Semiconductor and Digital Electronics

INTRODUCTION

The word "electronics' is derived from electron + dynamics which means the study of the behaviour of an electron under different conditions of externally applied fields.
This field of science deals with electronic devices and their utilization. An electronic device is a device in which conduction takes place by the movement of electron - through a vacuum, a gas or a semiconductor.
Some familiar devices are :
(i) Rectifier (ii) Amplifier (iii) Oscillator etc.

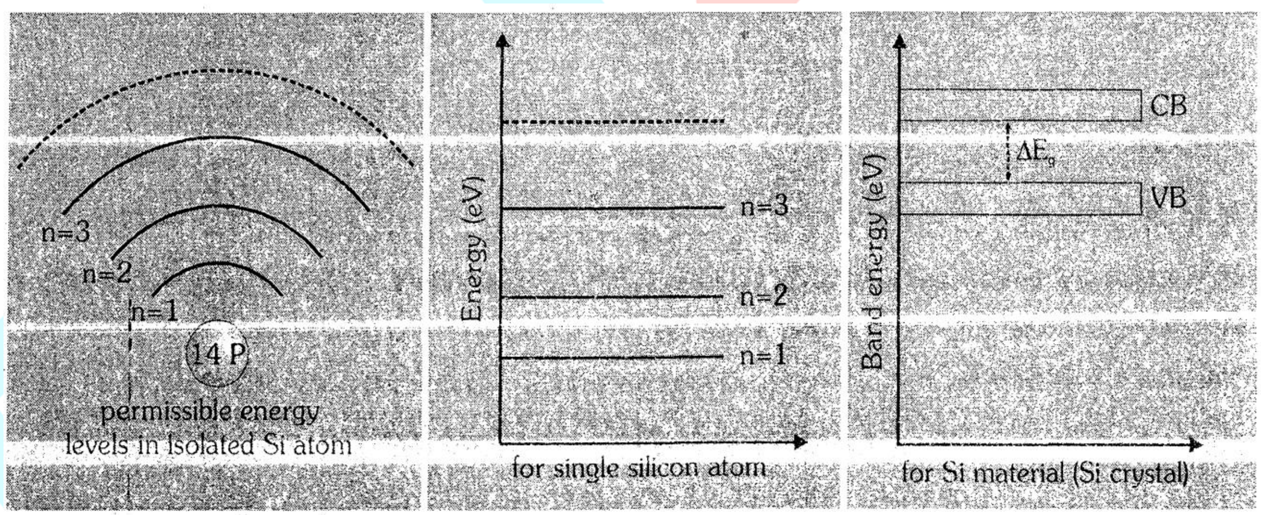
- **Application of Electronic**

Communication	Entertainment	Defence	Medical
Telephone Telegraph Mobile Phone FAX FM mic	TV Broadcast Radio Broadcast VCR, VCD	Radar Guided missiles	X-rays Electro cardio graph (ECG) CRO display E.E.G. (Electro Engio Graph)

- Main application of electronic is computer which is used in every field.
- All electronics equipments required D.C. supply for operation (not A.C. supply)

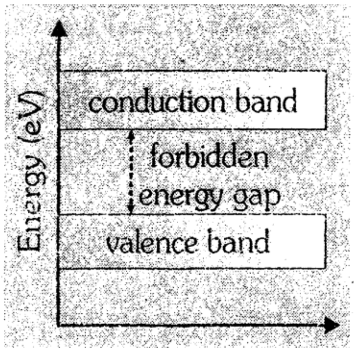
ENERGY BAND THEORY

Based on Pauli's exclusion principle



In an isolated atom, electrons are present in sharply defined energy levels. But in solids atoms are very close to each other. So because of their interactions, each electron doesn't have fixed energy. It has different energy levels in a certain (small) range called energy band.
The number of energy levels in a band depends upon the number of interacting atoms.
The energy band inch 1ding valence electrons is called valence band (VB) and the energy band including conducting (free) electrons is called conduction band (CB).

- **Band gap or Forbidden Energy gap (FEG) (ΔEg)**



$\Delta E_g = (CB)_{min} - (VB)_{max}$

(i) It is the energy gap between CB and VB.

(ii) It is also called forbidden energy gap because free electrons cannot exist in this gap.

(iii) Width of forbidden energy gap depends upon the nature of substance.

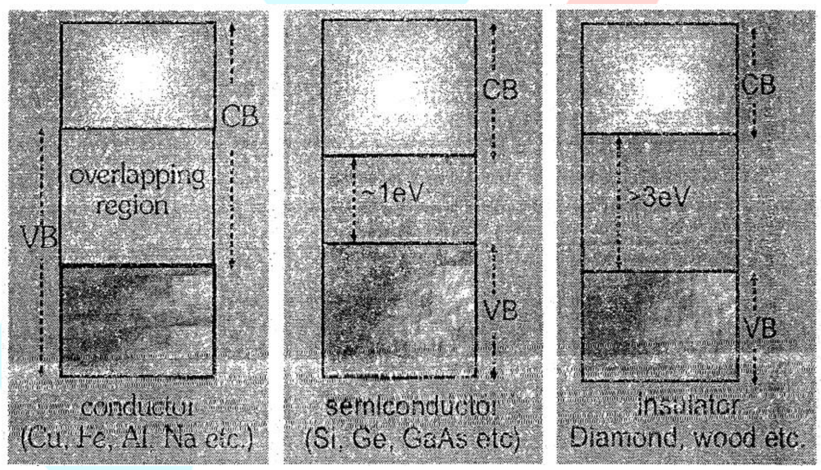
(iv) Width is more, then valence electrons are strongly attached with nucleus.

(v) Width of forbidden energy gap is represented in eV.

(vi) As temperature increases forbidden energy gap decreases (very slightly).

CLASSIFICATION OF SOLIDS ACCORDING TO ENERGY BAND THEROGY

According to energy band theory, solids are conductor, semiconductor and insulator:



- **Conductor**

In some solids conduction band and valence band are overlapped so there is no band gap between them, it means $\Delta E_g = 0$.

Due to this a large number of electrons are available for electrical conduction and therefore its resistivity is low ($\rho = 10^{-2} - 10^{-8}\ \Omega\text{–m}$) and conductivity is high [$\sigma = 10^2 - 10^8\ (\Omega\text{–m})^{-1}$]

Such materials are called conductors. For example gold, silver, copper, etc.

- **Insulator**

In some solids energy gap is large ($E_g > 3eV$).

So in conduction band there are no electrons and so no electrical conduction is possible. Here energy gap is so large that electrons cannot be easily excited from the valence band to conduction band to conduction band by any external energy (electrical, thermal or optical)

Such materials are called as "insulator". Their $\rho > 10^{11}\ \Omega$–m and $\sigma < 10^{-11}$ (Q–m)$^{-1}$

- **Semiconductor**

  In some solids a finite but small band gap exists ($E_g < 3$eV).

  Due to this small band gap some electrons can be thermally excited to "conduction band".

  These thermally excited electrons can move in conduction band and can conduct current. Their resistivity and conductivity both are in medium range, ρ ; $10^{-5} - 10^{6}\ \Omega$–m and σ ; $10^{-6} - 10^{5}\ \Omega$–m^{-1}

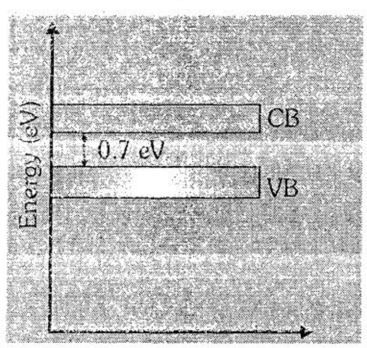
- **Example of semiconducting materials**

Elemental semiconductor :	Si and Ge	
Compound semiconductor	**Inorganic :**	CdS, GaAs, CdSe, InP etc.
	Organic :	Anthracene, Doped pthalocyanines etc.
	Organic Polymers :	Poly pyrrole, Poly aniline, polythiophene

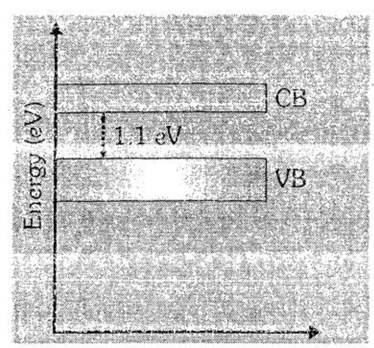
PROPERTIES OF SEMICONDUCTOR

- Negative temperature coefficient (a.), with increase in temperature resistance decreases.
- Crystalline structure with covalent bonding [Face centred cubic (FCC)].
- Conduction properties may change by adding small impurities
- Position in periodic table -t IV group (Generally}
- Forbidden energy gap (0.1 eV to 3 eV)
- Charge carriers : electron and hole.
- There are many semiconductors but few of them have practical application in electronics like

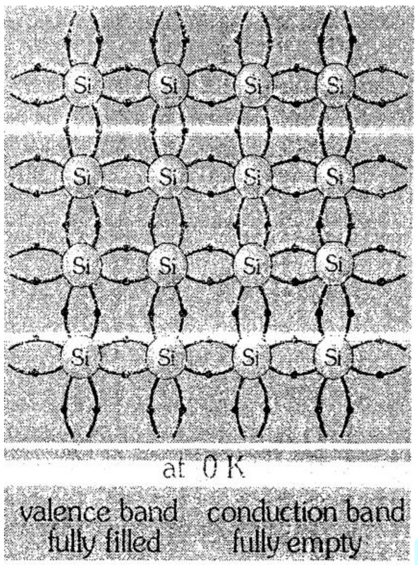
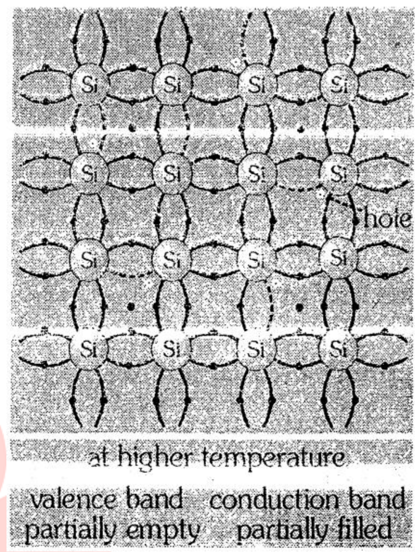
Ge^{32} : 2, 8, 18, 4



Si^{14} : 2, 8, 4



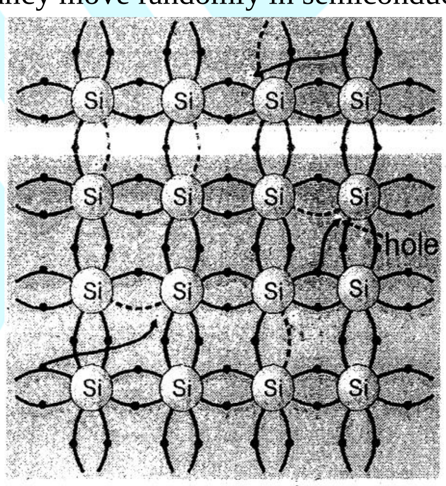
Effect of temperature

At absolute zero Kelvin temperature	Above absolute temperature
At this temperature covalent bonds are very strong and there are no free electrons and semiconductor behaves as perfect insulator. 	With increase in temperature some covalent bonds are broken and few valence electrons jump to conduction band and hence it behaves as poor conductor. 

