ELECTRONICS

Energy Bands Theory in Solids

Energy levels

The angular momentum of an electrons is always quantized and is integral multiple of $\frac{h}{2\pi}$. Thus the electrons can have certain orbital radii. The electrons in these orbits have only a certain values of energy. These certain values of energy of electrons in an atom are called the energy levels of the atom.

The energy levels of an isolated single atom are will defined usually represented by series of horizontal lines. When the two identical atoms are close to each other, their electrons move under the influence electromagnetic fields of two atoms. As the result, each energy level split into two levels, one higher and other lower than the corresponding level of the isolated atom.

Energy Band

When the numbers of atoms are brought together, as in a crystal, they interact with one another. As the result, each energy level splits up into several sub-levels. A group of such energy sub-levels are called an energy band.

The number of energy sub-levels in a band is equal to the number of atoms in a crystal. The energy band in a crystal corresponds to the energy level in an atom. And an electron in a crystal can have an energy that falls within one of these bands.

Forbidden Bands

The energy bands are separated by gaps in which there is no energy level. Such energy gaps are called forbidden bands. The electron may jump from one energy band to another by acquiring energy equal to the energy of forbidden energy gap.

Valence Bands

The electrons in the outermost shell of an atom are called valance electrons. Therefore, the energy band occupied by valance electrons is called the valance band. The valance band may be either completely filled or partially filled with the electrons but can never be empty.

Conduction Band

The energy band next to the valance band is called the conduction band. The valance and conduction bands are separated by forbidden energy gaps. The conduction band may be

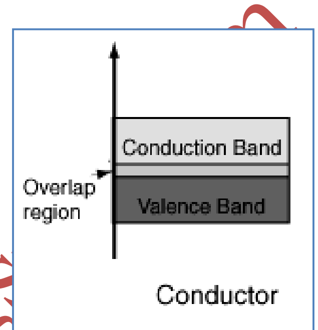
Written and composed by: Prof. Muhammad Ali Malik (M. Phil. Physics), Govt. Degree College, Naushera

empty or partially filled. The electrons in the conduction band can drift freely in the materials and are called free or conduction electrons.

The width of forbidden energy gap between valance and conduction band decide whether a material is a conductor, insulator or a semiconductor.

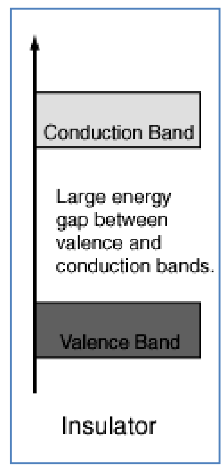
Distinction between Conductors, Insulators and Semiconductors on the basis of Band Theory of Solids

Conductors



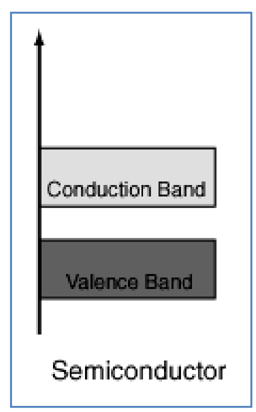
All metals are good conductors of electricity and their resistivity is of the order of $10^{-8}\ \Omega - m$. In case of conductors, there is no forbidden energy gap between the valance and the conduction band. The valance band and conduction band are partially filled at room temperature. So the electrons can easily jump from valance band to the conduction band. Due to this reason, the current can easily pass through conductors.

Insulators



The insulators have the very large value of resistivity which is of the order of $10^{10}\ \Omega - m$. In case of insulators, the valance band is completely filled and the conduction band is empty. The energy gap between the valance and conduction band is very large. Thus, no electron can jump from valence band to conduction band. As there are no free electrons in insulator, hence no current can pass through insulators.

Semiconductors

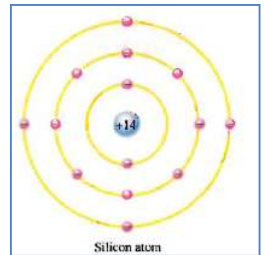


The materials which have intermediate values of resistivity (of the order of $10^{2}\ \Omega - m$) called semiconductor materials. The energy gap between the valance and conduction band is very small.

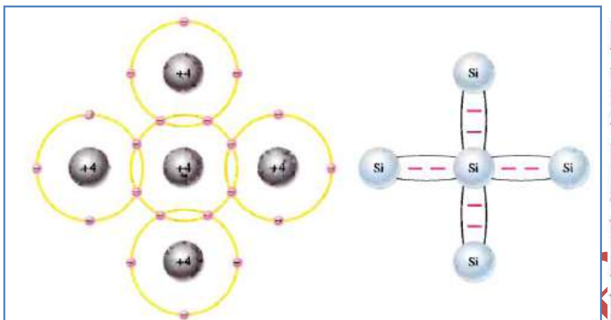
A semiconductor is a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. The most common single-element semiconductors are silicon,germanium, and carbon. Compound semiconductors such as gallium arsenide are also commonly used.

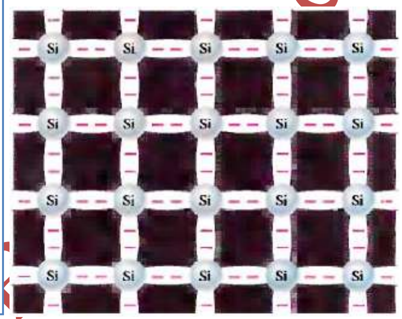
Intrinsic Semiconductors

A pure semiconductor is known as intrinsic semiconductor. The most common examples of intrinsic semiconducting materials are silicon. Each atom of silicon has four valance electrons. Moreover each atom of silicon is surrounded by four atoms.



A silicon (Si) atom with its four valence electrons shares an electron with each of its four neighbors to form covalent bond. This effectively creates eight shared valence electrons for each atom and produces a state of chemical stability.

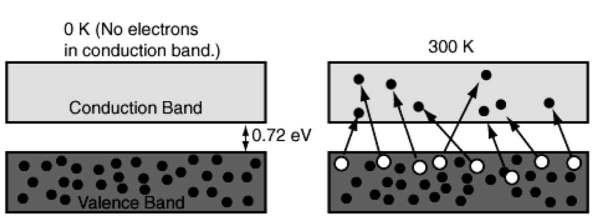




The semiconducting materials have negative temperature coefficient of resistivity. At low temperatures, the valence band is completely filled and conduction band is completely empty. Thus the semiconducting materials behave like insulator at low temperatures.

At comparatively higher temperature, the electrons in valance band acquire sufficient energy to jump in conduction band. As the temperature increases, the probability of the electrons to jump from valance to conduction band increases. Therefore, the conductivity of semiconductors increases with increase in temperature.

At absolute zero, the intrinsic semiconducting materials behaves like insulators because they have no free electrons. But as the temperature of increases, the thermal agitation in the atoms breaks some covelent bonds which result in formation of electron hole pairs. The electrons jump from valance band to conduction band by absorbing the thermal energy. As the result, the conductivity of semiconductor increases with increase in temperature.

