15 - SEMICONDUCTOR ELECTRONICS: MATERIALS, DEVICES AND SIMPLE CIRCUITS

15.1 Introduction

The word electronics is coined from the words electron mechanics. The subject of electronics deals with the study of devices in which specific current (I) versus voltage (V) relationship is obtained by controlling the production of electrons, theirs numbers and their conduction. Such relationships are different from the one obeyed by Ohm's law in good conductors in which electric current is directly proportional to the electric potential difference.

There are many substances found in nature in which the conduction of electricity is different from the one found in metals. Solid state devices are made having appropriate I - V relations by properly adding impurities in such a substance. Solid state devices are small in size and light in weight. They are very efficient and cheap.

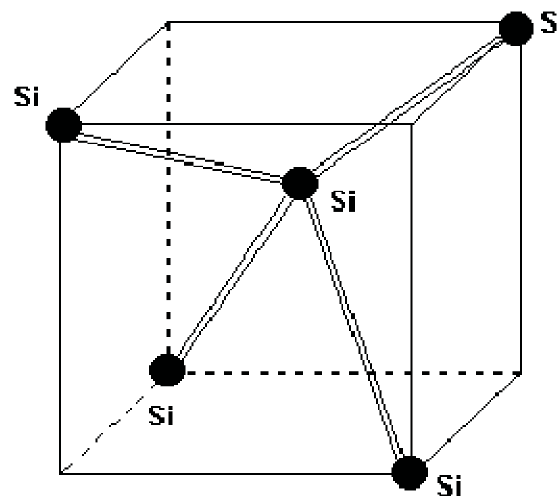
Semiconductor devices like the P – N junction diode, transistor LED (Light emitting diode), solar cell and logic circuits which is a basis for digital circuits shall be discussed in this chapter.

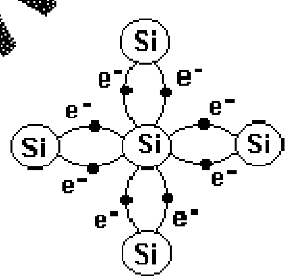
15.2 Conductors, Insulators and Intrinsic Semiconductors (A Bond Picture)

The elements in the first three groups of the periodic table like alkali metals, noble metals, Aluminium, etc. are good conductors due to the presence of free electrons. Non-metals are bad conductors of electricity due to lack of free electrons. The elements in the fourth group of the periodic table like Si and Ge have greater resistance than good conductors but less than bad conductors. They are known as semiconductors. They behave as bad conductors at absolute zero temperature in their pure form.

The resistivity of the good conductors increases with temperature, while the resistivity of the semiconductors decreases on increasing the temperature unto a certain limit. The conductivity of the semiconductors is changed by making radiation of suitable frequency incident on them.

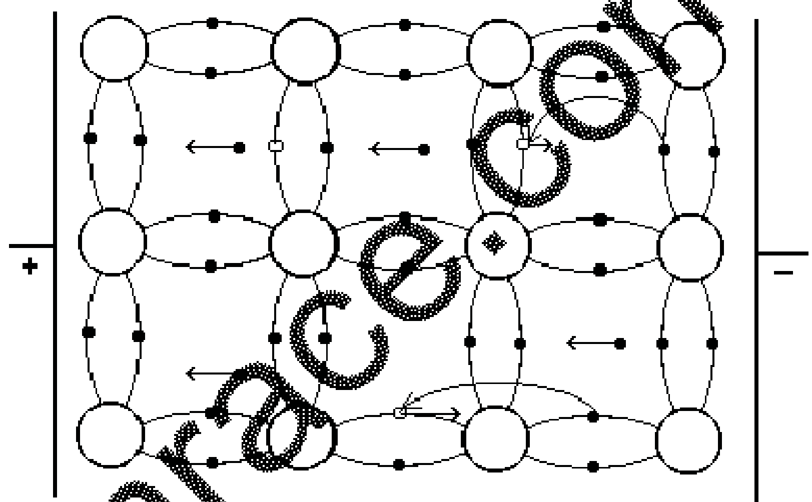
Two very important semiconductors Ge and Si are discussed here. Both have diamond crystal structure. If an atom of Si is considered at the centre of the tetrahedron, then its four nearest neighbours are at the vertices of a tetrahedron as shown in the figure. Diamond crystalline structure is obtained on extending this arrangement in a three dimensional space.





The electronic arrangement of Si is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$. The electrons in $1s^2\ 2s^2\ 2p^6$ completely occupy the K and L shells. $3s^2\ 3p^2$ electrons are the valence electrons. These 2 s orbitals and 2 p orbitals combine to form 4 sp^3 complex orbitals. These orbitals combine with similar such orbitals of the neighbouring atoms and form covalent bonds. Thus, each of the four valence electrons of the silicon forms a covalent bond with its four neighbouring atoms as shown in the figure.

At absolute zero temperature, Si and Ge behave as insulators as the valence electrons are bound in covalent bonds. At room temperature, these bonds break due to thermal oscillations of atoms freeing the electrons which increases conductivity. Deficiency of electron in a bond produces a vacant space which is known as a hole. The hole has the ability of attracting electrons and the randomly moving free electron can get trapped in a hole. Thus hole behaves as a positive charge though it is neither a real particle nor has any positive charge.

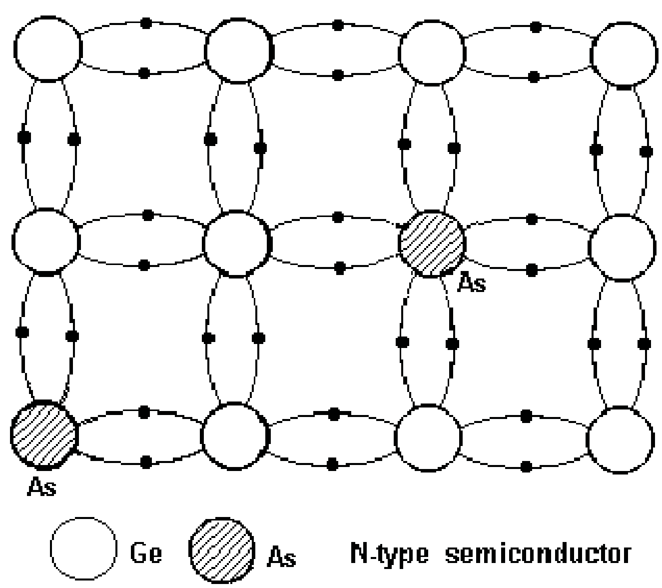


On applying p.d. between two ends of a crystal as shown in the figure, electric current gets set up. Now, thermal oscillations and external electric field cause covalent bonds to break and the free electrons produced get trapped in the holes during their motion. Simultaneously, new holes are produced by electrons breaking free from the covalent bonds. The free electrons move towards the positive end and the holes to the negative end. The motion of holes towards the negative end is equivalent to the motion of bound electrons towards the positive end. Thus current in a semiconductor is due to (i) motion of free electrons and (ii) motion of bound electrons. Both these currents are in the same direction.

The number density of free electrons (n_e) and holes (n_h) in a pure semiconductor are equal. Pure semiconductor is called intrinsic semiconductor. Hence electrons and holes are called intrinsic charge carriers and their number density is indicated by n_i. $n_e = n_h = n_i$.

15.3 N and P type Semiconductors (Extrinsic Semiconductors)

N-type semiconductor is prepared by adding pentavalent impurities like Antimony or Arsenic in pure semiconductor. P-type semiconductor is prepared by adding trivalent impurities like Aluminium, Gallium or Indium.

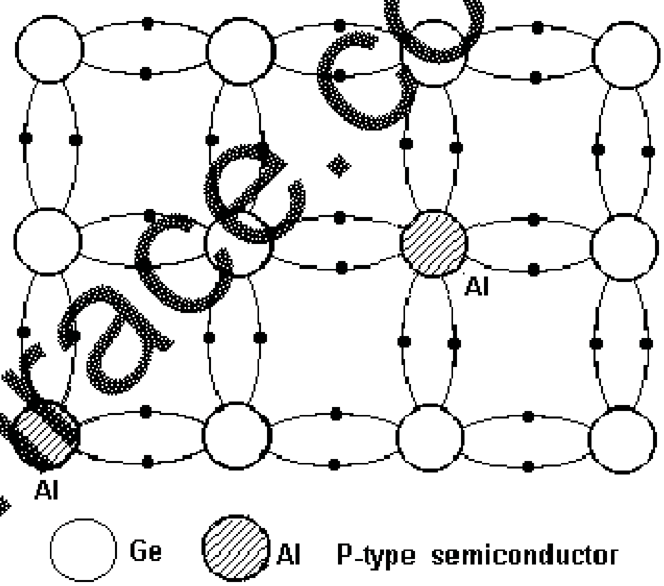


The figure shows N-type semiconductor in which two Arsenic atoms have replaced two Germanium atoms in the lattice structure of Ge crystal. Four of the five valence electrons of As atom are used up in forming covalent bonds and the fifth electron can act as a free electron with 0.01 eV energy. This energy is 0.05 eV in case of Silicon atom. This much energy is easily available at room temperature as thermal energy.

The pentavalent impurity is known as donor impurity as it donates the electric charge carrier, electron, to the host atom. It is added in proportion of 1 in 10^6 pure atoms. Hence in one mole of crystal, about 10^{17} impurity atoms and 10^{17} free electrons are present. A good conductor like copper contains nearly 10^{23} free electrons per mole. Besides these, some more free electrons and equal number of holes result from breaking of covalent bonds. As their number is very small as compared to the free electrons from the impurity atoms, electrons are the majority charge carriers and holes minority charge carriers in the case of N-type semiconductors ($n_e > n_h$).

P-type semiconductors:

If trivalent impurities like aluminium is added to Ge or Si, then three free electrons of this impurity atom form covalent bonds with its neighbouring three Ge or Si atoms. Thus there is a deficiency of one electron in the formation of the fourth covalent bond. This deficiency of electron can be considered as a hole which is present in one of the bonds between the aluminium and Ge or Si atoms. This hole has a tendency to attract electron. Hence aluminium atom is known as acceptor impurity. Here, holes which behave as positively charged particles are majority charge carriers and electrons are minority charge carriers. Hence such a semiconductor is known as P-type semiconductor ($n_h > n_e$). The figure shows symbolic representation of aluminium impurity added to Ge crystal lattice.