CONCEPT OF "HOLES" IN SEMICONDUCTORS

Due to external energy (temperature or radiation) when electron goes from valence band to conduction band (i.e. bonded electrons becomes free), vacancy of free e^- creates in valence band. The electron vacancy called as "hole" which has same charge as electron but positive.

This positively charged vacancy move randomly in semiconductor solid.



Properties of holes

- It is missing electron in valence band.
- It acts as positive charge carrier.
- It's effective mass is more than electron.
- It's mobility is less than electron.

Holes acts as virtual charge, although there is not physical charge on it.

EFFECT OF IMPURITY IN SEMICONDUCTOR

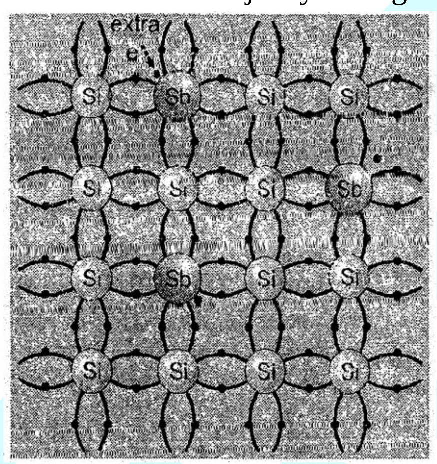
Doping is a method of addition of "desirable" impurity atoms to pure semiconductor to increase their conductivity.

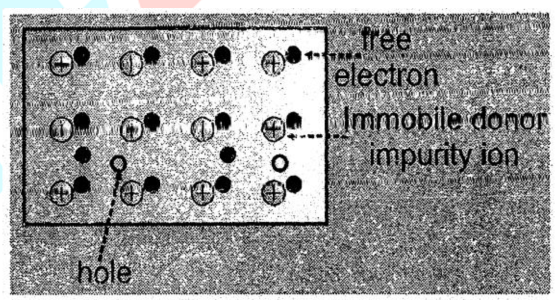
CLASSIFICATION OF SEMICONDUCTOR

Intrinsic semiconductor	Extrinsic semiconductor (Doped semiconductor)	
	N-type	P-type
(Pure form of Ge, Si) $n_e = n_h = n_i$	Pentavalent impurity (P, As, Sb) Donor impurity (N_D) $n_e >> n_h$	Trivalent impurity (B, In, Al) Acceptor impurity (N_A) $n_h >> n_e$

N-type semiconductor

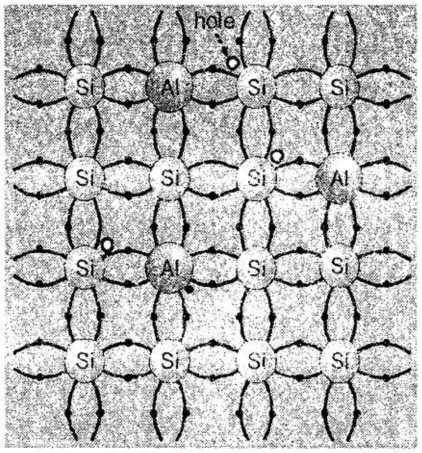
When a pure semiconductor (Si or Ge) is doped by pentavalent impurity (P, As, Sb) then four electrons out of the five valence electrons of impurity take part in covalent bonding, with four silicon atoms surrounding it and the fifth electron is set free. These impurity atoms which donate free e^- for conduction are called as Donors impurity (N_0). Here free e^- increases very much so it is called as "N" type semiconductor. Here impurity ions known as "Immobile Donor positive Ion". "Free e^-" called as "majority" charge carriers and "holes" called as "minority" charge carriers.

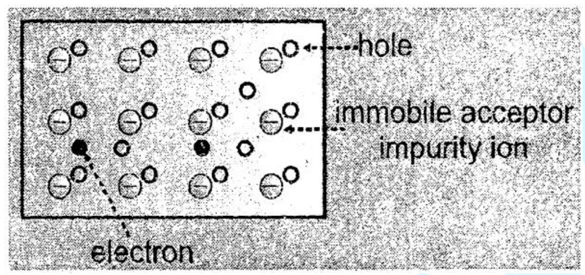


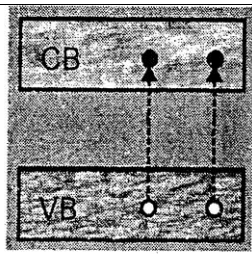
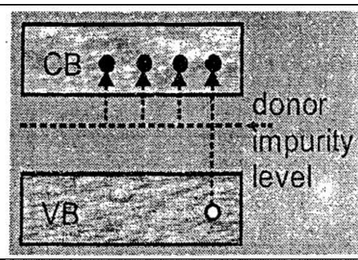
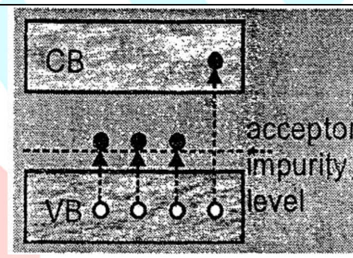
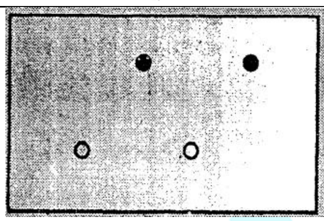
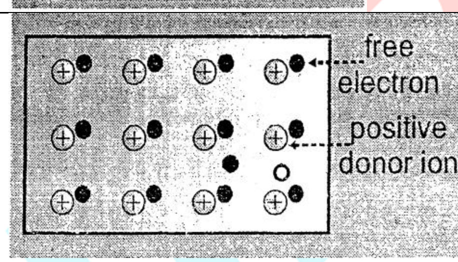
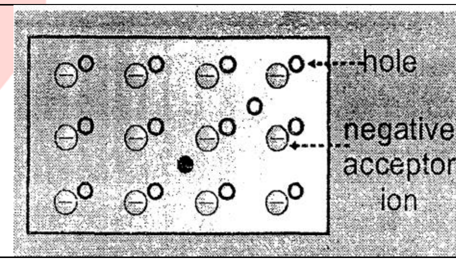


P-type semiconductor

When a pure semiconductor (Si or Ge) is doped by trivalent impurity (B, Al, In) then the outermost three electrons of the valence band of impurity, take part in covalent bonding with four silicon atoms surrounded by it. This shows that there remains a vacancy in the band. To fill this vacancy, an electron is accepted from the neighbouring atom leaving a hole from its own site. Thus an extra hole is formed. These impurity atoms accepting bonded e^- from valence band are called as Acceptor impurity (N_A). Here holes increases very much so it is called as "P" type semiconductor. Here impurity ions known as "Immobile Acceptor negative Ion", Free e^- are called as minority charge carries and holes are called as majority charge carriers.





	Intrinsic Semiconductor	N-type (Pentavalent impurity)	P-type (Trivalent impurity)
(1)			
(2)			
(3)	Current is due to both electrons and holes	Mainly due to electrons	Mainly due to holes
(4)	$n_e = n_h = n_i$	$n_e >> n_h$ (N_D ; n_e)	$n_e >> n_e$ (N_A ; n_h)
(5)	$I = I_e + I_h$	I ; I_e	I ; I_h
(6)	Entirely neutral	Entirely neutral	Entirely neutral
(7)	Quantity of electrons and holes are equal	Majority-Electrons Minority-Holes	Majority-Holes Minority-Electrons

MASS ACTION LAW

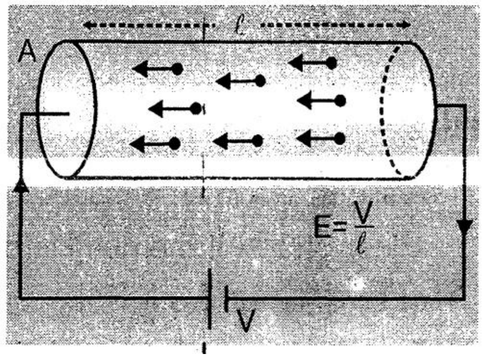
At room temperature, most of the acceptor atoms get ionised leaving holes in the valence band. Thus at room temperature the density of holes in the valence band is predominantly due to impurity in the extrinsic semiconductor. The electron and hole concentration in a semiconductor in thermal equilibrium is given by

$$n_e n_h = n_i^2$$

Though the above description is grossly approximate and hypothetical, it helps in understanding the difference between metals, insulators and semiconductors (extrinsic and intrinsic) in a simple manner.

RESISTIVITY AND CONDUCTIVITY OF SEMICONDUCTOR

- **Conduction in conductor**



As we know that the relation between current (I) and drift velocity (v_d) is

$I = n_e A v_d$

where n = number of electron in per unit volume

Current density $J = \frac{I}{A} nev_d$. ($\because$ drift velocity of electron $v_d = \mu E$)

$\therefore \quad J = ne\mu E = \sigma E$

$\therefore \quad$ Conductivity $\sigma = ne\mu = 1/\rho$

and Resistivity $\rho = \frac{1}{ne\mu}$

- **Conduction in Semiconductor**

Intrinsic semiconductor	**P-type**	**N-type**
$n_e = n_h$	$n_h >> n_e$	$n_e >> n_h$
$J = ne[v_e + v_h]$	$J \cong e\, n_h v_h$	$J \cong e\, n_e v_e$
$\alpha = \frac{1}{\rho} = en[\mu_e + \mu_h]$	$\alpha = \frac{1}{\rho} \cong en_h\mu_h$	$\alpha = \frac{1}{\rho} \cong en_e\mu_e$

GOLDEN KEY POINTS

- Number of electrons reaching from valence band to conduction band at temperature T is given by

  $n = AT^{3/2} e^{-\frac{\Delta Eg}{2\,kT}}$

  where k = Boltzmann constant = 1.38×10^{-23} J/K,
  T= absolute temperature,
  A= constant
  ΔE_g = energy gap between conduction band and valence band

- In silicon at room temperature out of 10^{12} Si atoms only one electron goes from valence band to conduction band.

- In germanium at room temperature out of 10^{9} Ge atoms only one electron goes from valence band to conduction band.