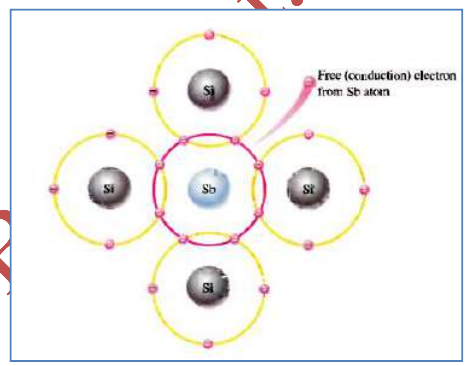


Extrinsic Semiconductors

The semiconductors doped with some impurity are called extrinsic semiconductors. The conductivity of silicon and germanium can be drastically increased by the controlled addition of impurities to the intrinsic (pure) semiconductive material. This process, called doping, increases the number of current carriers (electrons or holes). The two categories of impurities are n-type and p-type.

N-Type Semiconductor

To increase the number of conduction-band electrons in intrinsic silicon, pentavalent impurity atoms e.g., arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb) are added. Each pentavalent atom (antimony, in this case) forms covalent bonds with four adjacent silicon atoms. Four of the antimony atom's valence electrons are used to form the covalent bonds with silicon atoms, leaving one extra electron. This extra electron becomes a conduction electron because it is not attached to any atom.

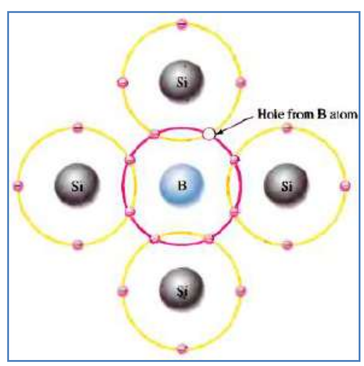


Because the pentavalent atom gives up an electron, it is often called a donor atom. The number of conduction electrons can be carefully controlled by the number of impurity atoms added to the silicon.

Majority and Minority Carriers in N-Type Semiconductor

In an n-type semiconducting material, most of the current carriers are electrons. So, the electrons are called the majority carriers in n-type material. Although the majority of current carriers in n-type material are electrons, there are also a few holes that are created when electron-hole pairs are thermally generated. Holes in an n-type material are called minority carriers.

P-Type Semiconductor



To increase the number of holes in intrinsic silicon, trivalent impurity atoms e.g., boron (B), indium (In), and gallium (Ga) are added. All three of the boron atom's valence electrons are used in the covalent bonds; and, since four electrons are required, a hole results when each trivalent atom is added. Because the trivalent atom can take an electron, it is often referred to as an acceptor atom. The number of holes can be carefully controlled by the number of trivalent impurity atoms added to the silicon.

Written and composed by: Prof. Muhammad Ali Malik (M. Phil. Physics), Govt. Degree College, Naushera

Majority and Minority Carriers in P-Type Semiconductor

In a p-type semiconducting material, most of the current carriers are holes. Holes can be thought of as positive charges because the absence of an electron leaves a net positive charge on the atom. The holes are the majority carriers in p-type material. Although the majority of current carriers in p-type material are holes, there are also a few free electrons that are created when electron-hole pairs are thermally generated. Electrons in p-type material are the minority carriers.

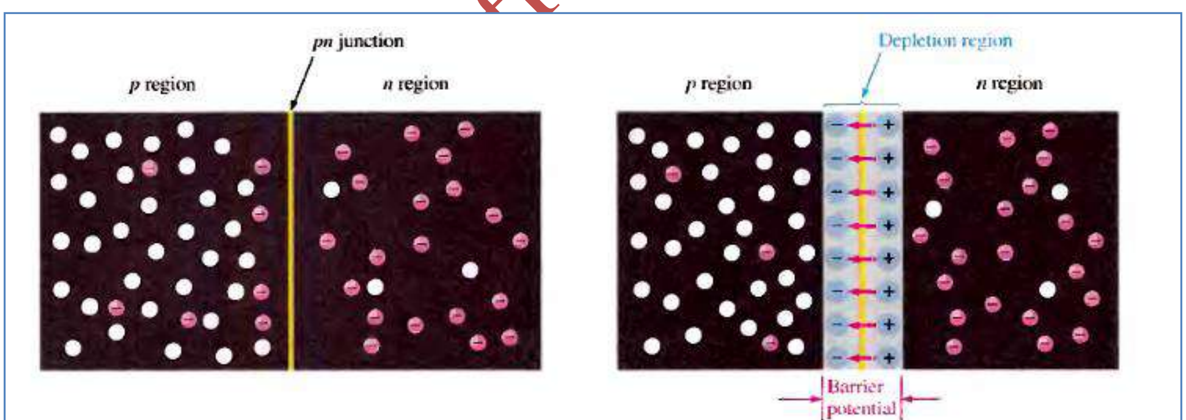
PN-Junction

If a piece of intrinsic silicon is doped so that a part is n-type and the other part is p-type, then the boundary between the p-type and n-type is called PN-junction.

The p region has many holes (majority carriers) from the impurity atoms and only a few thermally generated free electrons (minority carriers). The n region has many free electrons (majority carriers) from the impurity atoms and only a few thermally generated holes (minority carriers).

Formation of the Depletion Region

When a p-type semiconductor is brought close an n-type to form a PN-junction, then the free electrons near the junction in the n region begin to diffuse across the junction into the p-type region where they combine with holes near the junction, as shown in figure below:



When the PN-junction is formed, the n region loses free electrons as they diffuse across the junction. This creates a layer of positive charges (pentavalent ions) near the junction. As the electrons move across the junction, the p region loses holes as the electrons and holes combine. This creates a layer of negative charges (trivalent ions) near the junction. These two layers of positive and negative charges form the depletion region.

The term depletion refers to the fact that the region near the PN-junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction. After the initial surge of free electrons across the PN-junction, the depletion region has expanded to a point where equilibrium is established and there is no further diffusion of electrons across the junction. In other words, the depletion region acts as a barrier to the further movement of electrons across the junction.

Barrier Potential

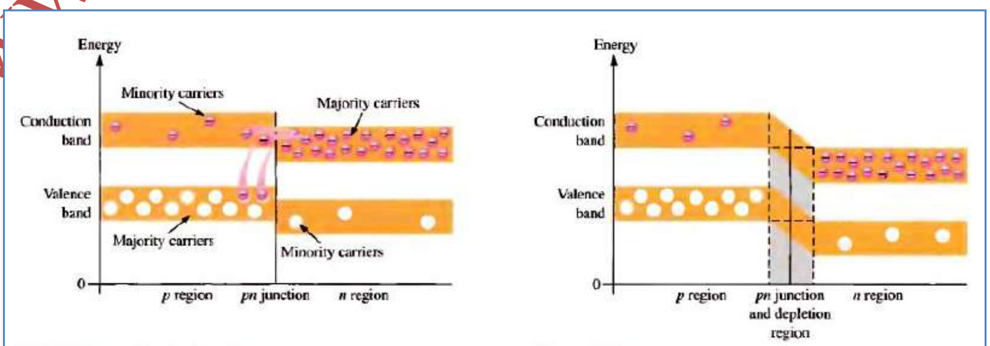
In the depletion region there are many positive charges and many negative charges on opposite sides of the PN-junction. The forces between the opposite charges form a "field of forces" called an electric field. This electric field is a barrier to the free electrons in the n region, and energy must be expended to move an electron through the electric field. That is, external energy must be applied to get the electrons to move across the barrier of the electric field in the depletion region.

