 to 10-4

5.7 Characteristics of common collector circuit:

The circuit diagram for determining the static characteristics of an N-P-N transistor in the common collector configuration is shown in fig. below.

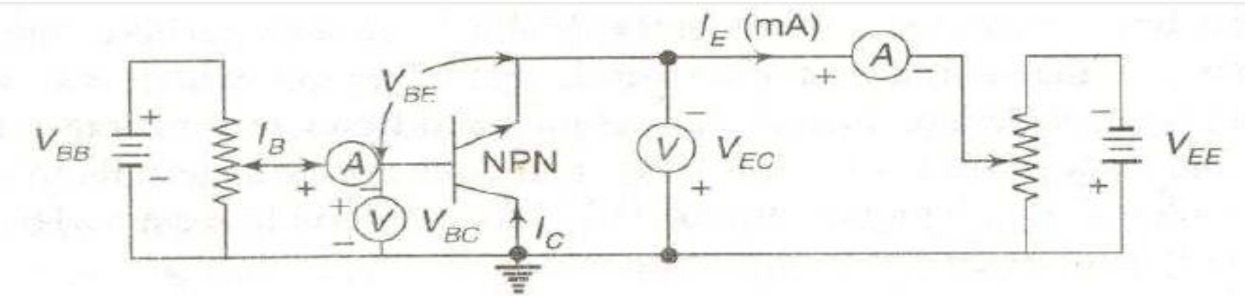


Fig. Circuit to determine CC static characteristics.

Input Characteristics:

To determine the input characteristic, VEC is kept at a suitable fixed value. The base collector voltage VBC is increased in equal steps and the corresponding increase in IB is noted. This is repeated for different fixed values of VEC. Plots of VBC versus IB for different values of VEC shown in figure are the input characteristics.

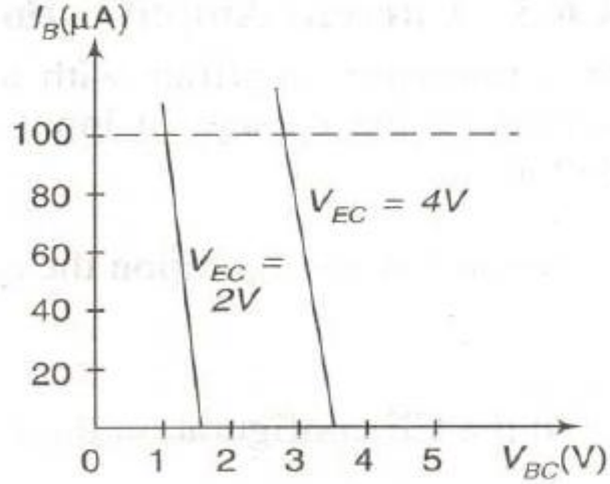


Fig. CC Input Characteristics.

Output Characteristics:

The output characteristics shown in figure below are the same as those of the common emitter configuration.

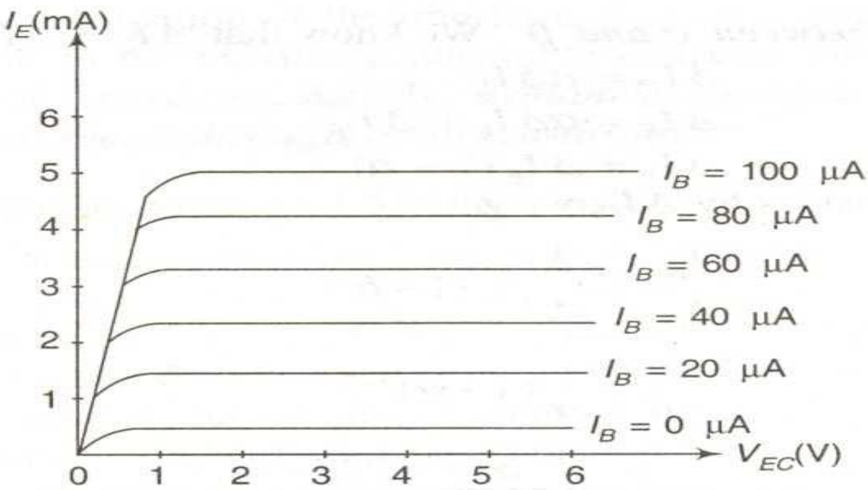


Fig. CC output characteristics.

Problem:

1 A Germanium transistor used in a complementary symmetry amplifier has ICBO=10μA at 27oC and hfe=50. (a) find IC when IB=0.25mA and (b) Assuming hfe does not increase with temperature; find the value of new collector current, if the transistor's temperature rises to 50oC.

Solution: Given data: ICBO = 10μA and hfe (=β) = 50

a) IC = βIB+(1+β)ICBO

= 50x(0.25x10-3)+(1+50)x(10x10-6)A
=**13.01mA**

b) I'CBO (β=50) = ICBO x 2(T2-T1)/10
= 10 X 2(50-27)/10
= 10 x 22.3 μA
= 49.2μA
IC at 50oC is
IC= βIB+(1+β)I'CBO
= 50x(0.25x10-3)+(1+50)x(49.2x10-6)
=15.01 mA.