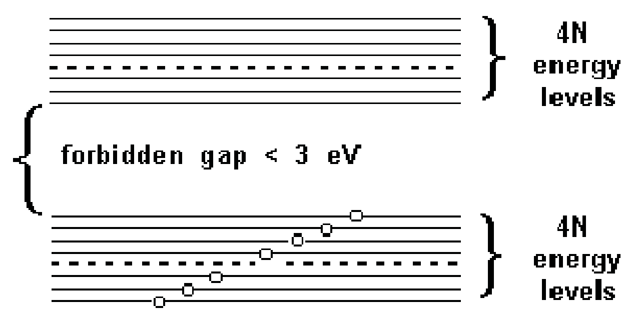
15.4 Conductors, insulators and semiconductors - (A Band Picture)

The insulators, semiconductors and conductors are classified on the basis of the energy levels of the atoms.

Insulators:

Consider the example of silicon to understand the electrical conductivity of the insulators.

Let there be N number of silicon atoms. There are two 3 s^2 and six 3 p^6 valence states of which four are filled.



Thus there are 8N valence states and the corresponding energy levels are indicated in the figure.

The closely spaced 4N levels form a band structure. By Pauli's exclusion principle, one electron occupies only one energy level. Thus with the 4N available electrons, the lower valence band is completely filled. As the band is completely filled, the electrons in this band have no available energy to move. Hence there is no electrical conductivity.

Above the valence band is the forbidden gap where there are no available energy levels. The width of the forbidden gap is < 3 eV.

Above the forbidden gap is the conduction band. At 0 K temperature, it is completely empty. If the electrons in the valence band acquire sufficient energy to cross the forbidden gap, then they can move to the conduction band and contribute to he electrical conductivity.

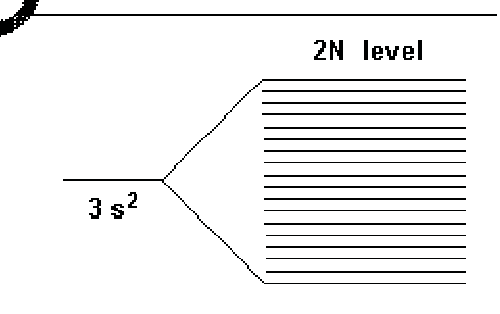
A hole is created when an electron moves from the valence band to the conduction band. In a pure semiconductor, the number of holes and electrons in the conduction band are equal and hence they contribute equally to the electrical conductivity.

Insulator substances:

Such substances have large forbidden gap (> 3 eV). Hence electrons are not able to move from the valence band to the conduction band and such substances are bad conductors of electricity.

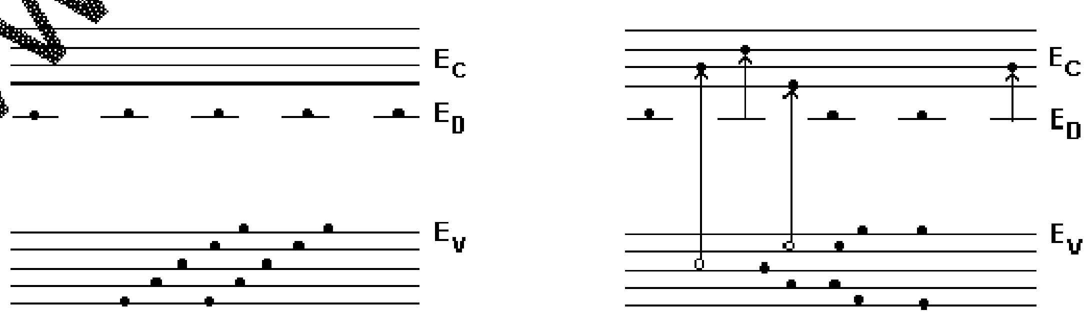
Conductors:

The figure sows the band structure of a sodium crystal containing N atoms which explains its good conductivity. The electronic configuration of sodium atom is given as $1s^2\ 2s^2\ 2p^6\ 3s^1$. There 2N number of 3s valence states of which N are filled due to one electron from each of the sodium atom. The remaining N states are empty. Hence, the electrons can easily move into the empty available states and contribute towards electrical conductivity. In any metals, the conduction and valence bands overlap with each other resulting in the electrons contributing in the electrical conduction.



Electrical Conduction in N and P – type Semiconductors

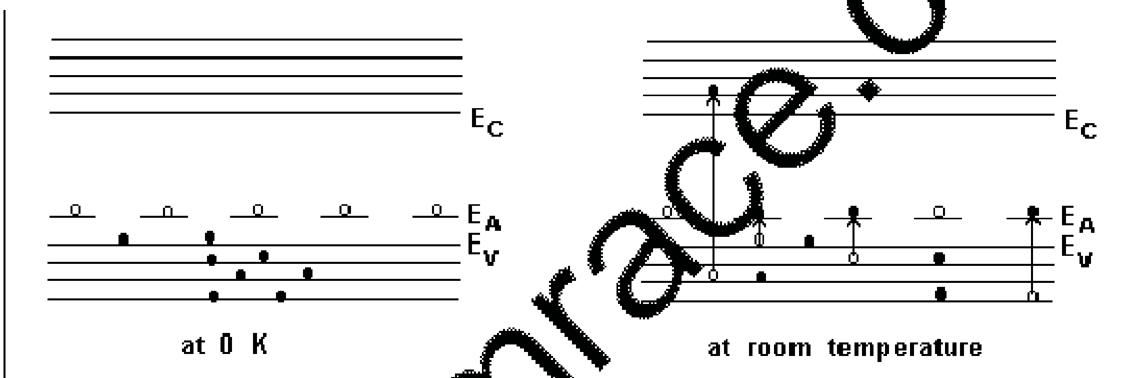
The following figure shows completely filled valence and completely empty conduction bands of N-type semiconductor at 0 K temperature. It also sows the valence energy levels of the impurity atoms by the dashed lines. As the impurity atoms are scattered in the crystal structure of the semiconductor, the wave functions of their valence states lie closer to the impurity atoms and are not present in he entire crystal. Hence the symbolic representation is shown by the dotted line.



at 0 K at room temperature

The difference between E_C and E_D being very less, more and more electrons from the valence band of the semiconductor and that of the impurity atoms cross over to the conduction band and occupy empty energy levels in it. Hence in a N-type semiconductor number of majority charge carriers, electrons is much more than in the pure semiconductors and also much larger than the number of holes ($n_e >> n_h$).

The following figure shows the energy levels and impurity atoms of a P-type semiconductor. Here, energy levels E_A of the trivalent impurity atoms, containing holes, are very close to the valence energy levels, E_V. The electrons of the valence band can easily occupy the empty energy levels of the impurity atoms and of the conduction band on getting sufficient energy at the room temperature leaving behind large number of holes in their place. Hence in a P-type semiconductor, the electrical conductivity is much more than that in a pure semiconductor ($n_h >> n_e$).



Some of the randomly moving electrons get trapped by the holes. Thus, the creation of the electron hole pair and its recombination process occur at the same time. In the equilibrium position, the rate of electron hole pair formation and their recombination are equal.

The recombination rate $\propto n_h n_e = R n_h n_e$, where R is the recombination coefficient.

For an intrinsic or pure semiconductor, $n_e = n_h = n_i$.

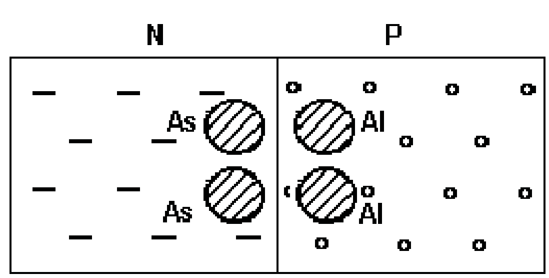
Hence, the recombination rate $= R n_h n_e = R n_i^2$

The recombination rate for an intrinsic semiconductor and its extrinsic semiconductor as per the laws of thermodynamics are equal.

$\therefore R n_h n_e = R n_i^2 \quad \therefore n_h n_e = n_i^2$

15.5 P-N Junction Diode

P-N junction is obtained by combining P-type semiconductor with an N-type semiconductor. The figure shows the P-N junction diode before the formation of the junction.

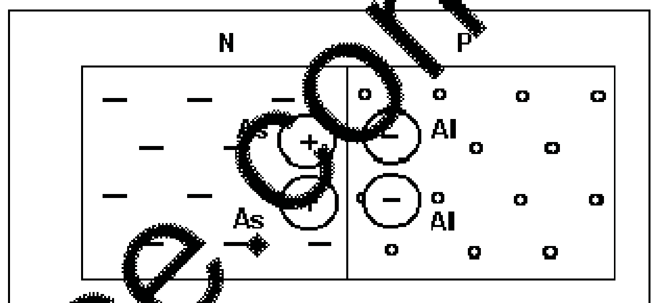


There are excess holes, shown as small circles, in the P-section which exist in the covalent bond between the host atoms and the impurity atoms. The figure shows two impurity atoms of Aluminium near the junction.

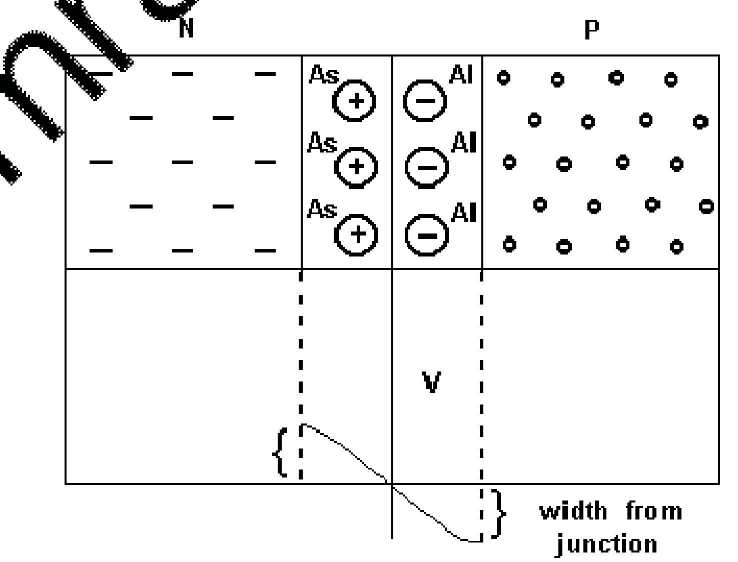
There are excess electrons in the N-section obtained from the pentavalent impurity atoms. The figure shows two Arsenic impurity atoms near the junction. Both N and P sections are electrically neutral.