The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field. This potential difference is called the barrier potential and is expressed in volts. The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at 25°C.

Energy Diagrams of the PN-Junction and Depletion Region

The valence and conduction bands in an n-type material are at slightly lower energy levels than the valence and conduction bands in a p-type material. This is due to differences in the atomic characteristics of the pentavalent and the trivalent impurity atoms. The valence and conduction bands in the n region are at lower energy levels than those in the p region, but there is a significant amount of overlapping.

The free electrons in the n region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction and temporarily become free electrons in the lower part of the p-region conduction band. After crossing the junction, the electrons quickly lose energy and fall into the holes in the p-region valence band as indicated in figure below:



(a) At the instant of junction formation (b) At equilibrium

As the diffusion continues, the depletion region begins to form and the energy level of the n-region conduction band decreases. The decrease in the energy level of the conduction band in the n region is due to the loss of the higher-energy electrons that have diffused across the junction to the p region. Soon, there are no electrons left in the n-region conduction band with enough energy to get across the junction to the p-region conduction band. At this point, the junction is at equilibrium; and the depletion region is complete because diffusion has ceased. There is an energy gradiant across the depletion region which acts as an "energy hill" that an n-region electron must climb to get to the p region.

Notice that as the energy level of the n-region conduction band has shifted downward, the energy level of the valence band has also shifted downward. It still takes the same amount of energy for a valence electron to become a free electron. In other words, the energy gap between the valence band and the conduction band remains the same.

Biasing

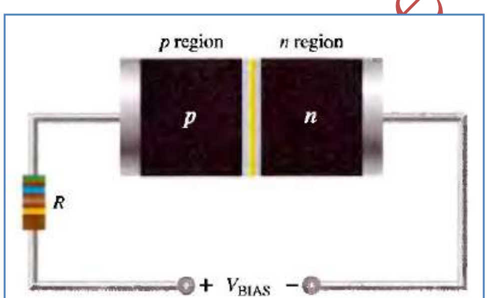
Application of an external voltage to the PN-junction is called biasing. There are two types of biasing:

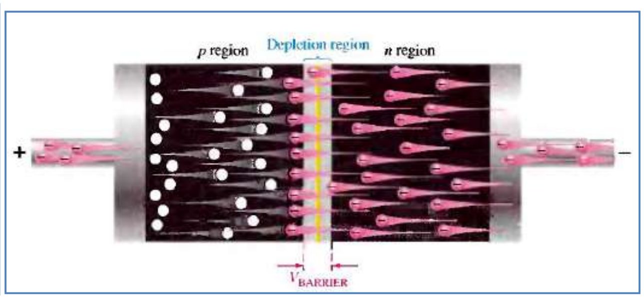
Forward Biasing

Reverse Biasing

Forward Biasing

A junction diode is said to be forward biased if its P-type region is connected to the positive terminal and N-type region is connected to the negative terminal of the battery.



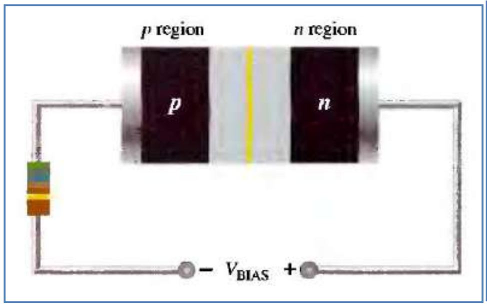


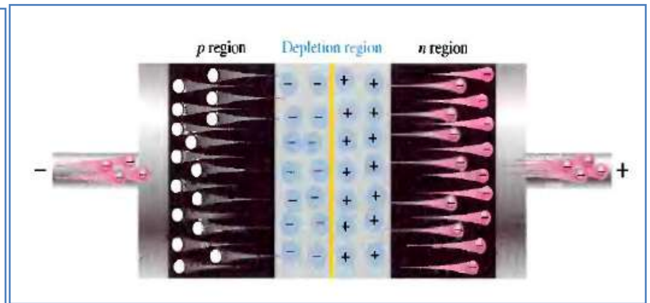
The emf of the battery should be greater than the barrier potential of the junction. Under such conditions, the electrons from N-type region and the holes from P-type region are pushed towards the junction and neutralize the positive and negative ions in depletion region. So the width of depletion region is decreased during forward biasing.

When the depletion region is decreased, then the electrons from N-type moves towards P-type and holes from P-type move towards N-type. This results in flow of current across the junction. Hence the junction diode is conductive when it is forward biased.

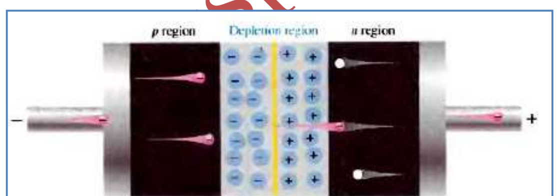
Reverse Biasing

A junction diode is said to be reversed biased, if its P-type region in connected with the negative terminal and N-type region with positive terminal of the battery.





In reverse biasing, the negative terminal attracts the holes and the positive terminal attracts the electrons away from the junction, so that the depletion region is widened and the barrier potential increases with increase in applied voltage. With increase of barrier potential there is no possibility of majority charge carriers to flow across the junction. Hence a junction diode does not conduct when it is reversed biased.



However a very small current (of the order of a few micro-amperes) flow in the circuit due to minority charge carriers, which is called a reverse current.

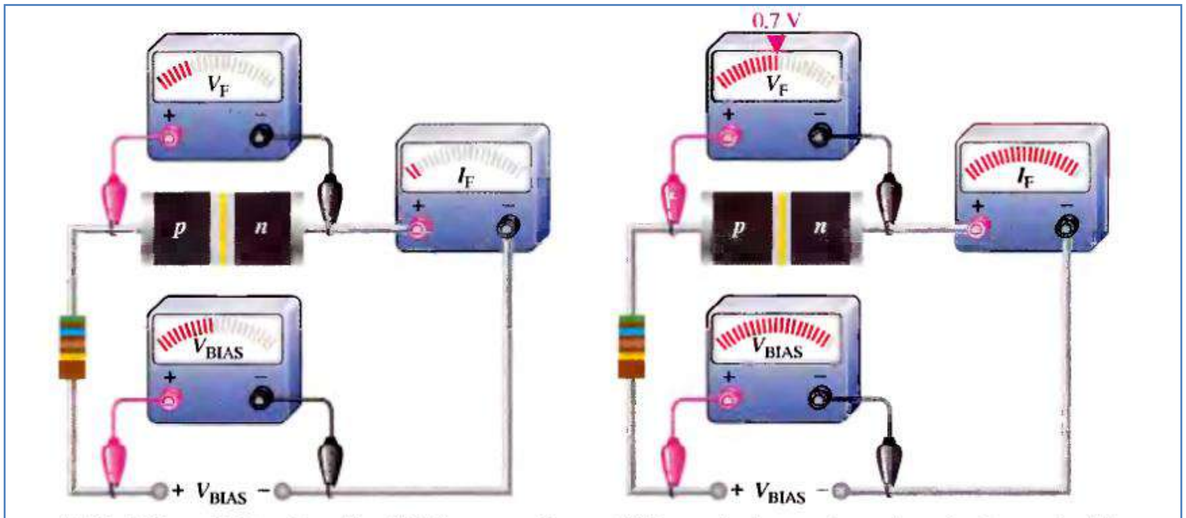
Characteristics of a PN-Junction

A graph between current and voltage applied across the PN-junction is called characteristics of PN-junction.