- In semiconductors, Ohms law is approximately obeyed only for low electric field (less than 10^6 Vm^{-1}). Above this field, the current becomes almost independent of applied field.

- The size of dopant (impurity atom) should be almost the same as that of crystal atom. So that crystalline structure of solid remain unchanged.
- Because of doping semiconducting lattice should not be disturbed therefore doping concentration is kept low. The doping ratio varies from
  Impure : pure : : 1: 10^6 to 1 : 10^{10}.
  In general it is 1 : 10^8
- Due to impurity the conductivity increases approximately 10^5 times.

ILLUSTRATIONS

Illustrations 1

A P type semiconductor has acceptor level 57 meV above the valance band. What is maximum wavelength of light required to create a hole?

Solution

$$E = \frac{hc}{\lambda} \quad \Rightarrow \quad \lambda = \frac{hc}{E} = \frac{6.62\times10^{-34}\times3\times10^{8}}{57\times10^{-3}\times1.6\times10^{-19}} = 217700 \text{ Å}$$

Illustration 2

A silicon specimen is made into a p-type semiconductor by doping on an average one indium atom per 5 × 10^7 silicon atom. If the number density of atoms in the silicon specimen is 5 × 10^{28} atoms/ m^3; find the number of acceptor atoms in silicon per cubic centrimeter.

Solution

The doping of one indium at6m in silicon semiconductor will produce one acceptor atom in p-type semiconductor. Since one indium atom has been clopped per 5 × 10^7 silicon atoms, so number density of acceptor atoms in silicon $= \frac{5\times10^{28}}{5\times10^{7}} = 10^{21}$ atom/m^3 = 10^{15} atom/cm^3

Illustration 3

Pure Si at 300 K has equal electron (n_e) and hole (n_h) concentrations of 1.5 × 10^{16} m^{-3}. Doping by indium n_h increases to 3 × 10^{22} m^{-3}. Calculate n_e in the doped Si.

Solution

For a doped semi-conductor in thermal equilibrium $n_e n_h = n_i^2$ (Law of mass action)

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5\times10^{16})^2}{3\times10^{22}} = 7.5\times10^{9}\,m^{-3}$$

Illustration 4

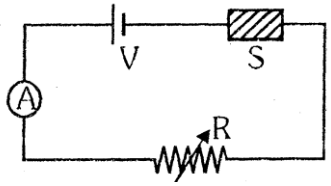
What will be conductance of pure silicon crystal at 300 K temperature? If electron hole pairs per cm^3 is 1.075 × 10^{10} at this temperature, μ_e = 1350 cm^2 / volt-s & μ_h = 480 cm^2 / volt-s.

Solution

$\sigma = n_i e\mu_e + n_i e\mu_h = n_i e(\mu_e + \mu_h) = 1.072 \times 10^{10} \times 1.6 \times 10^{-19} \times (1350 + 480) = 3.14 \times 10^{-6}$ mho/cm

BEGINNER'S BOX-1

1. The diagram shows a piece of pure semiconductor S; in series with a variable resistor R, and a source of constant voltage V. Would you increase or decrease the value of R to keep the reading of ammeter (A) constant, when semiconductor S is heated? Give reason.



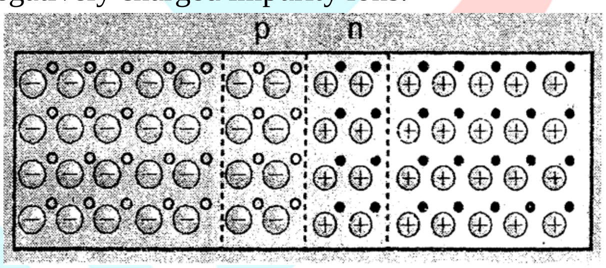
2. Pure Si at 300 K has equal electron n_e and hole n_h concentration of $1.5 \times 10^{16}/m^3$. Doping by indium increases n_h to $4.5 \times 10^{22}/m^3$. Calculate n_e in doped silicon.

3. Suppose a pure Si crystal has 5×10^{28} atoms m^{-3}. It is doped by 1 ppm concentration of pentavalent As. Calculate the number of electrons and hole. (Given that $n_i = 1.5 \times 10^{16}$ m^{-3}).

4. For given semiconductor contribution of current due to electron and hole is in ratio 3/1 and the ratio of drift velocity for electron and hole is 5/2, then calculate the ratio of electron to hole concentration.

P-N JUNCTION

Given diagram shows a P-N junction immediately after it is formed. P region has mobile majority holes and immobile negatively charged impurity ions.

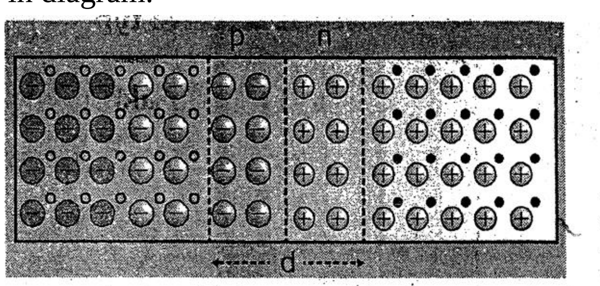


N region has mobile majority free electrons and immobile positively charged impurity ions.

Due to concentration difference diffusion of holes starts from P to N side and diffusion of e^-s starts from N to P side.

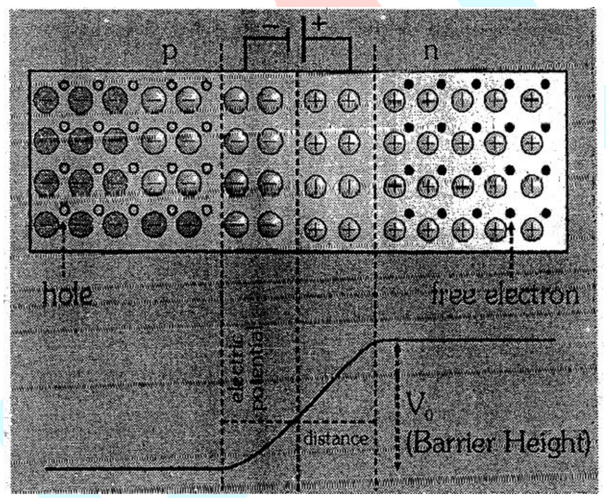
Due to this a layer of only positive ions (in side) and negative ions (in P-side) started to form which generate an electric field (N to P side) which oppose diffusion process, during diffusion magnitude of electric field increases due to this diffusion it gradually decreased.

The layer of immobile positive and negative ions, which have no free electrons and holes called as **depletion layer** as shown in diagram.



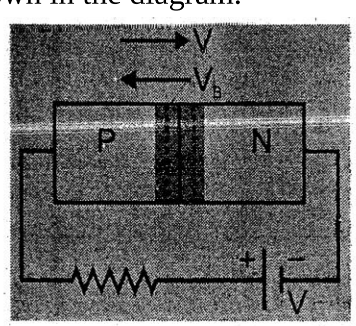
Due to internal electrical field; an electron on p-side of the junction moves to n-side and a hole on n-side of the junction moves to p-side. The motion of charge carriers due to the electric field is called drift. Thus a drift current flows, which is opposite in direction to the diffusion current.
Initially, diffusion current is large and drift current is small. As the diffusion process continues, the space-charge regions on either side of the junction extend, thus increasing the electric field strength and hence drift current. This process continues until the diffusion current equals the drift current.

At equilibrium condition
Direction of diffusion current : P to N side and drift current : N to P side
If there is no biasing then | diffusion current | = | drift current |
So total current is zero.
In junction N side is at high potential relative to the P side. This potential difference tends to prevent the movement of electron from the N region into the P region. This potential difference is called **Barrier potential**.



BEHAVIOR OF P-N JUNCTION WITH AN EXTERNAL VOLTAGE APPLIED OR BIAS

- **Forward Bias**
  In this type of biasing we apply a potential difference such that P-side is at high potential and N-side is at low potential as shown in the diagram.

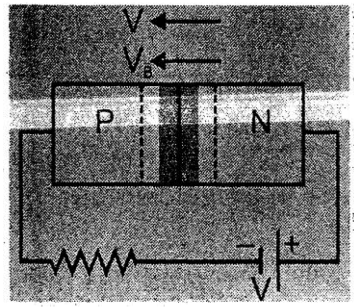


The applied voltage is opposite to the junction barrier potential.

Due to this effective potential barrier decreases; junction width also decreases, so more majority carriers will be allowed to flow across junction. It means the current flow in principally due to majority charge carries called as forward current (in mA).

- **Reverse Bias**

  In this type of biasing we apply a potential difference such that P-side is at low potential and N-side is at high potential as shown in the diagram.



The applied voltage is same side of to the junction barrier potential. Due to this effective potential barrier increased, junction width also increased, so no majority carriers will be allowed to flow across junction.

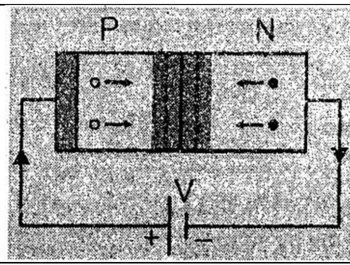
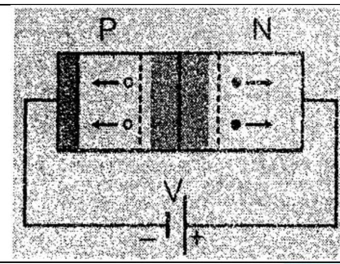
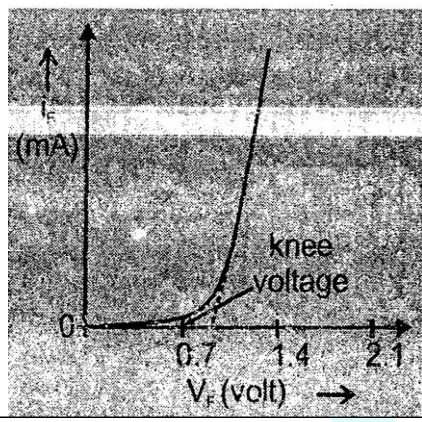
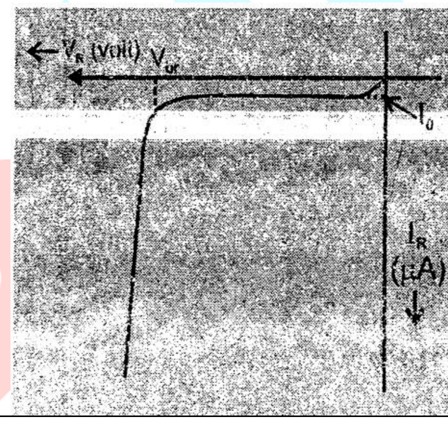
Only minority carriers are drifted. It means the current flow in principally due to minority charge carries and is very small (μA) called as reverse current.