The electrons diffuse from N to P section as the N section has excess of electrons as compared to P section. These electrons occupy holes of P side near the junction. A small amount of holes also diffuse from P to N section.

The adjoining figure shows the situation after some diffusion has occurred. Two electrons of Arsenic are shown to occupy the two holes near the Aluminium atoms. This leaves Arsenic atoms as positive ions and Aluminium atoms as negative ions. As the diffusion progresses, more and more Arsenic and Aluminium atoms become positive and negative ions respectively.



This results in a steady electric field near the junction due to the charges on the ions direction of which is from N to P region. The electrons have to overcome this increasing electric field to diffuse from N to P side. The diffusion of electrons stops when the electric field is sufficiently established to oppose the diffusion. This situation is shown in the following figure.

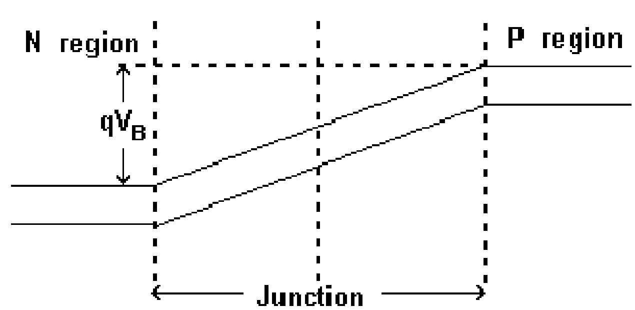


Two points are noteworthy.

(1) Electrons are no longer the majority charge carriers in the small region of the N-type material near the junction and the holes are not the majority charge carriers in the small region of the P-type semiconductor near the junction. These regions are known as depletion region as they are depleted of their majority charge carriers. The width of the depletion region is approximately 0.5 μm.

(2) The varying electric potential at the region near the junction is called the depletion barrier. Its value is about 0.7 V for Si and 0.3 V for Ge.

It can be seen from the band diagram of the P-N junction shown that the charge carriers need about qV_B energy to cross the junction and go into the other region of the diode.



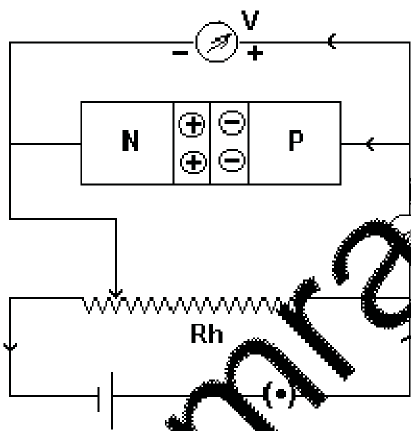
Less the amount of impurity atom added to the P and N type semiconductors, wider is the depletion region and weaker the electric field intensity near the junction.

The depletion region contains immobile positive and negative charges which constitute a capacitor having depletion capacitance or transition capacitance, C_d. The width of the depletion region increases with the increase in the reverse bias which decreases the value of the capacitance (since $C \propto 1/d$). Such diode in which value of the capacitance varies with voltage is known as varactor diode or variable diode.

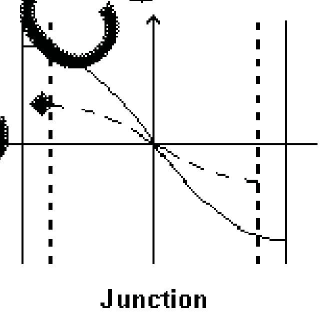
P-N Static Characteristics of P-N Junction Diode

The following figures show the circuit diagrams to study the I-V curves of the P-N junction diodes in the forward and reverse bias conditions and the corresponding characteristic curves.

Voltage across the diode can be varied with the rheostat. The milliammeter or the microammeter measures the current.



(a) Forward bias

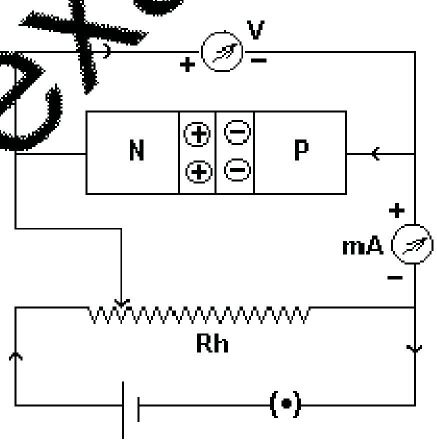


(b) the depletion region width in a forward bias situation and the reduction in the depletion region (indicated by broken lines)

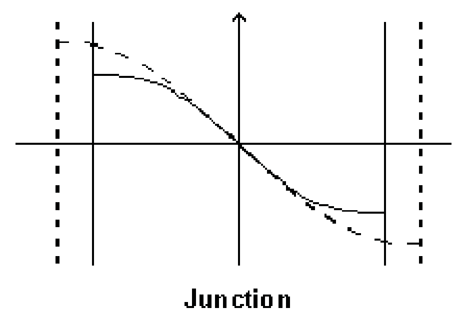
Forward Bias:

In forward bias circuit, the positive pole of the battery is connected to the P end of the diode and negative pole to the N end.

Here, emf of the battery and the p.d. across the depletion region oppose each other which reduces the depletion barrier p.d. and decrease in its width. The electrons flow from N-type to P-type in the diode and from positive pole to negative pole in the battery. The conventional current is in the reverse direction as shown in the figure.



(b) Reverse bias



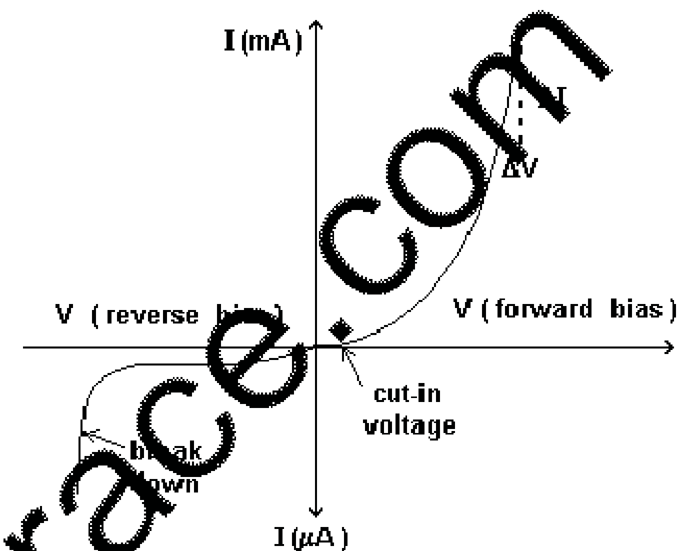
(b) the depletion region width in a reverse bias in a situation and its increase (indicated) by broken lines

The current increases with the increase in the applied voltage as shown in the graph on the next page. Initial increase in current is very less, but beyond a voltage known as 'cut in voltage', current increases rapidly (according to the fourth power). Here, current does not vary linearly as per Ohm's law and hence resistance of the junction is not given by it. The resistance of the junction is found as follows.

The dynamic resistance (r_{fb}) (*fb* = forward bias) of the diode at any point is given by

$r_{fb} = \dfrac{\Delta V}{\Delta I}$ where, ΔV and ΔI are the small changes in the voltage and current at the point. The value of r_{fb} is different at different points.

Reverse bias:

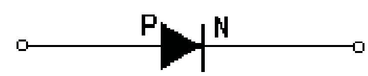


In reverse bias circuit, the positive pole of the battery is connected to the N end of the diode and negative pole to the P end as shown in the figure on the previous page. Here, emf of the battery and the p.d. across the depletion region are in series and assist each other. The electrons find it difficult to move from N to P type and holes from P to N type. The adjoining figure shows the I-V graph for the reverse bias condition. The current is negligible (of the order of μA) for smaller values of the voltage due to minority charge carriers.

The electric current is constant and is known as reverse saturation current. There is a sudden rise in the current on increasing the voltage beyond a certain point known as breakdown voltage. Normally, P-N junction diode is never used beyond the reverse saturation current in the reverse bias mode.

In the reverse bias mode, the value of the dynamic resistance (r_{rb}) is of the order of □$10^{6}\ \Omega$.

The symbolic representation of the P-N junction diode is shown in the adjoining figure. The arrow points in the direction of the conventional current. P is the anode and N, the cathode. As there are two electrodes, it is known as P-N junction diode.



15.6 P-N Junction Diode Rectifier

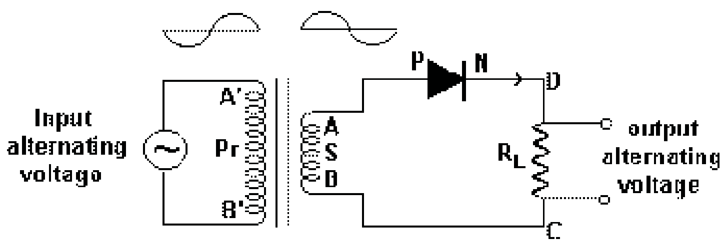
Rectification is the process of converting alternating voltage (or current) into direct voltage (or current). P-N junction diode can be used for this purpose. The conventional current flows from P to N in the forward bias mode, but the current is almost zero in the reverse bias mode. Thus, when alternating voltage is applied to the diode, current will flow in the circuit only in that half cycle for which the P-N junction is forward biased. In the next half cycle, there will be no current when the diode becomes reverse biased. When a resistor is in the circuit, then direct voltage varying with time will be obtained.