V-I Characteristic for Forward Bias

When a forward-bias voltage is applied across a diode, there is current. This current is called the forward current and is designated I_F as the forward-bias voltage is increased positively from 0 V. The resistor is used to limit the forward current to a value that will not overheat the diode and cause damage.

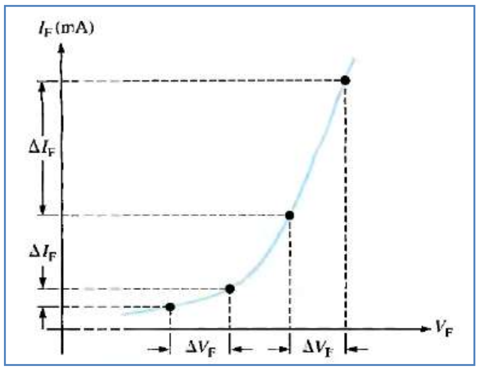
With 0 V across the diode, there is no forward current. As the forward-bias voltage is gradually increased, the forward current and the voltage across the diode gradually increase. When the forward-bias voltage is increased to a value where the voltage across the diode reaches approximately 0.7 V (barrier potential), the forward current begins to increase rapidly.



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

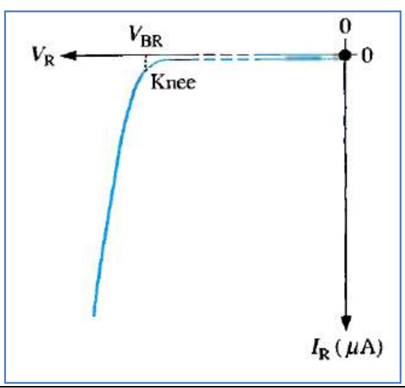
(b) Forward voltage reaches and remains at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

With 0 V across the diode, there is no forward current. As the forward-bias voltage is gradually increased, the forward current and the voltage across the diode gradually increase. When the forward-bias voltage is increased to a value where the voltage across the diode reaches approximately 0.7 V (barrier potential), the forward current begins to increase rapidly.



It can be seen from the curve that the forward current I_F is very small until the forward voltage V_F the barrier potential, of about 0.7 volts for silicon. As the forward voltage exceeds the value of barrier potential, called knee voltage, the current starts to increase rapidly. Beyond the knee of the forward characteristic, I_F increases almost linearly with increase in V_F.

V-I Characteristic for Reverse Bias



When a reverse-bias voltage is applied across a diode, there is only an extremely small reverse current (I_R) through the PN-junction. With 0 V across the diode. there is no reverse current. As you gradually increase the reverse-bias voltage, there is a very small reverse current and the voltage across the diode increases. When the applied bias voltage is increased to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), the reverse current begins to increase rapidly.

As you continue to increase the bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases very little above V_{BR}. Breakdown, with exceptions, is not a normal mode of operation for most PN-junction devices.

At breakdown voltage the covalent bonds of the crystal start breaking and charge carriers produced which result in heavy flow of reverse current through diode.

Rectification

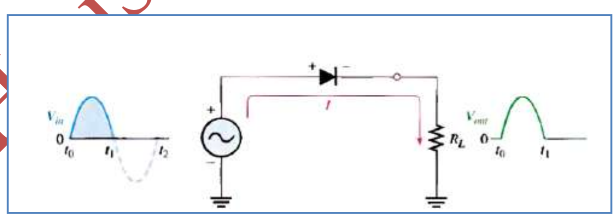
The conversion of alternating current into direct current is known as rectification. A PN-junction diode can conduct current only when it is forward biased and a very weak current flow across PN-junction when it is reversed biased. This action of junction enables us to use it as a rectifier. Rectifiers may be placed into following two categories:

i) Half wave rectification

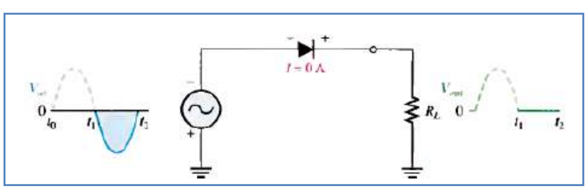
ii) Full wave rectification

Half Wave Rectification

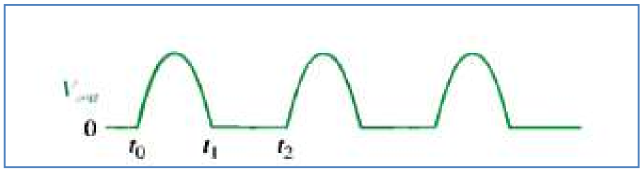
A half-wave rectifier allow current through the load only during one-half of the cycle. A diode is connected to an ac source and to a load resistor R_L forming a half-wave rectifier. When the sinusoidal input voltage (V_{in}) goes positive, the diode is forward-biased and conducts current through the load resistor. The current produces an output voltage across the load R_L which has the same shape as the positive half-cycle of the input voltage as shown in figure below:



When the input voltage goes negative during the second half of its cycle, the diode is reverse-biased. There is no current, so the voltage across the load resistor is 0 V, as shown in figure below:

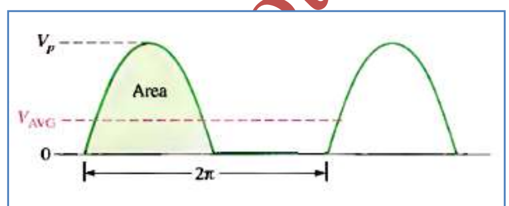


The net result is that only the positive ha]f-cycles of the ac input voltage appear across the load. Since the output does not change polarity, it is a pulsating dc voltage with a certain frequency as shown in the figure below:



Average Value of the Half-Wave Output Voltage

The average value of the half-wave rectified output voltage is the value you would measure on a de voltmeter. Mathematically, it is determined by finding the area under the curve over a full cycle, as illustrated in the figure below, then dividing by 2π, the number of radians in a full cycle.