The current under reverse bias is essentially voltage independent upto a critical reverse bias voltage, known breakdown voltage (V_{br}). When $V = V_{br}$, the diode reverse current increases sharply. Even a slight increase in the bias voltage causes large change in the current. This phenomena is known as **Breakdown**.

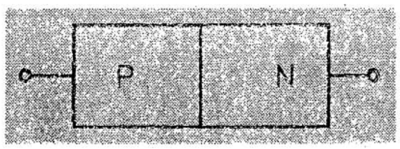
Breakdown are of two types :

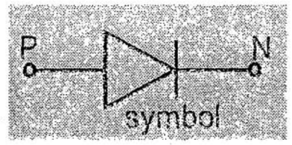
Zener Breakdown	**Avalanche Breakdown**
• Where covalent bonds of depletion layer, itself break, due to high electric field of very high Reverse bias voltage.	• Here covalent bonds of depletion layer are broken by collision of "Minorities" which acquire high kinetic energy from high electric field of very-very high reverse bias voltage.
• This phenomena takes place in (i) P-N junction having "High doping" (ii) P-N junction having thin depletion Layer	• This phenomena takes place in (i) P-N junction having "Low doping" (ii) P-N junction having thick depletion layer
• Here P-N junction does not damage permanently "In D.C. voltage stabilizer zener phenomena is used".	• Here P-N junction damages permanently due to abruptly increment of minorities during repetitive collisions.

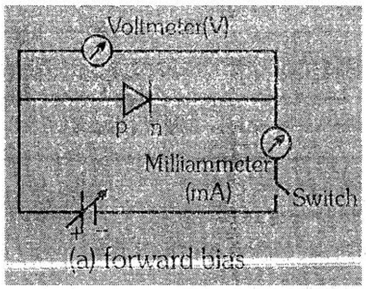
	Forward Bias		**Reverse Bias**
	P → positive N → negative		P → negative N → positive

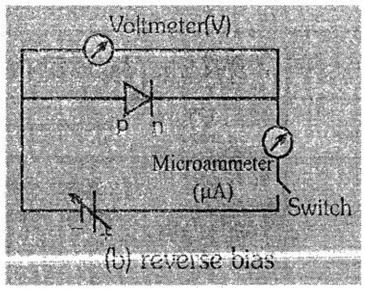
			
1.	Potential Barrier reduces.	1.	Potential Barrier increases.
2.	Width of depletion layer decreases.	2.	Width of depletion layer increases.
3.	P-N Junction provides very small resistance.	3.	P-N Junction provides high resistance.
4.	Forward current flow in circuit.	4.	Reverse current flow in circuit.
5.	Order of forwards current is milli ampere.	5.	Order of current is micros ampere (Ge) or Nano ampere (Si)
6.	Mainly majority current flows.	6.	Mainly minority current flows.
7.	Forward characteristic curve 	7.	Reverse characteristic curve 
8.	Forward resistance $R_f = \frac{\Delta V_f}{\Delta I_f} \cong 100\ \Omega$	8.	Reverse resistance $R_B = \frac{\Delta V_B}{\Delta I_B} \cong 10^6\ \Omega$
9.	Knee or cut in voltage Ge $\rightarrow$ 0.3 V, Si $\rightarrow$ 0.7 V	9.	Breakdown voltage Ge $\rightarrow$ 25 V, Si $\rightarrow$ 35 V
10.	Forward current equation $I = I_0\left[e^{+\frac{qV}{kt}} - 1\right]$ Q $e^{\frac{qv}{kt}} >> 1$ $\therefore$ $I \cong I_0 e^{\frac{qv}{kt}}$ (exp. increment) For Ge $\frac{R_B}{R_F} = 10^3 : 1$	10.	Reverse current equation $I = I_0\left[e^{-\frac{qV}{Kt}} - 1\right]$ Q $e^{-\frac{qv}{KT}} << 1$ $\therefore$ $I ; -I_0$ For Si $\frac{R_B}{R_F} = 10^4 : 1$

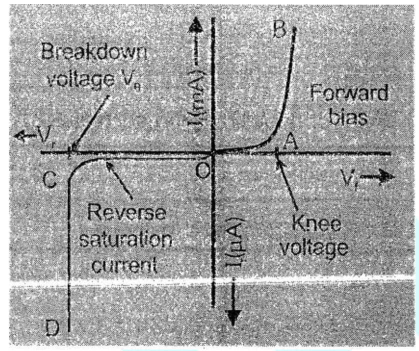
Characteristic Curve of P-N Junction Diode







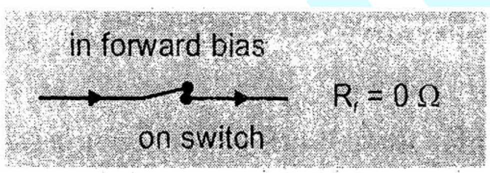


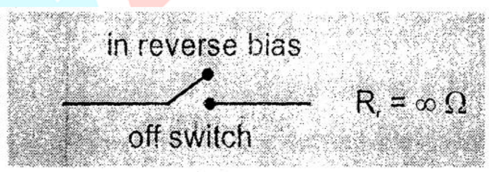


In forward bias when voltage is increased from 0V in steps and corresponding value of current is measured, the curve comes as OB of figure. We may note that current increases very sharply after a certain voltage knee voltage. At this voltage, barrier potential is completely eliminated and diode offers a low resistance.

In reverse bias a microammeter has been used as current is very very small. When reverse voltage is increased from 0V and corresponding values of current measured the plot comes as OCD. We may note that reverse current is almost constant hence called reverse saturation current. It implies that diode resistance is very high. As reverse voltage reaches value V_8 , called breakdown voltage, current increases very sharply.

For Ideal Diode





GOLDEN KEY POINTS

- Width of depletion layer ≅ 0.1 J μm
  (a) As doping increases, width of depletion layer decreases
  (b) P-N junction → nonohmic, due to nonlinear relation between I and V.
- Potential Barrier or contact potential for Ge → 0.3 V, for Si → 0.7 V
- Strength of junction field $E = \frac{\Delta V}{d} = \frac{0.5}{10^{-7}} \Rightarrow E \cong 10^6$ V/m
  This field prevents the respective majority carriers from crossing barrier region.
- In reverse bias, the current is very small and nearly constant with bias (termed as reverse saturation current). However interesting behaviour results in some special cases if the reverse bias is increased further beyond a certain limit, breakdown of depletion layer takes place.

ILLUSTRATIONS

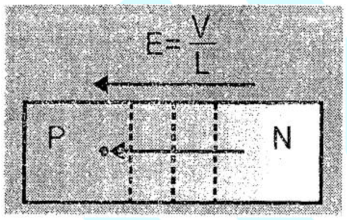
Illustrations 5

A potential barrier of 0.5 V exists across a p-n junction (i) If the depletion region is 5×10^{-7} m wide. What is the average intensity of the electric field in this region? (ii) An electron with speed 5×10^{5} m/s approaches the p-n junction from the n-side with what speed will it enter the p-side?

Solution

(i) Width of depletion layer $\Delta L = 5 \times 10^{-7}$ m

$$E = \frac{V}{\Delta L} = \frac{0.5\ V}{5 \times 10^{-7}} = 10^{6}\ \text{volt / m}$$



(ii) Work energy theorem $\frac{1}{2}Mv_i^2 = eV + \frac{1}{2}Mv_f^2$

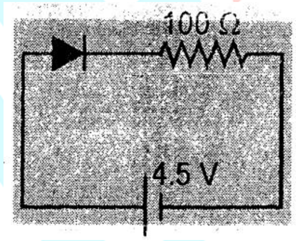
$$v_f = \sqrt{\frac{Mv_1^2 - 2eV}{M}} = 2.7 \times 10^{5}\ m/s$$

Illustration 6

Figure shows a diode connected to an external resistance and an e.m.f. Assuming that the barrier potential developed in diode is 0.5 V, obtain the value of current in the circuit in milliampere.

Solution

E = 4.5V, R = 100 Ω,



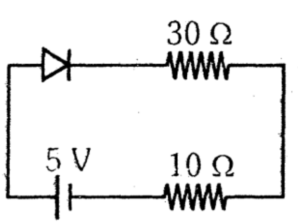
Voltage drop across p-n junction = 0.5 V

Effective voltage in the circuit V = 4.5 – 0.5 = 4.0 V

Current in the circuit $I = \frac{V}{R} = \frac{4.0}{100} = 0.04A$ = 0.04 × 1000 mA = 40 mA

Illustration 7

If current in given circuit is 0.1 A then calculate resistance of P-N junction.

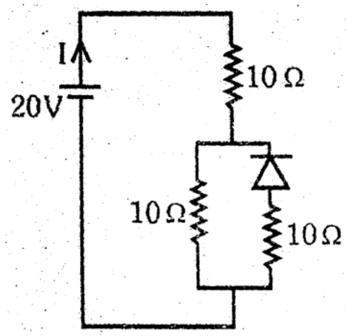


Solution

Let resistance of PN-junction be R then $I = \frac{5}{R + 30 + 10} = 0.1 \Rightarrow R = 10\ \Omega$

Illustration 8

What is the value of current I in given circuits?

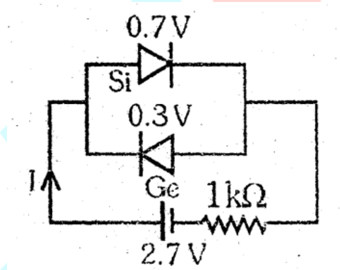


Solution

$$I = \frac{20}{10+10} = 1\text{ A}$$

Illustration 9

What is the value of current I in given circuits?

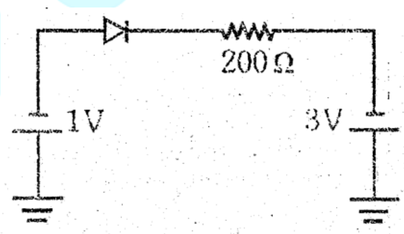


Solution

$$I = \frac{27-0.7}{1\times10^3} = 2\text{ mA}$$

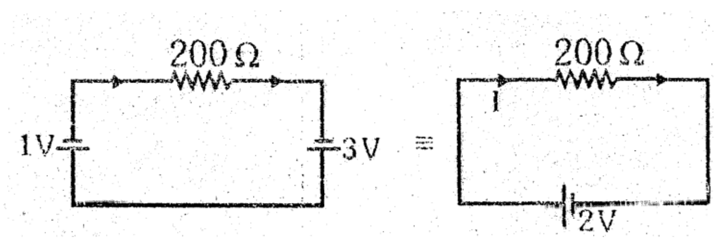
Illustration 10

In the given circuit. If P-N junction is ideal, then calculate current flowing through it.