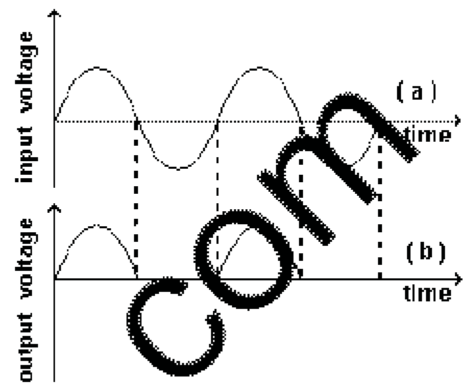
Half wave rectifier:

The circuit diagram for half wave rectification using P-N junction diode and the graphs for input and output voltages are shown on the next page.

The primary of the transformer (Pr) is connected to the alternating voltage source. One end of the secondary is connected to the P end (A) of the diode while the other end is connected to the N end (B) through the resistor R_L.

The alternating voltage wave figures are shown above the A'B' and AB ends of the transformer at any instant.

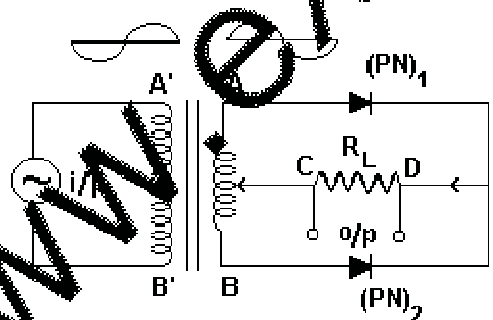


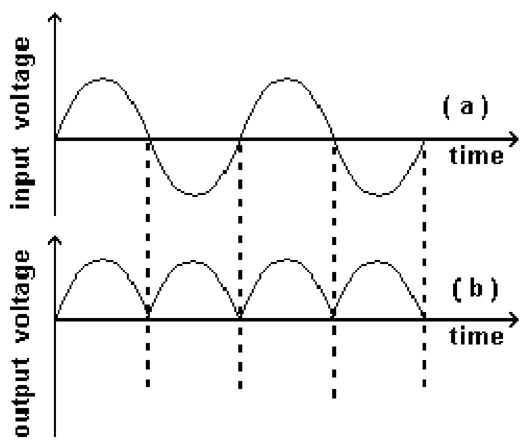


During the first half cycle, the A end of the secondary coil is positive with respect to B end making the P-N junction diode forward biased and the current flows from D to C through the resistor as shown in the figure. During the next half cycle, the A end becomes negative and the B end becomes positive making the P-N junction diode reverse biased and no current flows through the circuit and the resistor. The process is repeated in the subsequent half cycles. Thus direct varying current flows through the resistor and hence direct varying voltage develops across it during alternate half cycles and no current flows during the remaining alternate half cycles. The input and output voltages are as shown in the graph.

Full wave rectifier:

To obtain direct current and voltage during both the half cycles, two P-N junction diodes are used in the full wave rectifier circuit shown in the following figure. A centre tapped transformer is used in this circuit.





During the first half cycle, the A end of the secondary coil is positive with respect to central terminal (CT) and the central terminal is positive with respect to the B end which make $(PN)_1$ junction diode forward biased and the $(PN)_2$ junction diode reverse biased. During the second half cycle, the A end becomes negative with respect to CT and the CT becomes negative with respect to the B end which makes the $(PN)_1$ junction diode reverse biased and the $(PN)_2$ junction diode forward biased. Hence the conventional current flows in the resistor R_L in the same direction, i.e., from D to C during both the half cycles. Hence, direct varying current flows through the resistor in the same direction and hence direct varying voltage develops across it during both the half cycles. Such a voltage is the superposition of direct and alternating voltage of different frequencies from which the alternating component can be removed using suitable filter circuits.

15.7 Certain specific types of PN junction diodes

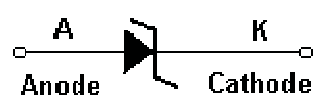
15.7 (a) Zener diode:

Very little current of the order of µA flows when the diode is reverse biased due to minority charge carriers. On increasing the reverse bias, at one particular voltage known as breakdown voltage, the current starts to increase suddenly and becomes of the order of milliampere if the concentration of impurity atoms is more. Two effects are responsible for this:
(1) Zener effect and (2) Avalanche effect.

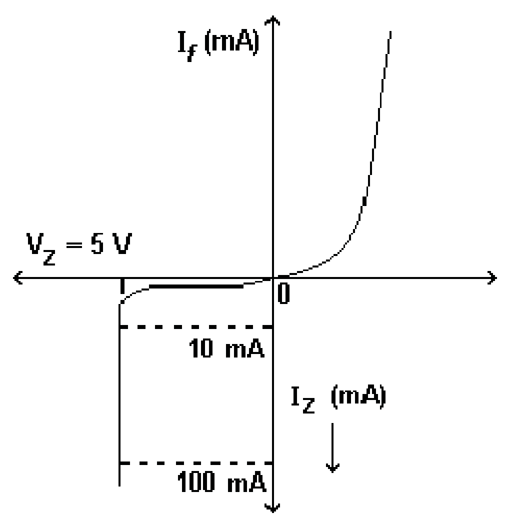
The width of the depletion region is very less at high impurity concentration resulting in high electric field intensity at the depletion region sufficient to break the covalent bonds and free the electrons. A large number of covalent bonds break resulting in the formation of a large number of electron-hole pairs and sudden increase in the reverse current (I_R). This explanation was given by the scientist, C. E. Zener. Hence it is known as Zener effect and such diodes are known as zener diodes.

The breakdown voltage is high if the impurity concentration is low. At high breakdown voltage, the electric field intensity is high. The charge carriers like electrons crossing the depletion region get accelerated due to high electric field and break many covalent bonds creating electron-hole pairs. Newly created electrons also get accelerated and break further covalent bonds and create more electron-hole pairs. This increases the electron current and the diode reaches the breakdown point. Such breakdown is called Avalanche effect and such diodes are known as Avalanche diodes.

Breakdown is due to Zener effect if the breakdown voltage is less than 4 V and Avalanche effect if it is more than 6 V. Between 4 V and 6 V, the breakdown is due to both the effects. All such diodes are called Zener diodes. The Zener diode is symbolically represented as shown in the adjoining figure in which cathode is in the form of Z.



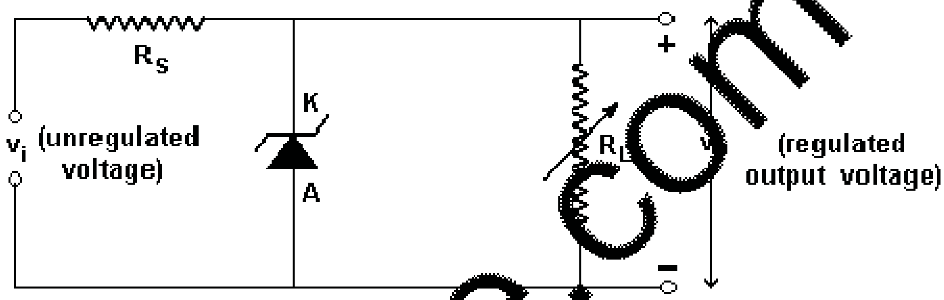
The adjoining graph gives the characteristic of the zener diode. The forward bias characteristic is similar to that of the PN junction diode. For low reverse bias voltage, the current is very small of the order of µA. Near the breakdown voltage (V_Z), current suddenly increases to the order of mA which is called zener current (I_Z).



The breakdown in this case is very sharp, i.e., a small change in voltage near the breakdown voltage, produces a large change in the current. Thus the voltage across the zener diode remains constant for large changes in the current. Such a diode can be used as a voltage regulator circuit.

Such a circuit is shown in the figure on the next page. The direct voltage output of the rectifier circuits changes with the change in the load current I_Z. Such a power supply is known as the unregulated power supply. If the output voltage remains constant with the change in the load current I_Z, then such a power supply is known as regulated power supply.

As shown in the circuit, the zener diode is connected in a reverse bias mode. A resistance R_S is connected in series with the zener diode and a load resistance R_L is connected in parallel with the zener diode. Hence zener voltage V_Z across the zener diode remains constant.

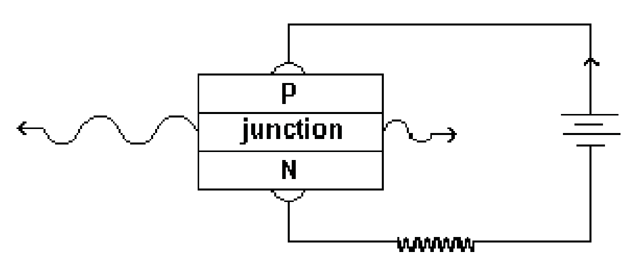


Let the unregulated voltage, v_i, of the above circuit be more than the break-down voltage, V_Z, of the zener diode. In this case, when the input direct voltage, v_i, increases then the current in the zener branch also increases. This increases the voltage drop across the resistor, R_s, which will be equal to the increase in the input voltage since the voltage across the zener diode, V_Z, is constant. The decrease in the input voltage produces an opposite effect. The voltage across R_S is reduced which will be equal to the decrease in the input voltage. The voltage across the zener remains constant. Thus the voltage across the load resistance, R_L, is constant. Hence we can regulate the voltage by using zener diode.

15.7 (b) LED (Light emitting diode):

Whenever electron in a Germanium or Silicon atom makes a transition from the conduction band to the valence band, then the excess energy of the electron is dissipated in the form of heat. In some semiconductors like Gallium Arsenide, the energy is obtained in the form of light. The maximum wavelength of the electromagnetic waves have a wavelength $\lambda = \frac{hc}{E_g}$, where E_g is the band gap energy.

To achieve this, the number of electrons in the conduction band and the number of holes in the valence band have to be large. For this, P-N junction is formed with large concentration of impurities.