$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin\theta \, d\theta = \frac{V_m}{2\pi}\,|-\cos\theta|_0^{\pi}$$

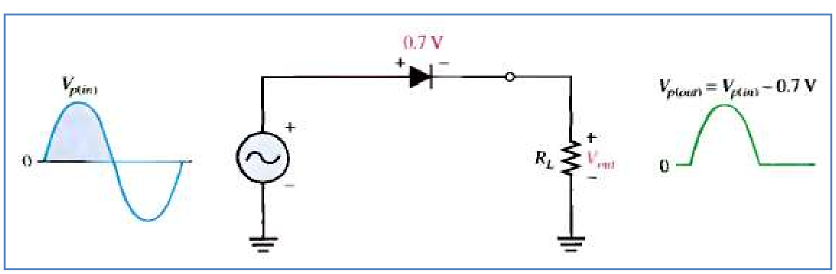
$$V_{dc} = \frac{V_m}{2\pi}\,[1-(-1)] = \frac{V_m}{2\pi}\,[2]$$

$$V_{dc} = \frac{V_m}{\pi} = 0.318\,V_m$$

Note that $V_m \sin\theta$ is the instantaneous AC voltage.

Effect of the Barrier Potential on the Half-Wave Rectifier Output

In the previous discussion, the diode was considered ideal. When the practical diode model is used with the barrier potential of 0.7 V taken into account, this is what happens. During the positive half-cycle, the input voltage must overcome the barrier potential before the diode becomes forward-biased. This results in a half-wave output with a peak value that is 0.7 V less than the peak value of the input, as shown in figure below:



The expression for the peak output voltage is

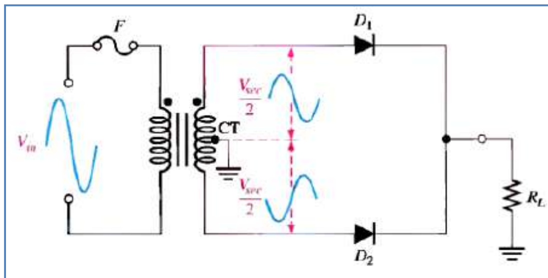
$$V_{p(out)} = V_{p(in)} - 0.7\,V$$

Full-Wave Rectifiers

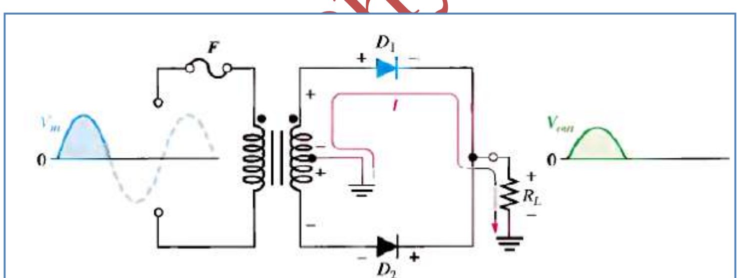
A full-wave rectifier allows unidirectional (one-way) current through the load during the entire 360° of the input cycle.

The Center-Tapped Full-Wave Rectifier

A center-tapped rectifier is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer, as shown in figure below. The input voltage is coupled through the transformer to the center-tapped secondary. Half of the total secondary voltage appears between the center tap and each end of the secondary winding as shown.

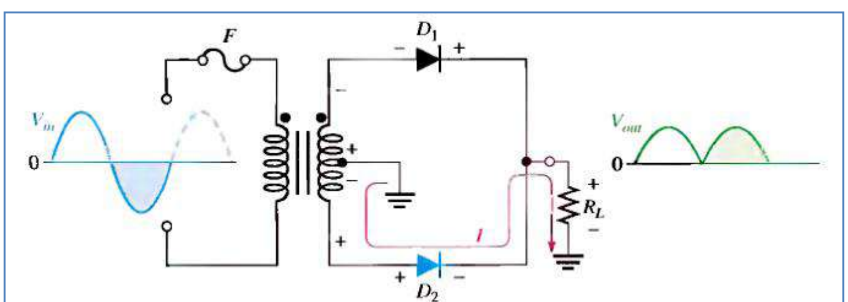


For a positive half-cycle of the input voltage, the polarities of the secondary voltages are as shown in Figure (a). This condition forward-biases diode D_1 and reverse-biases diode D_2. The current path is through D_1 and the load resistor R_L.



(a) During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased.

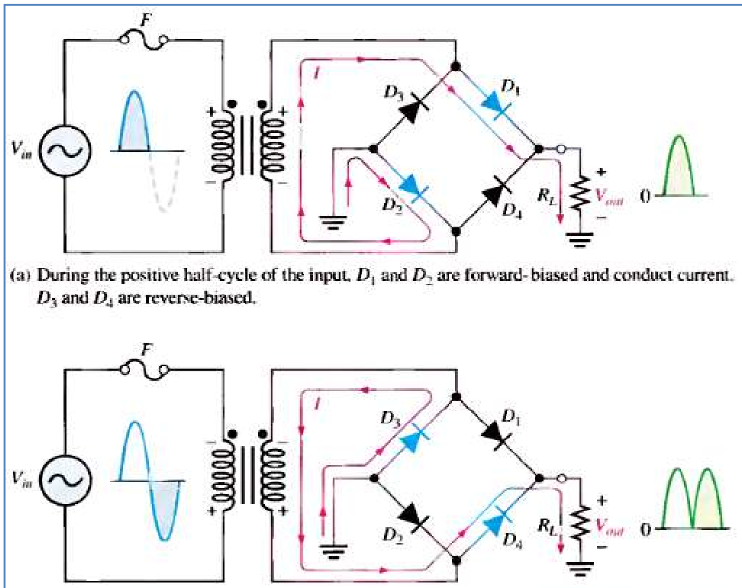
For a negative half-cycle of the input voltage, the voltage polarities on the secondary are as shown in Figure (b). This condition reverse-biases D_1 and forward-biases D_2. The current path is through D_2 and R_L as indicated. Because the output current during both the positive and negative portions of the input cycle is in the same direction through the load, the output voltage developed across the load resistor is a full-wave rectified dc voltage.



(b) During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.

The Bridge Full-Wave Rectifier

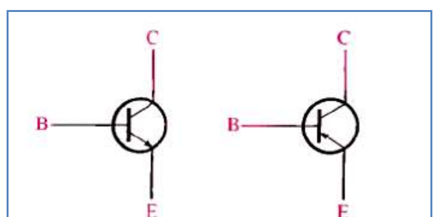
The bridge rectifier uses four diodes connected as shown in Figure 2-20_ When the input cycle is positive as in part (a), diodes D_l and D_2 are forward-biased and conduct current in the direction shown. A voltage is developed across R_L that looks like the positive half of the input cycle. During this time, diodes D_3 and D_4 are reverse-biased.



(a) During the positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.

(b) During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

When the input cycle is negative as in Figure (b), diodes D_3 and D_4 are forward-biased and conduct current in the same direction through R_L as during the positive half-cycle. During the negative half-cycle, D_l and D_2 are reverse-biased. A full-wave rectified output voltage appears across R_L as a result of this action.