Solution

In given condition



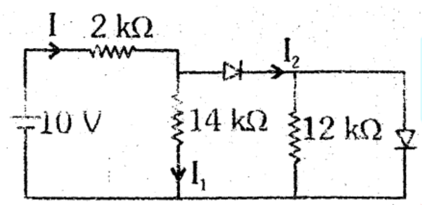
$\Rightarrow \quad I = \frac{2V}{200} = 0.01\,A$

BEGINNER'S BOX-2

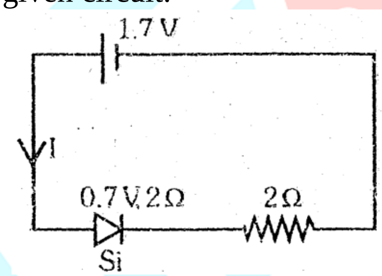
1. The potential barrier existing across an unbiased p-n junction is 0.2 volt. What minimum kinetic energy a hole should have to diffuse from the p-side to the n-side if -
(a) The junction is unbiased
(b) The junction is forward biased at 0.1 volt.
(c) The junction is reverse-biased at 0.1 volt.

2. A silicon P-N junction is in forward biased condition with a resistance in series, It has knee voltage of 0. 75 V and current flow in it is 10 mA. If the P-N junction is connected with 2.75 V battery then calculate the value of the resistance.

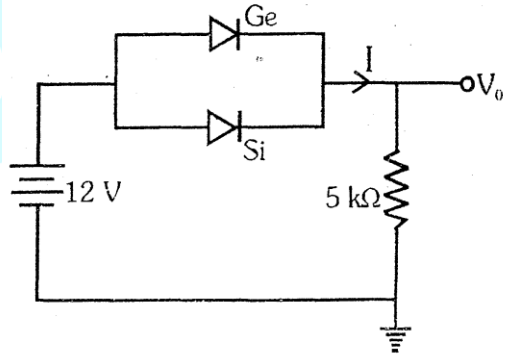
3. In given circuit determine I, I_1 and I_2



4. Find the value of current I in given circuit.



5. (a) Calculate the value of V_0 and I if the Si diode and the Ge diode start conducting at 0.7 V and 0.3 V respectively, in the given circuit.
(b) If the Ge diode connection be reversed, What will be the new values of V_0 and I ?

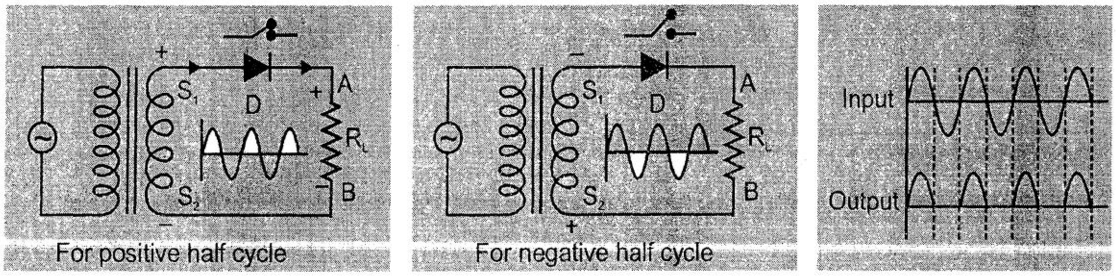


APPLICATION OF JUNCTION DIODE

1. Rectifier

It is device which is used for converting alternating current into direct current.

(i) Half wave rectifier : It rectifies only half of the ac input wave.



For positive half cycle
For negative half cycle

During the first half (positive) of the input signal, S_1 is at positive and S_2 is at negative potential. So, the PN junction diode D is forward biased. The current flows through the load resistance R_L and output voltage is obtained across the R_L.

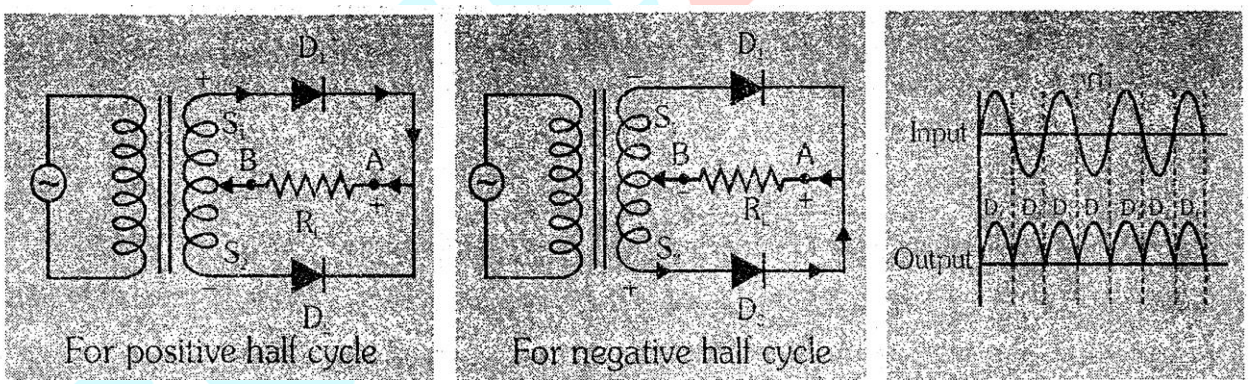
During the second half (negative) of the input signal, S_1 is at negative potential and S_2 is at positive potential. The PN junction diode will be reversed biased. In this case, practically no current would flow through the load resistance. So, there will be no output across the RL.

Thus, corresponding to an alternating input signal, we get a unidirectional pulsating output called rectified output.

2. Full wave rectifier

It rectifies both the cycles of input ac wave. It is of two types (fundamentally).

(i) Centre tape rectifier : Figure shows the experimental arrangement for using diode as full wave rectifier. When the alternating signal is fed to the transformer, the output signal appears across the load resistance R_L.



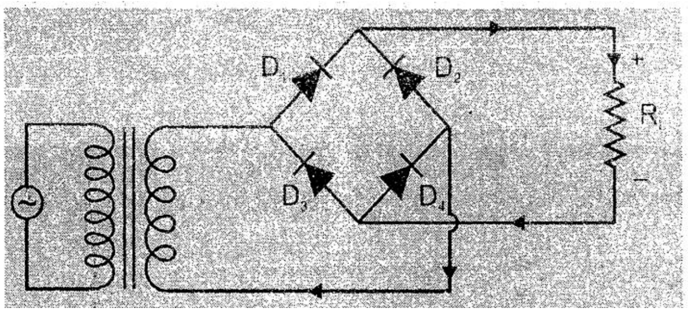
For positive half cycle
For negative half cycle

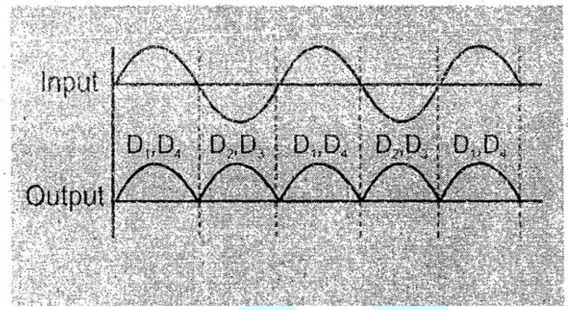
During the positive half of the input signal: S_1 positive and S_2 negative. In this case diode D_1 is forward biased and D_2 is reverse biased. So only D_1 conducts and hence the flow of current in the load resistance R_L is from A to B.

During the negative half of the input signal : S_1 is negative and S_2 is positive. So D_1 is reverse-biased and D_2 is forward biased. So only D_2 conduct and hence the current flows through the load resistance R_L again from A to B.

It is dear that whether the input signal is positive or negative, the current always flows through the load resistance in the same direction and thus output is called full wave rectified.

(ii) Bridge Rectifier





During positive half cycle

D_1 and D_4 are forward biased → 'On' switch

D_2 and D_3 are reverse biased → 'Off' switch

During negative half cycle

D_2 and D_3 are forward biased → 'On' switch

D_1 and D_4 are forward biased → 'Off' switch

- **Rectifier efficiency (η)**

  For half wave rectifier

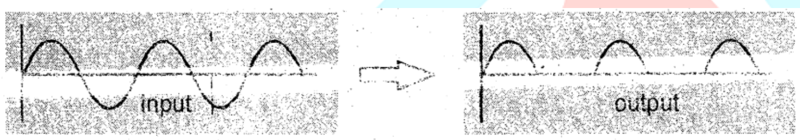
  $\eta_{max} = 40.6\%$

  For full wave rectifier or bridge wave rectifier

  $\eta_{max} = 81.2\%$

- **Ripple Frequency**

  (i) For half wave rectifier



Input frequency = 50 Hz   Ripple frequency = 50 Hz

  (ii) For full wave rectifier

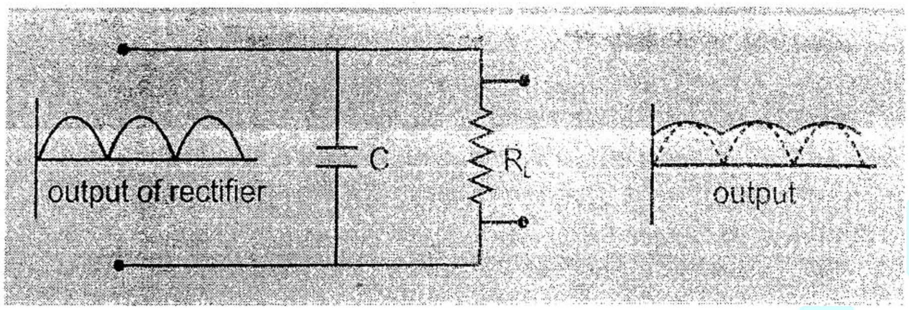
Input frequency = 50 Hz   Ripple frequency = 100 Hz

Filter Circuit

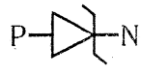
The rectified output is in the form of pulses or in shape of half sinusoids. Though it is unidirectional, it does not have a steady value. To get steady de output from the pulsating voltage, normally a capacitor is connected across the output terminals (parallel to the load R_L) called filter circuit.

- **Capacitor Filter**

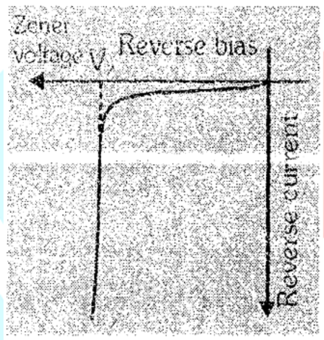
  When the voltage across the capacitor is rising, it gets charge. If there is no external load, it remains charged to the peak voltage of the rectified output. When there is a load, it gets discharged through the load and the voltage across it begins to fall. In the next half-cycle of rectified output it again gets charged to the peak value but due to large value of time constant of capacitor, voltage across the capacitor approximate remains constant.