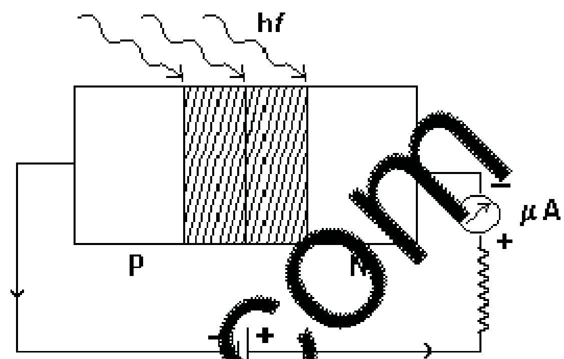
The PN junction diode is kept in a large forward bias condition which results in high current due to large concentration of impurities. As the width of the depletion barrier is extremely small, of the order of μm, electrons easily cross the junction and recombine with the holes.

To obtain visible light, Arsenic and Phosphorous impurities are added in Gallium semiconductor.

15.7 (c) Photo diode:

There is a window in a photo diode through which the light enters and is incident on the diode. The photo diode is always connected in a reverse bias mode.

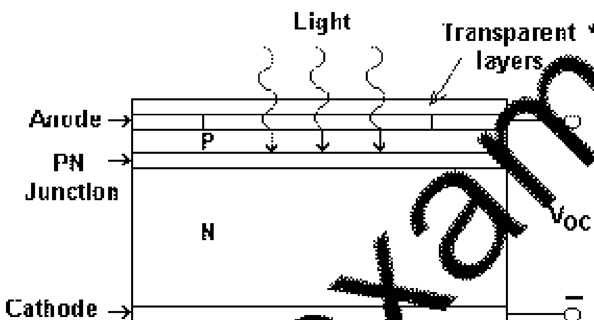
Reverse saturation current flows through the PN junction diode which can be increased either by increasing the temperature of the diode or making more light incident over it. When the energy of the light incident on the junction $\frac{hc}{\lambda} > E_g$, large number of covalent bonds are broken near the junction which produces a large number of electron-hole pairs. Thus increase in the minority charge carriers increase the reverse current which is of the order of μA.

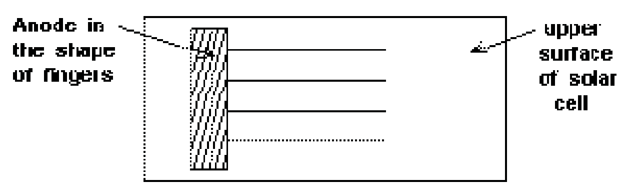


The reverse current flowing through the diode in the absence of the incident light is known as dark current. The electron-hole pairs increase on increasing the intensity of light. This results in proportionate increase in current.

15.7 (d) Solar Cell:

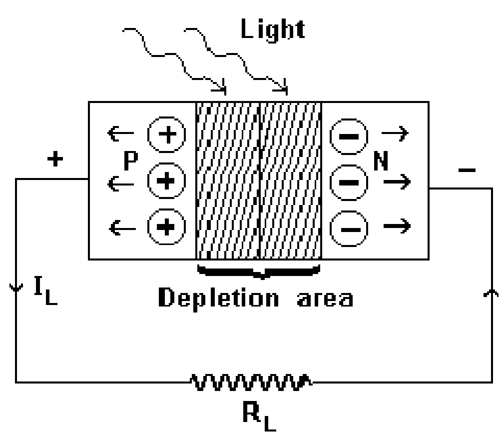
Solar cell is a semiconductor device which converts light energy into electrical energy. It works like a photo diode, but there is no external battery in it.





The above figure shows the construction of a solar cell. PN junction is made up of thin layers of N and P type semiconductors. The metal part connected to the N-section is the cathode and the metal connection taken from the P-section is the anode. P type semiconductor is the emitter and N type is the base. The incident light is directly incident on the PN junction as the P-type material is made up of a very thin layer.

The active region of the PN junction is kept very large to obtain large amount of power. Electron-hole pair is produced when the incident photon energy $h\nu > E_g$. The electrons move towards the N-type material and the holes to the P-type material. emf produced is of the order of 0.5 V to 0.6 V. The photo current, I_L, flows through the external circuit when it is connected with a resistor R_L. The value of the current depends on the intensity of light.



Si, GaAs, Cadmium Sulphide (CdS), Cadmium Selenide are some of the semiconductors used in the solar cell. The arrangement of solar cells connected in series or parallel is called a solar panel. Such panels are used in satellites as a storage battery which are charged during day time and used during the night time. They are used in calculators, electronic watch and camera.

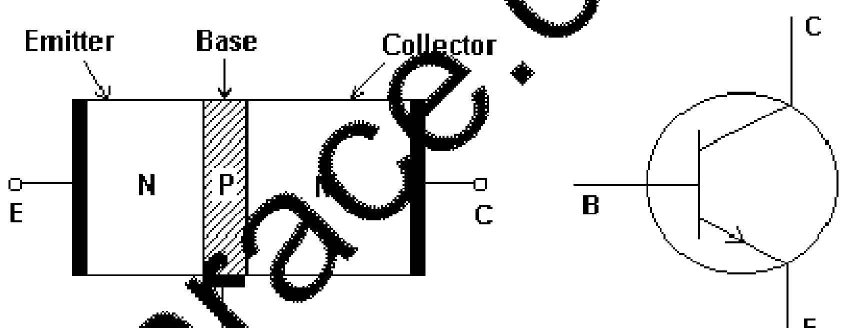
15.8 Transistor

John Bardeen, Walter Braten and William Schotky invented transistor in the Bell laboratory and were awarded Nobel prize. Transistor is a device made up of two PN junction diodes. There are two types of transistors.

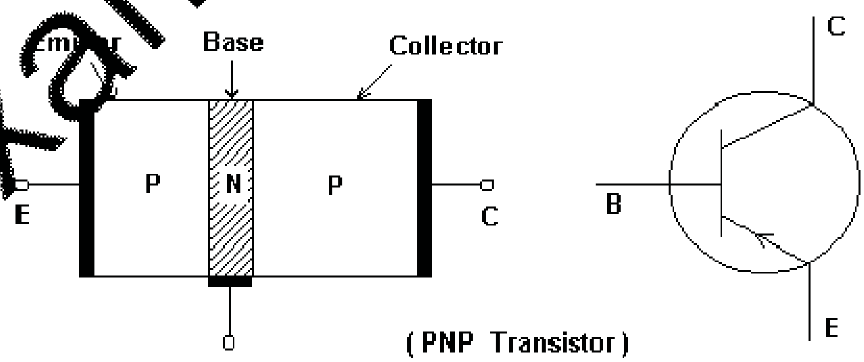
(i) PNP transistor: It is made by sandwiching a thin N-type semiconductor between two P-type semiconductors.

(ii) NPN transistor: It is made by sandwiching a thin P-type semiconductor between two N-type semiconductors.

The figures show the construction and symbols of NPN and PNP transistors.



(NPN Transistor)



(PNP Transistor)

The central chip is the base, on one side of which is the emitter and on the other side is the collector.

The collector has more volume than the emitter. The impurity concentration in base is more than that of the collector but less than that of the emitter. The resistivity of the base is high and that of the emitter is low.

The emitter base junction of the transistor is always forward biased, while the collector base junction is always reverse biased in all types of transistor circuits. The arrows in the symbols of the NPN and PNP transistors indicate the direction of the current.

The current in the transistor is due to both the electrons and the holes. Hence it is called bipolar junction transistor or BJT.

15.8 (a) The Working of a Transistor:

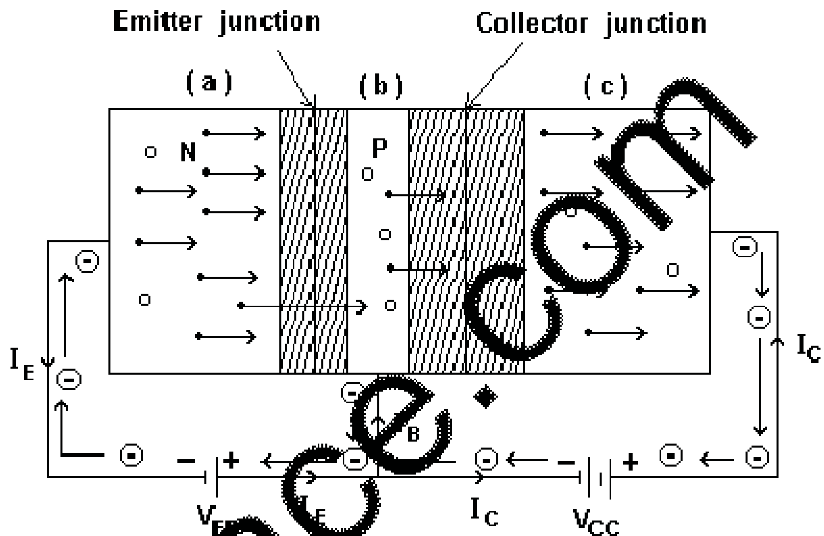
NPN transistors are the most widely used. Its circuit diagram is shown on the next page. The emitter junction is forward biased using the battery V_{EE} of voltage 0.5 V to 1.0 V and the collector junction is reverse biased using the battery V_{CC} having voltage 5 V to 10 V. The emitter junction width is less as it is forward biased and the collector junction width is more as it is reverse biased. The electrons move easily into the base as the emitter junction is forward biased and constitute emitter current I_E. As the base has less width and less impurity concentration, only 5 % of the electrons entering the base recombine with the holes while the rest go to the collector due to the battery V_{CC} constituting collector current I_C.

The electrons recombining with the holes in the base are attracted by battery V_{EE} constituting base current I_B.

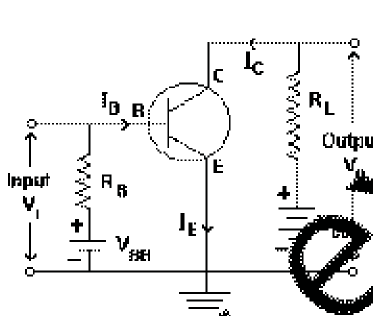
Applying Kirchhoff's law at the junction point,

$I_E = I_B + I_C$

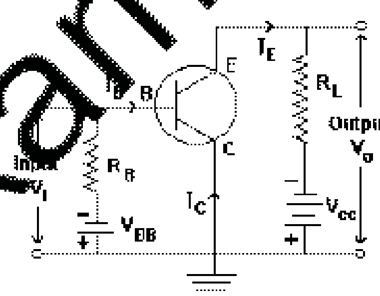
The working of the PNP transistor can be explained in a similar way.