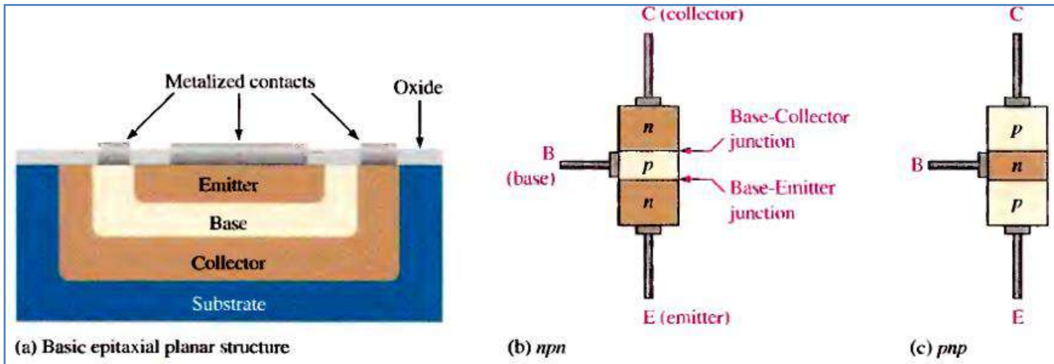


(a) *npn* (b) *pnp*

Transistor

The BJT (bipolar junction transistor) is constructed with three doped semiconductor regions separated by two pn junctions. The three regions are called emitter, base, and collector. One type consists of two n regions separated by a p region (npn), and the other type consists of two p regions separated by an n region (pnp). The term bipolar refers to the use of both holes and electrons as carriers in the transistor structure.

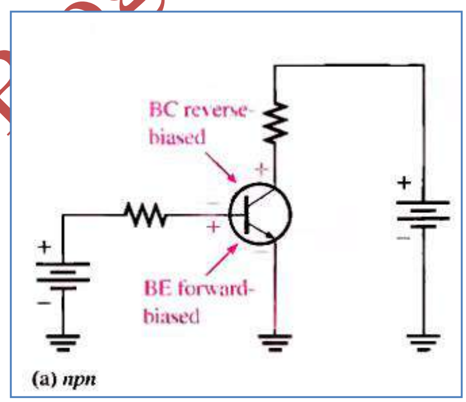
The pn junction joining the base region and the emitter region is called the base-emitter junction. The pn junction joining the base region and the collector region is called the base-collector junction. The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions. The schematic symbols for the npn and pnp bipolar junction transistors is shown in the figure:



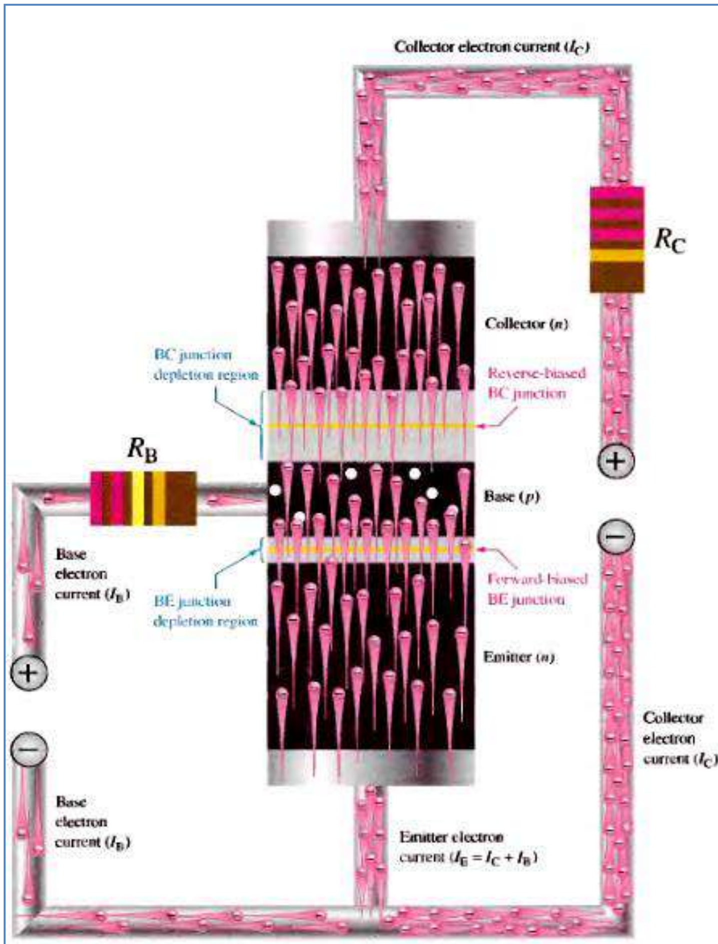
Transistor biasing

For the normal operation of a transistor, its emitter base junction is always forward biased and collector base junction is always reversed biased.

To illustrate transistor action, let's examine what happens inside the npn transistor. The forward bias from base to emitter narrows the BE depletion region, and the reverse bias from base to collector widens the BC depletion region. The heavily doped n type emitter region is teeming with conduction-band (free) electrons that easily diffuse through the forward-biased BE junction into the p-type base region. The base region is lightly doped and very thin so that it has a limited number of holes. Thus, only a small percentage of all the electrons flowing through the BE junction can combine with the available holes in the base. These relatively few recombined electrons flow out of the base lead as valence electrons, forming the small base electron current.



Most of the electrons flowing from the emitter into the thin, lightly doped base region do not recombine but diffuse into the BC depletion region. Once in this region they are pulled through the reverse-biased BC junction by the electric field set up by the force of attraction between the positive and negative ions. The electrons now move through the collector region, out through the collector lead, and into the positive terminal of the collector voltage source.



Transistor Currents

The arrow on the emitter of the transistor symbols points in the direction of conventional current.

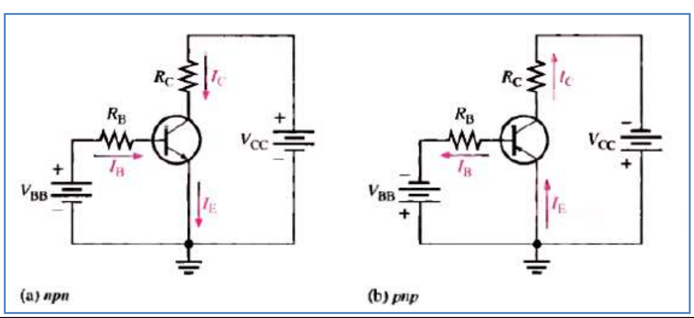
This diagrams shows that the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows:

$I_E = I_C + I_B$

Transistor Parameters

Consider a transistor is connected to dc bias voltages for both npn and pnp types. V_{BB} forward-biases the base-emitter junction, and V_{cc} reverse-biases the base-collector junction.

DC Beta (β_{dc})



The ratio of the dc collector current (I_C) to the dc base current (I_B) is the dc beta (β_{dc}), which is the dc current gain of a transistor. Typical values of β_{dc} lies in the range of 50 to 400.

$$\beta_{dc} = \frac{I_C}{I_B}$$

DC Alpha (α_{dc})

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc alpha. Typically, values of α_{dc} range from 0.95 to 0.99 or greater, but α_{dc} is always less than 1.

$$\alpha_{dc} = \frac{I_C}{I_E}$$

Transistor in a Circuit

Transistor has three terminals:

(i) Emitter (ii) Base (iii) Collecor

When we put the transistor in a circuit, one terminal acts as input terminal and the other as output terminal. The third terminal acts as a common terminal to both input and output circuits. Any one of the three terminals can be made common. So a transistor con be connected in a circuit in three ways.