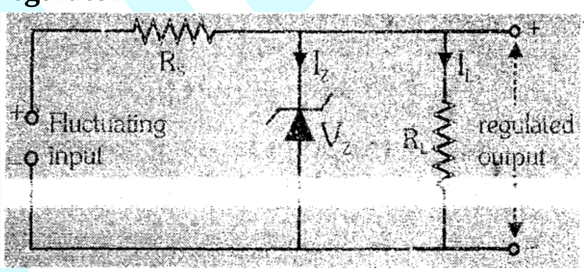
ZENER DIODE

It is a special purpose diode, designed to operate under the reverse bias in the breakdown region and used in voltage regulation. Symbol of Zener diode is 

In reverse bias of zener diode after the breakdown voltage V_z, a large change in the current can be produced by almost insignificant change in the reverse bias voltage. In other words zener voltage remains constant, even through current through the zener diode varies over a wide range. This property of the zener diode is used for regulating voltage.



Zener diode as a voltage regulator



The unregulated de voltage (filtered output of a rectifier) is connected to the zener diode through a series resistance R_S such that the zener diode is reverse biased. If the input voltage increases, the current through R_S and zener diode also increase. This increases the voltage drop across R_S without any change in the voltage across the zener diode. This is because in the breakdown region, zener voltage remains constant even though the current through the zener diode changes. Similarly, if the input voltage decreases, the current through R_S and zener diode also decreases. The voltage drop across R_S decreases without any change in the voltage across the zener diode. Thus any increase/decrease in the input voltage results in, increase/decrease of the voltage drop across R_S without any change in voltage across the zener diode. Thus the zener diode acts as a voltage regulator.

OPTOELECTRONIC JUNCTION DEVICES

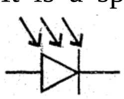
1. Light Emitting Diode (LED

It is a heavily doped P-N junction which under forward bias emits spontaneous radiation. Its symbol is  when LED is forward biased then electrons move from N→P and holes move from P→N. At the junction boundary these are recombined. On recombination, energy is released in the form of photons of energy equal to or slightly less than the band gap.

When the forward current of the diode is small, the intensity of light emitted is small. As the forward current increases, intensity of light increases and reaches a maximum. Further increase in the forward current results in decrease of light intensity. LEOs are biased in such a way that the light emitting efficiency should be maximum.

In case of Si or Ge diodes, the energy released in recombination lies in infra-red region. Therefore to form LED, such semiconductors are to be used which have band gap from 1.8 eV to 3 eV. Hence $GaAs_{1-x}P_x$ is used in forming LED.

2. Photodiode

It is a special purpose junction diode used to sense and measure incident light. Its symbol is .

It is operated under reverse bias.

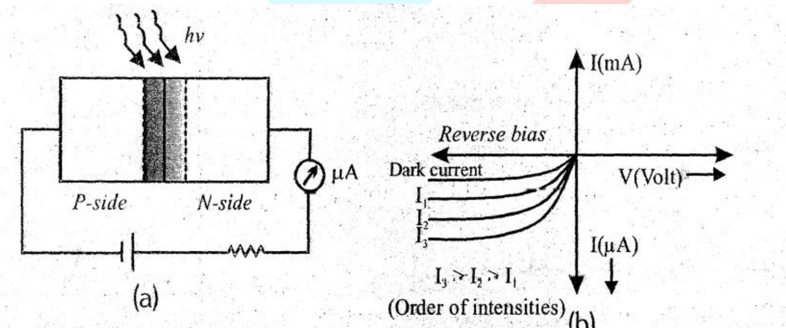
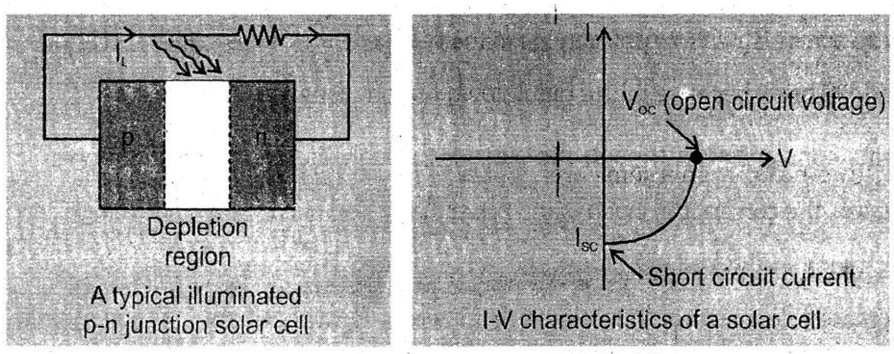


Figure (a) An illuminated photodiode, under reverse bias
(b) I-V characteristics of a photodiode for different illumination intensity $I_3 > I_2 > I_1$

When light of energy "hv" falls on the photodiode (Here hv > energy gap) more electrons move from valence band to conduction band, due to this current in circuit of photodiode in "Reverse bias", increases. As light intensity is increased, the photo current goes on increasing. So photo diode is used "to detect light intensity". Example used in "Video camera".

3. Solar Cell

A p-n junction which generates emf when solar radiation falls on it, called solar cell. It works on the same principle (photovoltaic effect) as the photodiode, except that no external bias is applied and the junction area is kept much larger for solar radiation to be incident because we are interested in more power.



(a) (b)

When light falls on, emf generates due to the following three basic processes: generation, separation and collection- (i) generation of e-h pairs due to light (with hν > Eg) in junction region; (ii) separation of electrons and holes due to electric field of the depletion region. Electrons are swept to n-side and holes to p-side by the junction field; (iii) On reaching electrons at n-side and holes on at p-side. Thus n-side becomes negative and p-side becomes positive potential and giving rise to photovoltage.

GOLDEN KEY POINTS

- RMS and average (dc) current

	for Half wave rectifier	for Full wave rectifier
	$I_{rms} = \frac{I_0}{2}$	$I_{rms} = \frac{I_0}{\sqrt{2}}$
	$I_{dc} = \frac{I_0}{\pi}$	$I_{dc} = \frac{2I_0}{\pi}$

- Maximum efficiency of half wave rectifier is 40.6% and of full wave rectifier is 81.2%.
- Ripple and ripple factor (r) : In the output of rectifier some A.C. components are present, these are called ripples and their measurement is given by a factor called ripple factor. For good rectifier ripple factor must by very low.

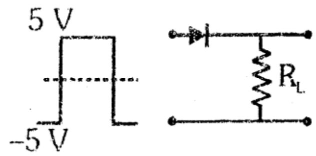
  For HWR r = 1.21,

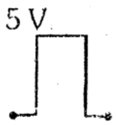
  For FWR r = 0.48
- **Dark Current :** When no light is incident then the reverse saturation current in photo diode is called dark current.
- LED have power and low operating voltage.
- Solar cell converts solar energy into electrical energy.
- Zener diode is heavily doped with thin depletion region.

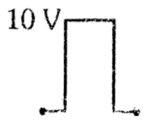
ILLUSTRATIONS

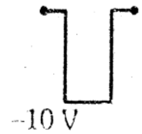
Illustrations 11

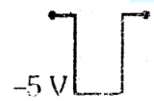
If in a p-n junction diode. A square input signal of 10 V is applied as shown. Then the output signal across R_L will be **[AIEEE-2007]**



(1) 

(2) 

(3) 

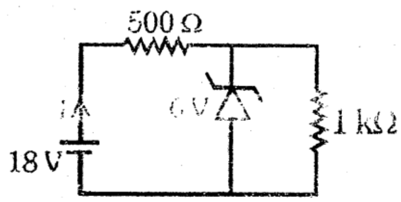
(4) 

Solution

Ans. (1)

Illustration 12

What is the value of current I in given circuits?



Solution

$$I = \frac{18-6}{500} = 24\text{mA}$$

Illustration 13

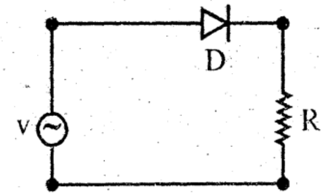
A photodetector is made from a semiconductor with E_g = 0.75 eV. Calculate the maximum wavelength which it can detect?

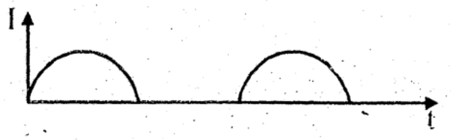
Solution

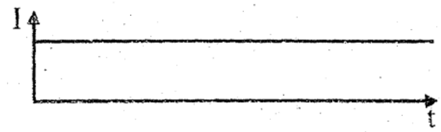
$$\lambda_{max} = \frac{hc}{E_g} = \frac{6.62\times10^{-34}\times3\times10^{8}}{0.75\times1.6\times10^{-19}} = 16553\ \text{Å}$$

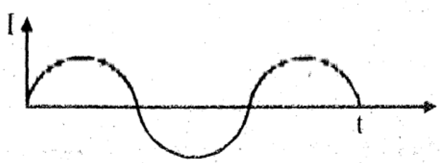
BEGINNER'S BOX-3

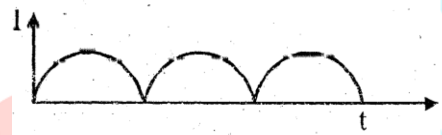
1. A p-n junction diode (D) shown in the figure can act as a rectifier. An alternating current source (V) is connected in the circuit. The current (I) in the resistor (R) can be shown by **[AIEEE-2009]**



(1) 

(2) 

(3) 

(4) 

2. A zener diode of voltage V_2 (= 6 V) is used to maintain a constant voltage across a load resistance R_L (=1000 Ω) by using a series resistance R_S (= 100 Ω). If the e.m.f. of source is E (= 9V), calculate the value of current through series resistance, Zener diode and load resistance. What is the power being dissipated in Zener diode?

3. A Zener diode is specified having a breakdown voltage of 9.1 V with a maximum power dissipation of 364 mW. What is the maximum current that the diode can handle?

4. A semiconductor (GaAs) has an energy gap of 1.43 eV. What is the maximum wavelength emitted when a hole and an electron recombine in such semiconductor?

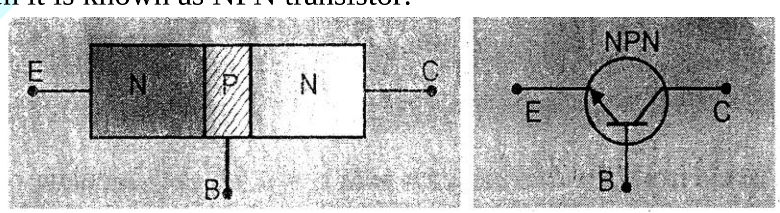
TRANSISTOR

Transistor is a three terminal device which transfers a singal from low resistance circuit to high resistance circuit. It is formed when a thin layer of one type of extrinsic semiconductor (P or N type) is sandwitched between two thick layers of other type of extrinsic semiconductor.