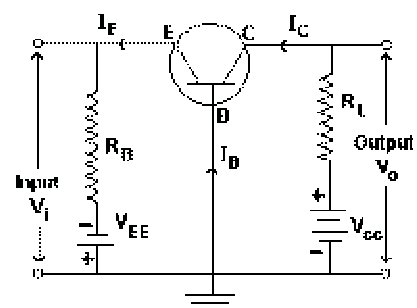
There are three types of transistor circuits:
(1) Common - Base circuit, (2) Common – Emitter circuit, (3) Common – Collector circuit.
All these three circuits for NPN transistor are shown in the following figures.



Common Emitter (CE) circuit



Common Collector (CC) circuit



Common Base (CB) circuit

In a CB circuit, I_C is the output current and I_E is the input current.

□ current gain, $\alpha_{dc} = \frac{I_C}{I_E} < 1$ ($\because$ $I_C < I_E$)

For a CE circuit, I_C is the output current and I_B is the input current.

□ current gain, $\beta_{dc} = \frac{I_C}{I_B} >> 1$ ($\because$ $I_C >> I_B$)

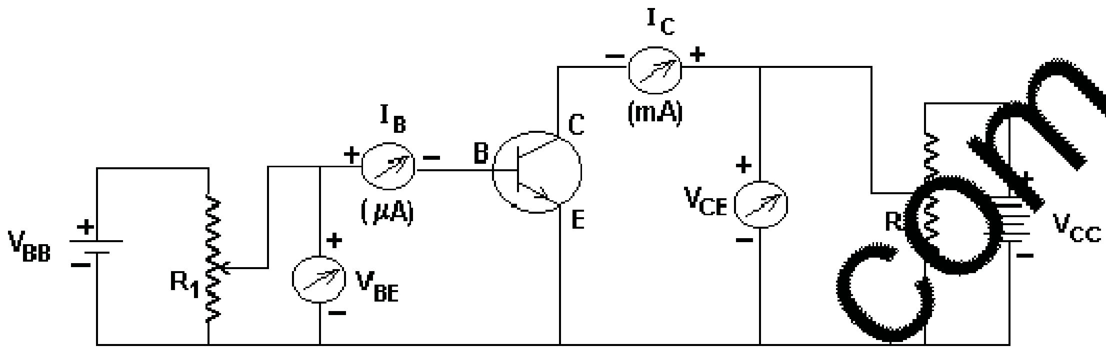
15.8 (b) Characteristics of a Transistor:

(1) Static characteristic curve - the curve showing relationship between voltage and corresponding current for a transistor

(2) Input characteristic curve - the curve showing relationship between the input voltage and the input current for given output voltage

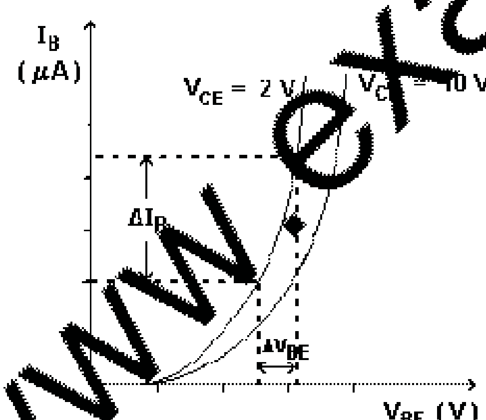
(3) Output characteristic curve - the curve showing relationship between the output voltage and the output current for given input current

The following figure shows the circuit to study the static characteristics of a CE transistor circuit.

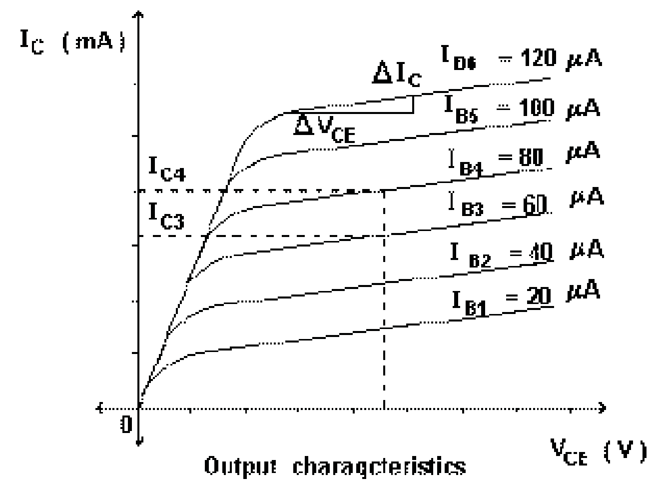


The emitter junction is forward biased due to battery V_{BB} and the collector junction is reverse biased with the help of battery V_{CC}. Rheostat R_1 is used to vary the base voltage V_{BE} and rheostat R_2 is used to vary the collector voltage V_{CE}.

To study input characteristics, the collector voltage V_{CE} is set to any one value and base current I_B is noted for different values of the voltage V_{BE} set with the help of rheostat R_1. The plot of input characteristic curves I_B vs. V_{BE} for two values of V_{CE} (2 V and 10 V) are shown on the left side of the following figures. Such a characteristic curve is similar to the one for a PN junction diode.



Input characteristics



Output charaqcteristics

To study output characteristics, the base current I_B is set to any one value and collector current I_C is noted for different values of the voltage V_{CE}. The plot of output characteristic curves I_C vs. V_{CE} for six values of I_B (varying from 20 μA to 120 μA) are shown on the right side of the above figures. The central portion of the curve is known as the active region in which the collector current is independent of the value of V_{CE} and is almost constant. The transistor when used as an amplifier is used in this region.

The transistor parameters can be found from the characteristic curve as under:

(1) Input resistance:

Input resistance, $r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE} = \text{constant}}$ can be found from the input characteristic curve and its value is of the order of k Ω.

(2) Output resistance:

Output resistance, $r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B = \text{constant}}$ can be found from the output characteristic curve and its value is normally between 50 to 100 kΩ.

(3) Current gain:

Current gain, $\beta = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE} = \text{constant}}$ can be found from the active region of the output characteristic curve. Normally, its value is between [illegible] and 100.

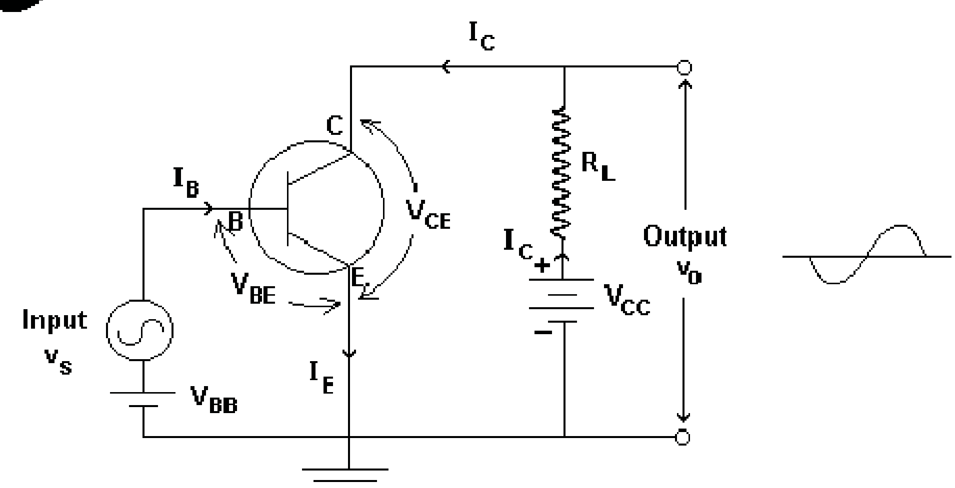
(4) Transconductance:

Transconductance, $g_m = \frac{\Delta I_C}{\Delta V_{BE}} = \frac{\beta}{r_i}$. The unit of transconductance is mho.

15.8 (c) Transistor as an amplifier:

The circuit diagram of the most widely used NPN CE transistor amplifier is shown in the following figure.

The emitter junction is forward biased by battery V_{BB} and the collector junction is reverse biased using battery V_{CC}. The A.C. signal is applied across base-emitter junction of the transistor. The amplified signal is obtained between the collector and emitter terminals or in other words across R_L.



The alternating signal (V_s) causes the change, ΔV_{BE}, in the base emitter voltage. This results in the change, ΔI_B, in the base current which is of the order of microampere and the change, $\beta \, \Delta I_B$, which is of the order of milliampere. The large amplified output voltage is obtained across large value of R_L connected in the output circuit. The ratio of output voltage to input voltage is known as voltage gain.

The working of the circuit

(1) Input circuit:

In the absence of the input voltage, V_s, to be amplified, as per Kirchhoff's second law,

$V_{BB} = V_{BE}$ ... ... (1)

On applying the signal voltage, V_s, the change in the base emitter voltage is ΔV_{BE}.

□ $V_{BB} + V_s = V_{BE} + \Delta V_{BE}$ ... ... (2)

□ $\Delta V_{BE} = V_s$ [from equations (1) and (2)] $= r_i \Delta I_B$ ... ... (3)

(2) Output circuit:

Applying Kirchhoff's second law to the collector emitter loop,

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

□ $\Delta V_{CC} = R_L \cdot \Delta I_C + \Delta V_{CE}$

But $\Delta V_{CC} = 0$ as the battery voltage remains constant.

□ $0 = R_L \cdot \Delta I_C + \Delta V_{CE}$

□ $\Delta V_{CE} = - R_L \cdot \Delta I_C = V_o$ ... ... (4)

ΔV_{CE} is the output across two ends of the load resistor and is the output voltage V_o.

Voltage gain (A_V)

Voltage gain, $A_V = \dfrac{\text{output voltage}}{\text{input voltage}} = \dfrac{V_o}{V_s}$

$= - \dfrac{R_L \cdot \Delta I_C}{r_i \cdot \Delta I_B}$ [substituting from equations (4) and (3)]

$= - \beta \dfrac{R_L}{r_i}$

where, $\beta = A_i = \dfrac{\Delta I_C}{\Delta I_B}$ and is known as the current gain of the transistor. $\dfrac{\beta}{r_i}$ is known as the transconductance of the transistor (g_m).