(i) Common Base Configuration

(ii) Common Emitter Configuration

(iii) Common Collector Configuration

Common Emitter Configuration

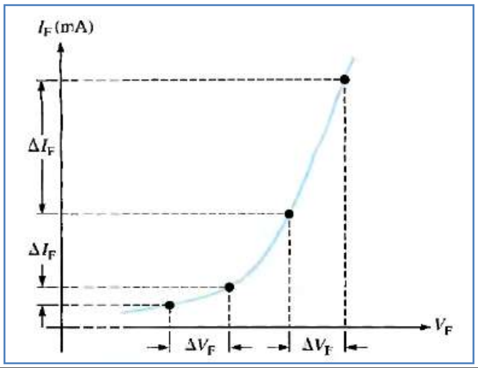
Figure shows the common emitter configuration of pnp transistor. It is called common emitter configuration because emitter is common to both input and output circuits. Two sets of curves are required to completely describe the behavior of CE configuration. One set of curves are called input characteristics and the other set is called output characteristics.

Input Characteristics

The input characteristics show a relationship between input current I_B and input voltage V_{BE} for different values of output voltage V_{CE}. The set of curves obtained from input characteristics is called base curves.

Base Curves

These are the curves obtained by plotting I_B against V_{BE} with V_{CE} as parameter as shown in the figure. The characteristics are similar to that of a forward biased diode. This is because of the reason that base emitter region is forward biased. We obtain two hybrid parameters or transistor constants from the input characteristics.



Input Resistance

It is the ratio of the change in base-emitter voltage (ΔV_{BE}) to the change in base current (ΔI_B) at constant V_{CE}. i.e.,

$$R_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}$$

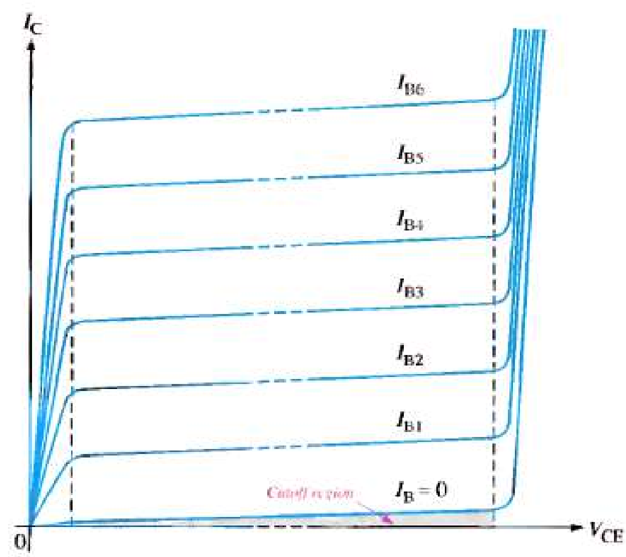
Voltage Gain

It is the ratio of the change in collector-emitter voltage (ΔV_{CE}) to the change in base-emitter voltage (ΔV_{BE}) at the constant values of I_B.

$$\text{Voltage Gain} = \left(\frac{\Delta V_{CE}}{\Delta V_{BE}}\right)_{I_B}$$

Output Characteristics

The output characteristics show a relation between the output current (I_C) and the output voltage (V_{CE}) for the different values of input current I_B. the set of curves obtained from input characteristics are called collector curves.



(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$ etc.)

Collector Curves

These are the curves obtained by plotting I_C against V_{CE} with I_B used as parameter. These curves shows

- I_C increases rapidly with increase in V_{CE}
- These curves also show that for a fixed values of V_{CE}, I_C increases with increase in I_B.

The hybrid parameters obtained from output characteristics are

Output Resistance

It is the ratio of change in collector-emitter voltage ΔV_{CE} to the change in collector current ΔI_C at constant I_B.

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

Current Gain or Current Amplification Factor β

The ratio of change in collector current ΔI_C to the change in base current ΔI_B at constant V_{CE}. i.e.,

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

Relation Between α and β

α is the ratio of collector current ΔI_C and emitter current ΔI_E. i.e.,

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \qquad \text{------------- (1)}$$

β is the current amplification factor for CE configuration, which is described as:

$$\beta = \frac{\Delta I_C}{\Delta I_B} \qquad \text{------------- (2)}$$

Now as

$$I_E = I_B + I_C$$

$$\Longrightarrow \Delta I_E = \Delta I_B + \Delta I_C$$

$$\Longrightarrow \Delta I_B = \Delta I_E - \Delta I_C$$

Putting values in (2), we get:

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

Dividing the numerator and denominator by ΔI_E

$$\beta = \frac{\Delta I_C / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

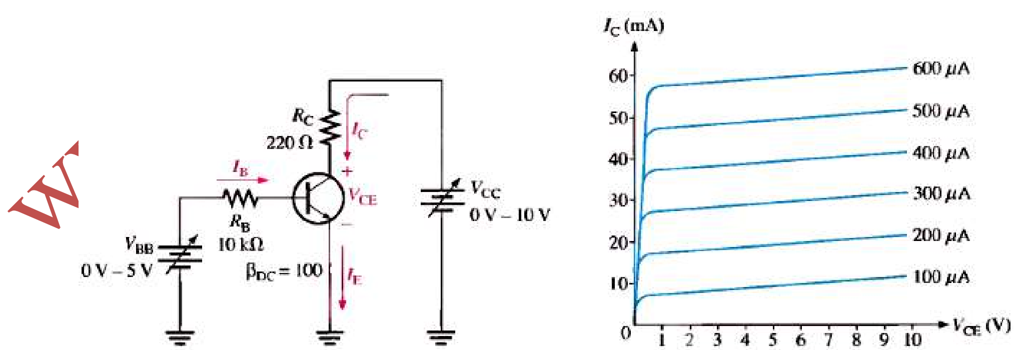
$$\beta = \frac{\Delta I_C / \Delta I_E}{1 - \frac{\Delta I_C}{\Delta I_E}}$$

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

This is the relation between α and β.

DC Load Line

It is the line on the output characteristics of a transistor circuit which gives the values of I_C and V_{CE} when no signal is applied. Consider an npn transistor used as a common emitter amplifier as shown in the figure below:



(a) DC biased circuit (b) Collector characteristic curves

From the output circuit, we have:

$$V_{CC} = V_{CE} + I_C R_L$$

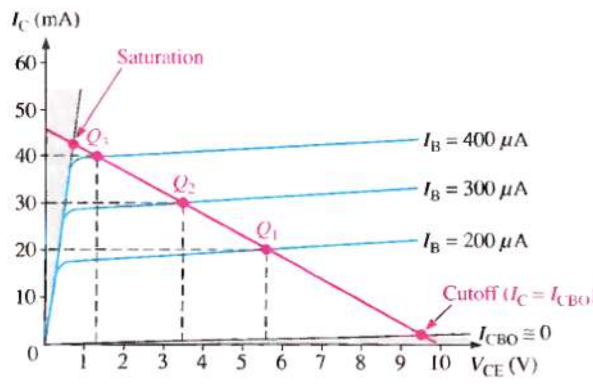
$$V_{CE} = V_{CC} - I_C R_L \qquad \text{------------ (1)}$$

This is the equation of dc load line in V_{CE} - I_C plane. The dc load line can be plotted the two end points on the straight line.