Transistors are of two types

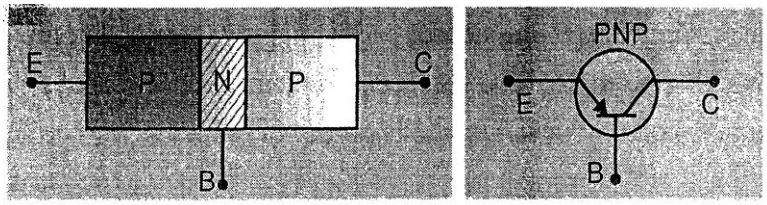
- **N-P-N Transistor**

  If a thin layer of P-type semiconductor is sandwitched between two thick layers of N-type semiconductor, then it is known as NPN transistor.



- **P-N-P Transistor**

If a thin layer of N-type of semiconductor is sandwitched between two thick layer of P-type semiconductor, then it is known as PNP transistor.



Each transistor has three terminals and these are :

(i) **Emitter :** It is the left most part of the transistor which emits the majority carriers towards base. It is **highly doped** and **medium in size**.

(ii) **Base :** It is the middle part of transistor which is sandwitched by emitter (E) and collector (C). It is **lightly doped** and **very thin in size**.

(iii) **Collector :** It is right part of the transistor which collects the majority carriers which is emitted by emitter. It has **large size** and **moderate doping**.

Every transistor has following two junctions

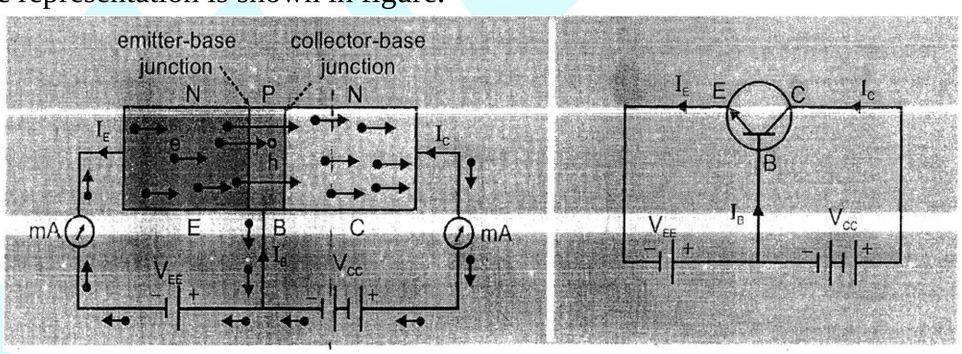
(i) The junction between emitter and base is known as emitter-base junction **(J_{EB}).**

(ii) The junction between base and collector is known as base-collector junction **(J_{BC}).**

WORKING OF TRANSISTOR

1. Working of NPN Transistor

The emitter base junction is forward biased and base collector junction is reversed biased to study the behavior of transistor. It is called active state of transistor. N-P-N transistor in circuit and symbolic representation is shown in figure.



In active state of n-p-n transistor majority electrons in emitter are sent towards base.

The barrier of emitter base junction is reduced because of forward bias therefore electrons enter into the base.

About 5% of these electrons recombine with holes in base region results very small current (I_B) in base.

The remaining electron ($\approx$95%) enters into the collector region because these are attracted towards the positive terminal of battery results collector current (I_C).

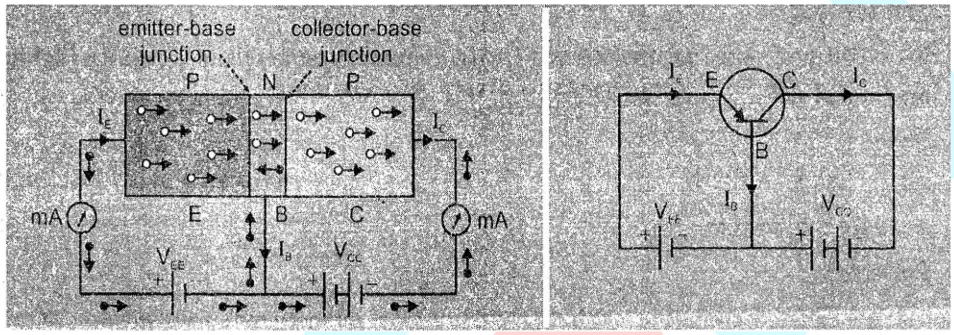
The base current is the difference between I_E and I_C and proportional to the number of electron hole recombination in the base.

$I_E = I_B + I_C$

We also see I_E ; I_C because I_B is very small.

2. Working of PNP Transistor

When emitter-base junction is forward biased, holes (majority carriers) in the emitter are repelled towards the base and diffuse through the emitter base junction. The barrier potential of emitter-base junction decreases and hole enters into then-region (i.e. base). A small number of holes (≈ 5%) combine with electrons of base-region resulting small current (I_B). The remaining holes (≈ 95%) enter into the collector region because these are attracted towards negative terminal of the battery connected with the collector-base junction. These hole constitute the collector current (I_C).



As one hole reaches the collector, it is neutralized by the battery. As soon as one electron and a hole is neutralized in collector, a covalent bond is broken in emitter region and an electron hole pair is produced. The released electron enters the positive terminal of battery and holes moves towards the collector. So $I_E = I_B + I_C$

CONFIGURATIONS OF A TRANSISTOR AND ITS CHARACTERISTICS

The transistor is connected in either of the three ways in circuit.

(i) Common base configuration

(ii) Common emitter configuration

(iii) Common collector configuration

In these three, common emitter is widely used and common collector is rarely used.

- **Common emitter transistor characteristics**

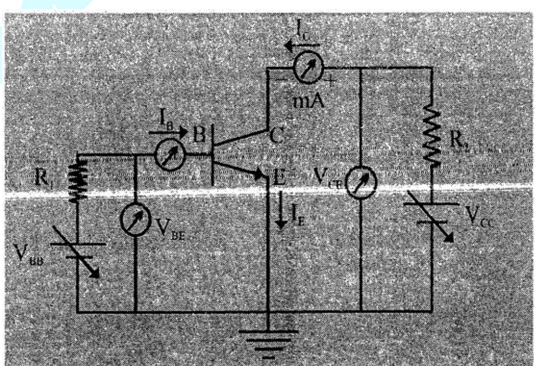
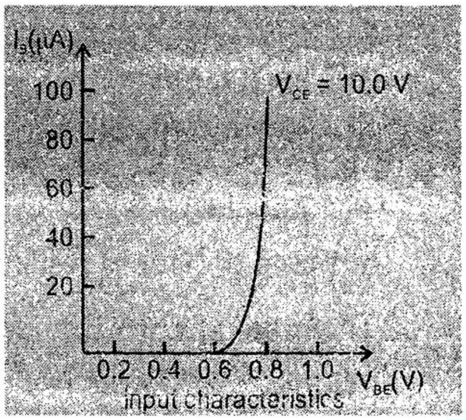


Figure : Circuit diagram for characteristics curve of n-p-n transistor (CE)

- **Input Characteristics**

The variation of base current (I_B) (input) with base emitter voltage (V_{EB}) at constant collector emitted voltage (V_{CE}) is called input characteristic.



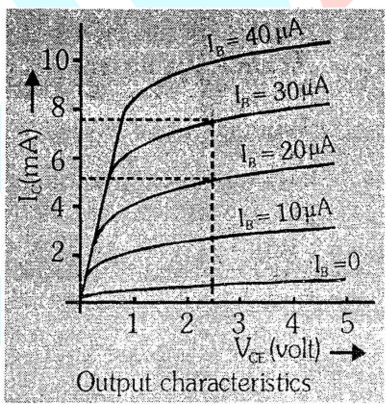
(i) Kept the collector-emitter voltage (V_{CE}) constant (say V_{CE} = 10V)

(ii) Now change emitter base voltage V_{BE} in steps of 0.1 volt and note the corresponding values of base current (I_B).

(iii) Plot the graph between V_{BE} and I_B.

- **Output characteristics**

The variation of collector current I_C (output) with collector-emitter voltage (V_{CE}) at constant base current (I_B) is called output characteristic.



(i) Keep the base current (I_B) constant (say I_B = 10 μA)

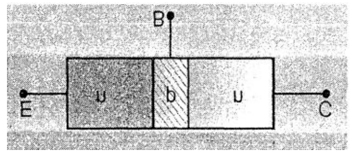
(ii) Now change the collector-emitter voltage (V_{CE}) and not the corresponding values of collector current (I_C) .

(iii) Plot the graph between V_{CE} and I_C.

(iv) A set of such curves can also be plotted at different fixed values of base current (say 20 μA, 30 μA etc.)

GOLDEN KEY POINTS

Emitter	Medium size	High doping
Base	Smallest size	Low doping
Collector	Largest size	Medium doping



- Transistor have two P-N Junction J_{EB} and J_{CB}. On the basis of junction condition transistor work in for regions

Emitter-Base	**Collector-Base**	**Region of working**
Forward biased	Reverse biased	Active
Reverse biased	Forwards biased	Inverse active
Reverse biased	Reverse biased	Cut off
Forward biased	Forward biased	Saturation

- The collector region is made physically larger than the emitter. Because collector has to dissipate much greater power.
- Transistor mostly works in active region in electronic devices to use as an amplifier.
- Transistor i.e. It is a short form of two words "Transfer resistors". Signal is introduced at low resistance circuit and output is taken at high resistance circuit.
- Base is lightly doped, otherwise the most of the charge carries from the emitter recombine in base region and none of the emitted carrier reaches at collector.
- Transistor is a current operated device i.e. the action of transistor is controlled by the motion of charge carriers.
- From transistors characteristics,

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

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

  (iii) Current gain $\beta = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE} = \text{constant}}$

- The ratio of change in output current to change in input voltage is known as transconductance.

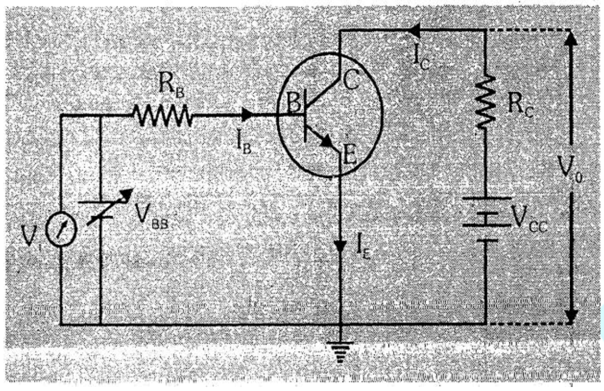
  In CE transistor transconductance $(g_m) = \frac{\Delta I_C}{\Delta V_{in}}$.