□ $A_V = - g_m \cdot R_L$

(Negative sign indicates a phase difference of 180° between input and output voltage.)

Power gain (A_P):

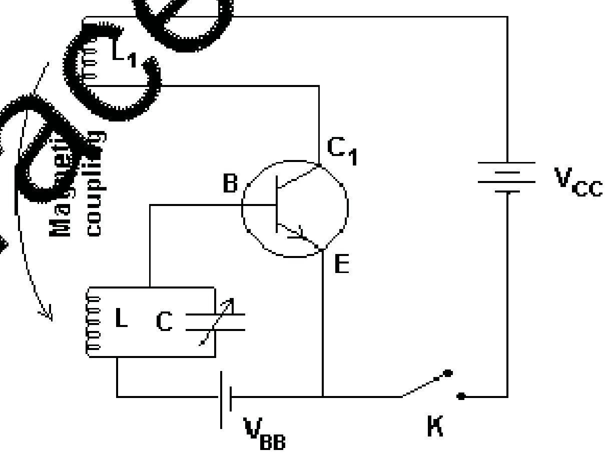
Power gain, $A_P = \dfrac{\text{Output A. C. Power}}{\text{Input A. C. Power}} = A_V \times A_i = \left(-\beta \dfrac{R_L}{r_i}\right)(\beta)$

□ $|A_P| = \beta^2 \cdot \dfrac{R_L}{r_i}$ (The energy for power gain is supplied by the battery V_{CC} .)

15.8 (d) Transistor Oscillator:

The electrical oscillations in an L-C circuit get damped with the passage of time. Necessary energy has to be supplied to the circuit to sustain them. This can be done in a circuit shown in the figure which is known as an oscillator.

Here L-C network is connected in the emitter base circuit and inductor L_1 in the collector emitter circuit. The EB junction is kept forward biased with the battery V_{BB} and C_1B junction reverse biased with the battery V_{CC}.



Working:

When the key K is closed, the collector current starts increasing through the coil L_1 increasing the magnetic flux linked with it. This increases magnetic flux linked with the coil L. The emf induced charges the capacitor which helps in the forward bias of the transistor. This increases the emitter current which also results in the increase of the collector current. In turn, the flux linked with the coils L_1 and L also increase. The emf induced in the coil L further increases the forward bias and hence the emitter and collector current. This continues till the collector current reaches saturation.

Now the flux linked with the coil L_1 and L stop changing. This results in no further induced emf in the LC circuit, discharge of capacitor through L and reduction in the forward bias voltage. This reduces the emitter and collector current and the process continues till the collector current becomes zero. The capacitor is now completely discharged and there is no opposition to the forward bias. The emitter current starts to increase again thereby increasing the collector current and the process keeps on repeating. Thus the collector current oscillates between the maximum and the zero value.

The frequency of oscillations, $f = \dfrac{1}{2\pi\sqrt{LC}}$

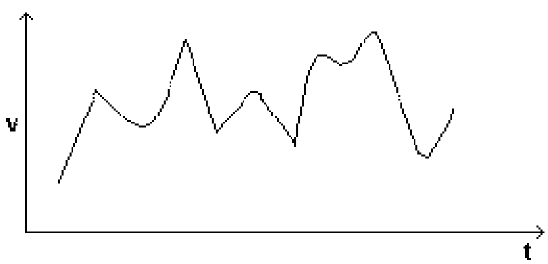
The necessary energy comes from the collector battery, V_{CC} . Thus D. C. electrical energy is converted into A. C. electrical energy.

Oscillators are used to generate high frequency carrier signals for Radio and TV signal communications and in electronic apparatus like A.F.O. and function generator in the laboratory. In such apparatus, oscillators are used to generate signals of very low frequency to very high frequency of the order of 10^9 Hz.

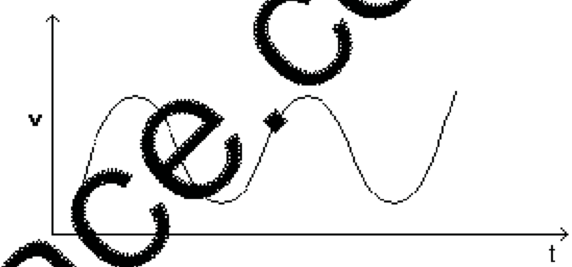
15.9 Digital Electronics and Logic Circuits

George Boole, a mathematician, developed Boolean algebra based on the science of logic. In 1938, a scientist called Shenon developed electrical circuits based on the Boolean algebra which are known as logic circuits.

In amplifier or oscillator circuits, the current or the voltage continuously changes with time from minimum to maximum. Such a signal is called analog signal. Two different types of analog signals are shown in the following figure.



(Analog signal)



(Analog signal)

In the following figure, the voltage or the current has only two values, the maximum value indicated by '1' and the minimum by '0'. Such a signal is known as a digital signal.

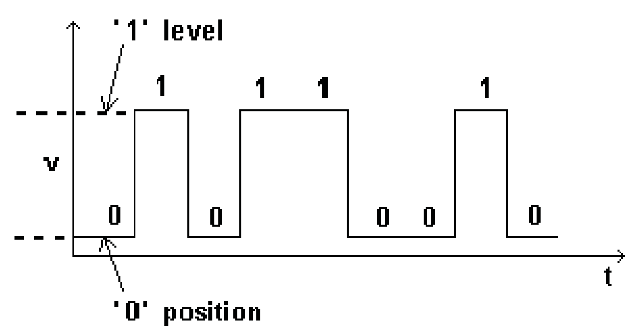
There are two types of systems adopted for a logic circuit.

(1) Positive Logic System:

In this type of system, the higher positive voltage is taken as high level or '1' and the lower positive voltage is taken as low level or '0'.

(2) Negative Logic System:

In this type of system, the more negative voltage is taken as '1' and the less negative voltage is taken as '0'.



(Digital signal)

Positive logic system is used in the subsequent discussions. It means +5 V will be taken as '1' state and 0 V as '0' state.

Some of the terms used in digital electronics are explained below.

Logic Gate: The logic circuit in which there is one or more than one input but only one output is called a logic gate. OR gate, AND gate and NOT gate are the basic logic gates. The other gates like the NAND and NOR gates can be obtained from these basic gates.

Boolean Equation: The Boolean equation represents the special type of algebraic representation, which describes the working of the logic gates.

Truth Table: The table which indicates the output for different combinations of the input voltage is known as the truth table.

15.9 (a) OR gate:

The following figure shows the circuit containing the bulb and the two switches A and B connected in parallel to illustrate the working of an OR gate.

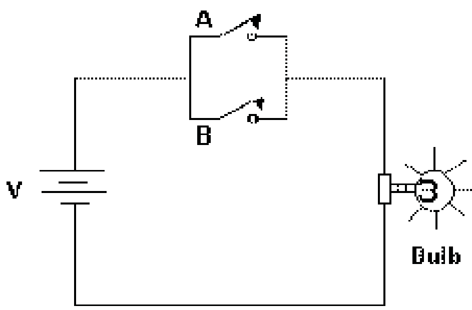


Table 1

A	B	Bulb
Open	Open	OFF
Open	Close	ON
Close	Open	ON
Close	Close	ON

Table 2

A	B	Y = A + B
0	0	0
0	1	1
1	0	1
1	1	1

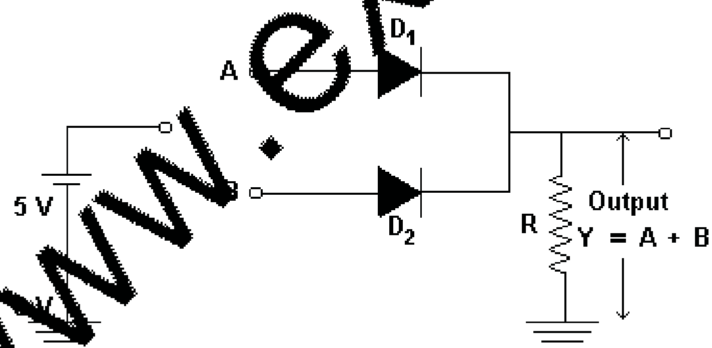
The status of the bulb with respect to the switch positions are shown in table 1.

In this table, if the switch A is taken as input A and the switch B is taken as input B and the status of the bulb is taken as output Y, we get the truth table 2 of an OR gate. In this table, the ON state is taken as '1' and the off state as '0'. The truth table 2 describes the characteristics of the OR gate.

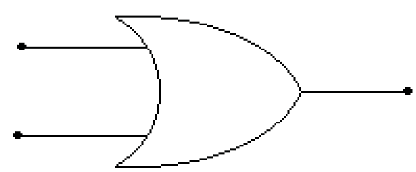
"Whenever any one or both inputs are '1', then we get the output '1'."

Boolean equation is given as : $Y = A + B$ is read as "Y is equal to A or B". Here '+' sign indicates OR operator.

A two input OR gate in electronics can be constructed using diodes and a resistor. OR gate circuit and its symbolic representation are shown in the following figures.



(OR gate circuit)



(Circuit symbol of OR gate)

For two inputs in the above circuit, there are four different combinations for the input ($2^2 = 4$). For three inputs, there would be $2^3 = 8$ combinations. Y is the output across the resistor R. The 0 volt and +5 V are indicated by he states '0' and '1' respectively.

(i) For A = 0 and B = 0, none of the diodes conduct and the output voltage is zero. (Y = 0)

(ii) For A = 0 and B = 1, diode D_1 does not conduct, but D_2 being in forward bias conducts. Treating resistance of the diode as negligible, output voltage $\approx$ input voltage. In this case, $Y \approx +5$ V. This output state is indicated as '1' state (Y = 1).

(iii) For A = 1 and B = 0, D_1 is forward biased and D_2 does not conduct and the output voltage Y ≈ +5 V. This output state is indicated as '1' state (Y = 1).

(iv) For A = 1 and B = 1, both the diodes are conducting and the output voltage Y ≈ +5 V. This output state is indicated as '1' state (Y = 1).

All the above resulted are shown in table 2.