To get the 1st end point on the I_C axis, we put $V_{CE} = 0$ in equation (1). So

$$0 = V_{CC} - I_C R_L$$

$$I_C = \frac{V_{CC}}{R_L}$$



To get the 2nd end point on V_{CE} axis, we put $I_C = 0$ in equation (1).

$$V_{CE} = V_{CC}$$

By joining the both end points, dc load line is obtained.

With the construction of dc load line on the output characteristics, we get the complete information about the output circuit of transistor amplifier in the zero signal condition.

Operating Point

The zero signal values of I_C and V_{CE} are called the operating points. It is also called Q point or quiescent point. It is the point where the load line intersects the collector curve for a given base current. It is usually selected at the middle of the load line.

Cut Off Region

If the signal voltage is made negative then the base current decreases and point Q moves downward along the load line. If the signal voltage is made very much negative, such that the base current $I_B = 0$, then the transistor is said to be in cut off region.

So the point where the load line intersects $I_B = 0$ curve is called the cut off point.

Saturation region

If the signal voltage is made positive then the base current increase and point Q moves upward along the load line. If the signal voltage is made very much positive such that $I_B = I_B(saturation)$, then the transistor is said to be in saturation region. So point where the load line intersects the $I_B = I_B(saturation)$ curve is called the saturation point.

Active region

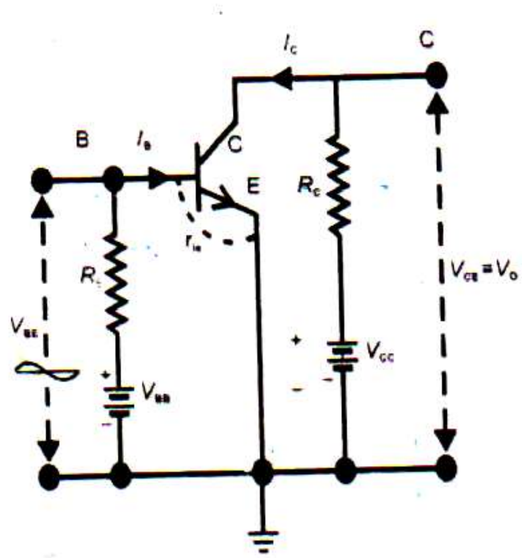
The region between the cut off and saturation region is called active region. A transistor is normally operated in active region.

Transistor as an Amplifier

Amplification is the process of linearly increasing the amplitude of an electrical signal. In majority of the electronic circuits, transistors are basically used as amplifiers. An amplifier is thus the building block of every complex electronic circuit.

Consider an npn transistor in common emitter mode. The common emitter mode is widely used, since it provides much greater power gain as compare to common base or common collector mode.

The input signal is applied between the emitter-base junction and output is taken across the load R_C connected in the collector circuit. The common emitter transistor as an amplifier is shown in the figure:



DC Analysis

The battery V_{BB} forward biases the base emitter junction and V_{CC} reverse biases the collector base junction. V_{BE} and V_{CE} are the input and output voltages respectively. The base current I_B current flowing through the input circuit is given by the relation:

$$I_B = \frac{V_{BE}}{r_{ie}}$$

Where r_{ie} is the base emitter resistance of the transistor.

The transistor amplifies the base current β −times. So the current passes through the output circuit is given by the expression:

$$I_C = \beta I_B = \beta \frac{V_{BE}}{r_{ie}}$$

The output voltage $V_0 = V_{CE}$ is determined by the applying the Kirchhoff Voltage Rule on the output loop:

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

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

$$\Rightarrow V_0 = V_{CC} - \beta \frac{V_{BE}}{r_{ie}} R_C \quad --------- \quad (1)$$

AC Analysis

When small signal voltage ΔV_{in} is applied at the input, the input voltage changes from V_{BE} to $V_{BE} + \Delta V_{in}$. This causes a little changes in base from I_B to $I_B + \Delta I_B$ due to which the collector current changes from I_C to $I_C + \Delta I_C$. As the collector current changes, the voltage drop across R_C i.e., $I_C R_C$ also changes due to which the output voltage V_0 changes by ΔV_0. Substituting the changed values in equation (1), we get:

$$V_0 + \Delta V_0 = V_{CC} - \beta\left(\frac{V_{BE} + \Delta V_{in}}{r_{ie}}\right) R_C \quad --------- \quad (2)$$

Subtracting equation (1) and (2), we get:

$$\Delta V_0 = -\beta\left(\frac{\Delta V_{in}}{r_{ie}}\right) R_C$$

$$\Rightarrow \frac{\Delta V_0}{\Delta V_{in}} = -\frac{\beta R_C}{r_{ie}}$$

Where $\frac{\Delta V_0}{\Delta V_{in}} = A_v$ is the voltage gain.

$$\Rightarrow A_v = -\frac{\beta R_C}{r_{ie}}$$

The factor $\frac{\beta R_C}{r_{ie}}$ is of the order of hundred, so the input signal is amplified. The negative sign shows that there is a phase shift of 180^0 between the input and output signals.

Example

Suppose in a common emitter circuit, there is a load resistance R_C = 5 kΩ. Suppose the change of 0.1 V in the signal voltage produces a change of 1 mA in emitter current. The same change of current takes place in collector current i.e., 1 mA. This collector current through R_C produces a voltage = $(5\,k\Omega)(1\,mA) = 5\,V$.

Thus a change of 0.1 V in the input signal has produced a change of $5\,V$ in the output signal. So the transistor has raised the voltage from $0.1\,V$ to $5\,V$ i.e., the voltage amplification in this case is $= \frac{5}{0.1} = 50$.

Digital Systems

A system which deals with quantities and variables having two discrete values or states are called is called digital system. In these circuits, the input and output can have any one of the two values "1" or "0". Following are the examples of such quantities:

- A switch can either open or closed.
- The answer of a question can be either yes or no.
- A certain statement can be either true or false.
- A bulb can be either on or off.

In all these situations, one of the states is represented by "1" and the other state by "0".

- 1 represents:
  - **i.** ON circuit
  - **ii.** High voltage
  - **iii.** True statement
- 0 represents:
  - **i.** OFF circuit
  - **ii.** Low voltage
  - **iii.** False statement

Logic gates solve problems by using a special algebra, known as "Boolean Algebra". Boolean algebra is based upon three basic operations namely:

i. AND operation
ii. OR operation
iii. NOT operation

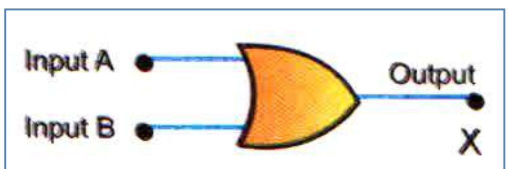
Logic Gates

The electronic circuits which implement the various logic operations are known as logic gates. There are three basic types of logic gates:

i. AND Gate
ii. OR Gate
iii. NOT Gate

OR Gate

OR gate implements the logic of OR operation. It has two or more inputs and a single output. The symbolic representation of an OR gate is shown in the figure.



OR gate

The output of the OR gate has a value "0" when