15.9 (b) AND gate:

The following figure shows the circuit containing the bulb and the two switches A and B connected in series to illustrate the working of an AND gate.

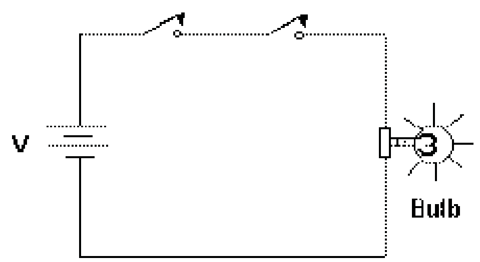


Table 3

A	B	Bulb
Open	Open	OFF
Open	Close	OFF
Close	Open	OFF
Close	Close	ON

Table 4

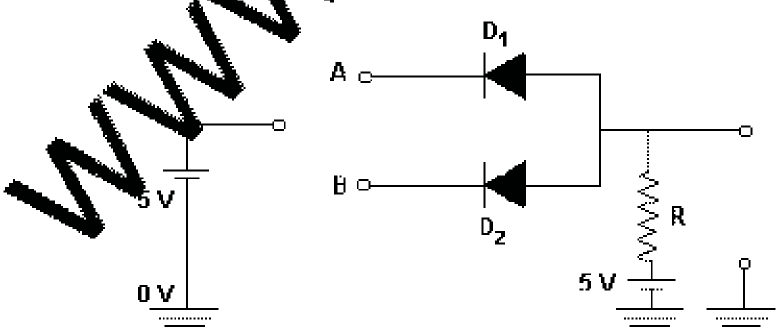
A	B	Y = A · B
0	0	0
0	1	0
1	0	0
1	1	1

Table 3 indicates the position of the switch and the corresponding state of the bulb. The truth table of the AND circuit is shown in table 4. The truth table 4 describes the characteristics of the OR gate as follows.

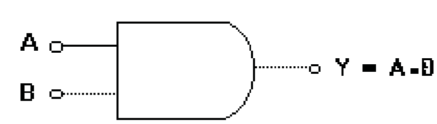
"The output of the AND gate is '1' only if all the inputs are equal to '1'. For all other conditions of the input it is equal to '0'."

Boolean equation is given as : Y = A [B is read as "Y is equal to A and B". Here '[' sign indicates AND operator.

A two input AND gate in electronics can be constructed using diodes and a resistor. AND gate circuit and its symbolic representation are shown in the following figures.



(AND gate circuit)



(Circuit symbol of AND gate)

The output states for different combinations of input states are discussed as under.

(i) For A = 0 and B = 0, both diodes are at 0 V (grounded). Their anodes are connected to +5 V through the resistor R. Thus both diodes are forward biased and current flows through the resistor R. Voltage drop across R is ≈ +5 V. Hence the output Y = 0.

(ii) For A = 1 and B = 0, D_1 is reverse biased and hence no current flows through R. D_2 is at zero voltage (grounded) and the anode has positive voltage. Hence current flows through R. Voltage drop across R is $\approx$ +5 V. Hence the output Y = 0.

(iii) For A = 0 and B = 1, D_2 is reverse biased and D_1 is forward biased. Hence current flows through D_1 and the resistor R. Voltage drop across R is $\approx$ +5 V. Hence the output Y = 0.

(iv) For A = 1 and B = 1, both the diodes are reverse biased and no current flows through them and the resistor. The output voltage is 5 V and Y = 0.

All the above resulted are shown in table 4.

15.9 (c) NOT gate:

Refer to the following figure for explanation of the operation of the NOT gate.

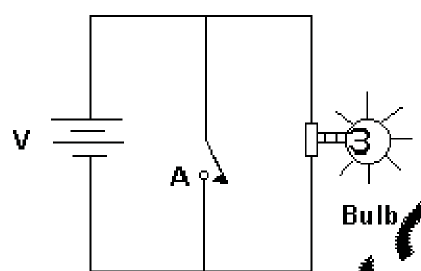


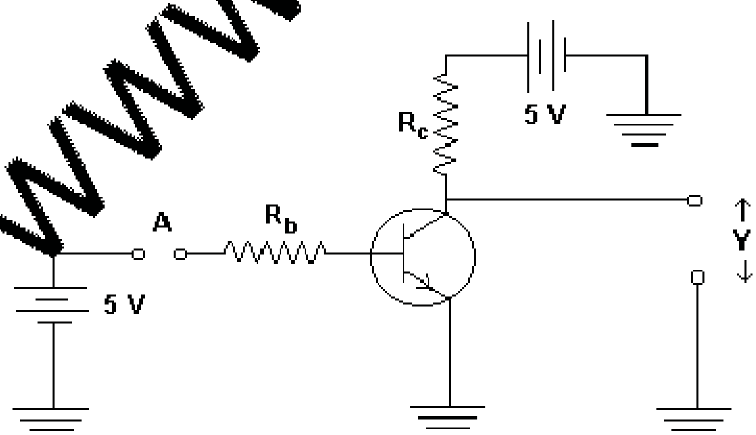
Table 5

A	Bulb
Open	ON
Close	OFF

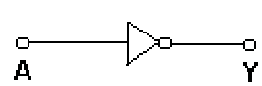
Table 6

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

NOT gate has only one input and output terminal. This gate inverts the input voltage. When the switch A is open, current flows through the bulb and it is on. When the switch A is closed, no current flows through the bulb and it is off. These results are summarized in table 5 and in the truth table 6 of the NOT gate. The following figure shows the construction of the NOT gate using the transistor which functions as an ON / OFF switch and the resistor. The output is taken across the collector emitter terminals.



(Circuit of NOT gate)



Symbol

(Circuit symbol of NOT gate)

As there is only one input, there are two possibilities of the input state discussed below.

(i) For A = 0, the base current and voltage are zero and hence voltage drop across R_C is zero. Voltage across collector and emitter, $V_{CE} \approx +5$ V, is maximum. Hence the output Y = 1.

(ii) For A = 1, the emitter junction is forward biased since + 5 V is applied at the base of transistor which results in collector current I_C due to base current I_B. Voltage across R_C is almost + 5 V resulting in voltage across collector and emitter, $V_{CE} \approx 0$. Hence the output Y = 0.

The truth table 6 describes the characteristics of the NOT gate as follows:

"Whenever input is '1' the output is '0' and when the input is '0' the output is '1'." Hence this gate is also called the inverter.

Boolean equation is given as : $Y = \overline{A}$ and is read as "Y is equal to NOT A". The NOT operator is indicated by the '−' (bar) symbol.

The AND, OR and NOT logic gates are called the basic logic gates in digital electronics. These gates can be combined in different ways to get newer gates. Two such logic gates are discussed below.

15.9 (d) NOR gate:

The NOR gate is constructed by combining the OR gate and the NOT gate (OR + NOT = NOR). Here the output of the OR gate is given as input to the NOT gate.

Boolean equation is given as: $Y = \overline{A + B}$ and is read as "Y is equal to NOT A or B."

The circuit diagram of the NOR gate, its symbol and the truth table 7 are given below.

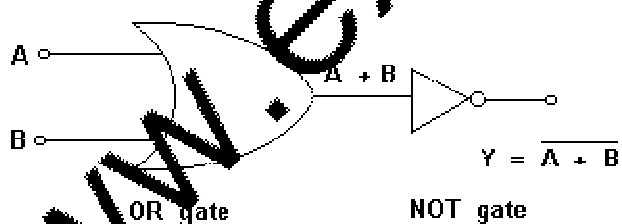
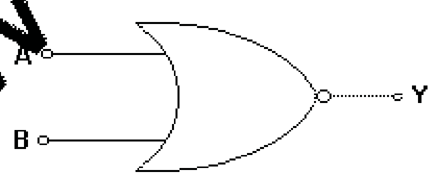


Table 7

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



Symbol of NOR gate

The characteristic of the NOR gate is given as follows:

"The output is '0' whenever any one input is '1'. Whenever all the inputs are '0', the output is equal to '1'."

15.9 (e) NAND gate:

NAND gate is constructed by combining the AND gate and the NOT gate (AND + NOT = NAND). Here the output of the AND gate is given as input to the NOT gate.

Boolean equation is given as: $Y = \overline{A \cdot B}$ and is read as "Y is equal to NOT A and B."

The circuit diagram of the NAND gate, its symbol and the truth table 8 are given below.

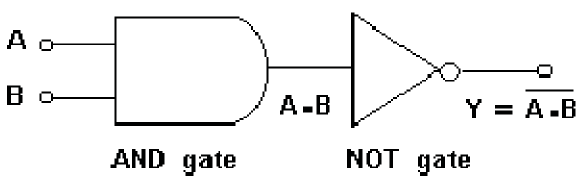
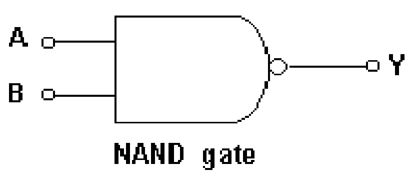


Table 8

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



The characteristic of the NAND gate is given as follows:

"The output is equal to '1' when any one input is equal is equal to '0' and the output is equal to '0' when all the inputs are equal to '1'."

15.10 Primary Concept of IC

About 50 years back, the electronic circuits were prepared from transistors, diodes and resistors by joining them using conducting wires. In the next generation, printed circuit board (PCB) came into existence. Here the electronic components are arranged on a board and connected with the help of metal strips which helped reduce the size of the electronic circuits. Later, these three dimensional circuits were made two dimensional to further reduce their size which gave rise to integrated circuits (I. C.) size of which is about 1 mm × 1 mm. In an I. C., a small sized crystal (or chip) is taken and transistors, diodes, resistors and capacitors are internally connected which reduced both the size as well as the cost of the electronic gadgets.

I. C. is basically of three types:

(1) Film Circuit: This I. C. consists of components like resistors and capacitors only.

(2) Monolithic Integrated Circuit: This I. C. has components like transistors, diodes, resistors and capacitors. It is made from only one type of semiconductor (Si or Ge) and hence called Monolithic I. C.

(3) Hybrid Integrated Circuit: This type of I. C. is a combination of film circuit and monolithic type and contains more than one chip.