- Voltage gain $A_V = \frac{\Delta V_O}{\Delta V_{in}} = \frac{(\Delta I_C) R_C}{\Delta V_{in}} = g_m \times R_C$

APPLICATIONS OF TRANSISTOR

1. Transistor as a switch

When a transistor is used in the cut off (off state) or saturation state (on state) only, it acts as a switch. To study this behaviour, we understand base biased CE transistor circuit.

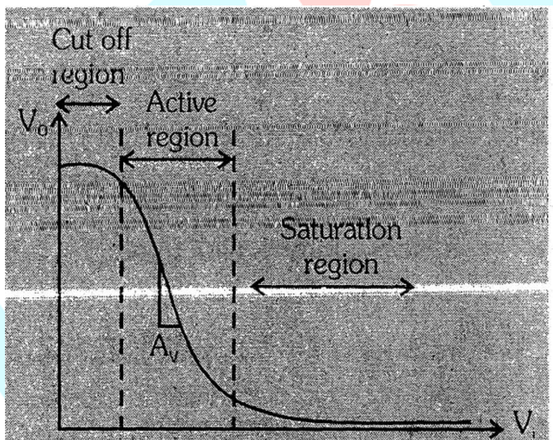


Applying Kirchhoff's voltage rule to the input and output sides of this circuit we get

$V_i = I_B R_B + V_{BE}$ (V_i = dc input voltage)

and $V_O = V_{CC} - I_C R_C$ (V_O = dc output voltage)

Now we can analyse how V_O changes as V_i increase from zero onwards. In case of Silicon transistor, if V_i is less than 0.6 V, I_B will be zero, hence I_C will zero and transistor will be said to be in cut-off state, and $V_O = V_{CC}$. When V_i become greater than 0.6 V, some I_B flows, so some I_C flows (transistor is in active state now) and output V_O decreases as the term $I_C R_C$ increase. With increase in V_i the I_C increase almost linearly and so V_O decreases linearly till its value becomes less than about 1.0 volt.



Transfer characteristic

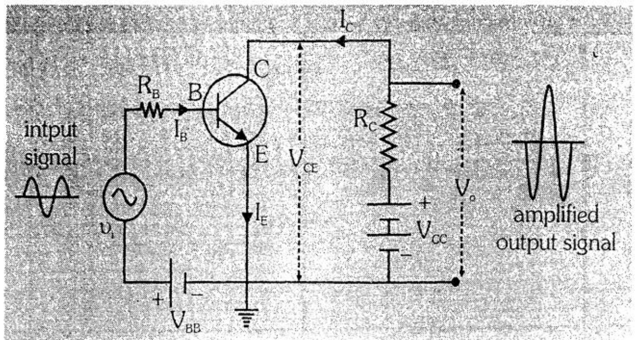
Beyond this, the change becomes non linear and transistor goes into saturation state. With further increase in V_i the output voltage is found to decrease further forwards zero (however, it may never becomes zero).

It we draw the V_O versus V_i curve called transfer characteristic (see figure), we see that between cut off state and active state and also between active state and saturation state there are regions of non-linearity showing that the transition from cut-off state to active state and from active state to saturation state are not sharply defined.

2. Transistor as an amplifier

The process of increasing the amplitude of input signal without distorting its wave shape and without changing its frequency is known as amplification.

A device which increase the amplitude of the input signal is called amplifier.



common emitter amplifier NPN transistor

To operate the transistor as an amplifier it is necessary to fix its operating point somewhere in the middle of its active region. If we fix the value of V_{BB} corresponding to a point in the middle of the linear part of the transfer curve then the de base current I_B would be constant and corresponding collector current I_C will also be constant. The dc voltage $V_{CE} = V_{CC} - I_C R_C$ would also remain constant. The operating values of V_{CE} and I_B determine the operating point, of the amplifier.

If a small sinusoidal voltage with amplitude υ_i is superposed in series with the V_{BB} supply, then the base current will have sinusoidal variations superimposed on the value of I_B. As a consequence the collector current also will have sinusoidal variations superimposed on the value of I_C producing in turn corresponding change in the value of V_0.

Mathematical Analysis :

From KVL equation of base biased CE transistor circuit

$V_i = I_B R_B + V_{BE}$

$\Rightarrow \quad \Delta V_i = (\Delta I_B)R_B + \Delta V_{BE} \qquad Q \qquad \Delta V_{BE} = 0$

$\Rightarrow \quad \Delta V_i = (\Delta I_B)R_B$

Similarly $V_o = V_{CC} - I_C R_C$

$\Rightarrow \quad \Delta V_o = V_{CC} - (\Delta I_C)R_C \qquad Q \qquad \Delta V_{CC} = 0$

$\Rightarrow \quad \Delta V_o = -(\Delta I_C)R_C$

So voltage gain of CE amplifier

$$A_V = \frac{\Delta V_o}{\Delta V_{in}} = \frac{-(\Delta I_C)R_C}{(\Delta I_B)R_B} = -\beta\frac{R_C}{R_B}$$

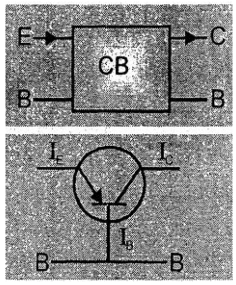
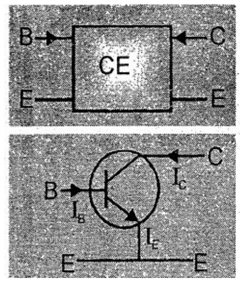
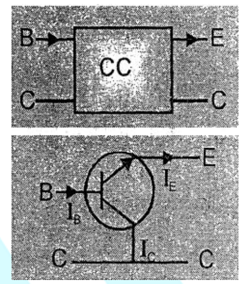
The negative sign represents that output voltage is opposite in phase with the input voltage.

Power gain (A_p) = current gain × voltage gain = $\beta_{ac} \times A_V \Rightarrow A_P > 1$

However is should be realized that transistor is not a power generating device. The energy for the higher ac power at the output is supplied by the battery V_{CC}.

Comparative study of transistor configuration

1. Common Base **(CB)** **2.** Common Emitter **(CE)** **3.** Common Collector **(CC)**

	CB	CE	CC
			
Input Resistance	Low (100 Ω)	High (750 Ω)	Very High ≅ 750 Ω
Output Resistance	Very High	High	Low
Current Gain	(A_1 or α) $\alpha = \frac{I_C}{I_E} < 1$	(A_1 or β) $\beta = \frac{I_C}{I_B} > 1$	(A_1 or γ) $\gamma = \frac{I_E}{I_B} > 1$
Voltage Gain	$A_V = \frac{V_o}{V_i} = \frac{I_C R_L}{I_E R_i}$ $A_v = \alpha \frac{R_L}{R_i}$	$A_V = \frac{V_o}{V_i} = \frac{I_C R_L}{I_B R_i}$ $A_v = \beta \frac{R_L}{R_i}$	$A_V = \frac{V_o}{V_i} = \frac{I_E R_L}{I_B R_i}$ $A_v = \gamma \frac{R_L}{R_i}$
Power Gain	$A_p = \frac{P_o}{P_i}$ $A_p = \alpha^2 \frac{R_L}{R_i}$	$A_p = \frac{P_o}{P_i}$ $A_p = \beta^2 \frac{R_L}{R_i}$	$A_p = \frac{P_o}{P_i}$ $A_p = \gamma^2 \frac{R_L}{R_i}$
Phase difference (between output and input)	Same phase	Opposite phase	Same phase
Application	For High Frequency amplifier	For Audible frequency amplifier	For Impedance matching

Relation between α, β and γ

α, β	β, γ	α, γ
$I_E = I_B + I_C$ Divide by I_C $\frac{I_E}{I_C} = \frac{I_B}{I_C} + 1$ $\frac{1}{\alpha} = \frac{1}{\beta} + 1$ $\beta = \frac{\alpha}{1-\alpha}, \alpha = \frac{\beta}{1+\beta}$	$I_E = I_B + I_C$ Divide by I_B $\frac{I_E}{I_B} = 1 + \frac{I_C}{I_B}$ $\gamma = 1 + \beta$	$I_E = I_B + I_C$ Q $\gamma = 1 + \beta$ $\gamma = 1 + \frac{\alpha}{1-\alpha}$ $\gamma = \frac{1}{1-\alpha}$ $\alpha \cdot \gamma = \beta$

CONCEPT OF FEEDBACK

When some part of output signal is fed back to the input of amplifier then this process is known as feedback. Feedback of two types :

- **Positive feedback**

  When input and output are in the same phase then positive feedback is there. It is used in oscillators. Voltage gain after feedback $A_f = \frac{A}{1-A\beta}$

- **Negative feedback**

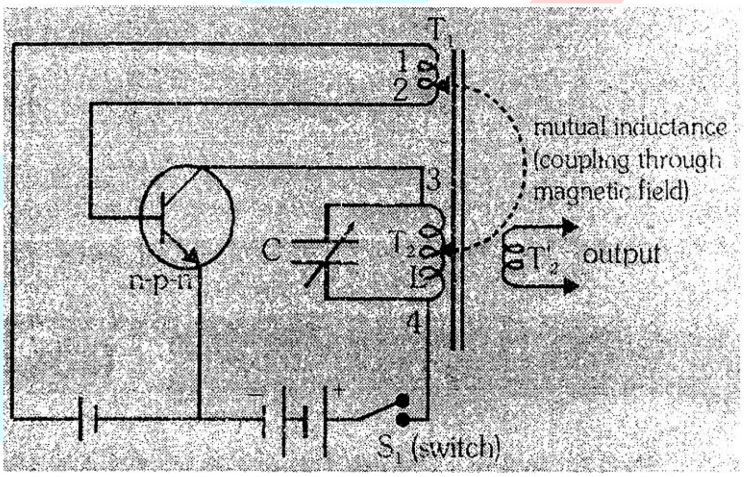
  If input and output are out of phase and some part of that is feedback to input then it is known as negative feedback. It is used to get constant gain amplifier.

  Votage gain after feedback $A_f = \frac{A}{1+A\beta}$

3. Transistor as an Oscillator

Oscillator is device which delivers ac output wave form of desired frequency without any external input wave form.

The electric oscillations are produced by. L–C circuit (i.e. tank circuit containing inductor and capacitor). These oscillations are damped one i.e. their amplitude decrease with the passage of time due to the small resistance of the inductor. In other words, the energy of the L-C oscillations decreases. If this loss of energy is compensated from outside, then undamped oscillations (of constant amplitude) can be obtained.



This can be done by using feedback arrangement and a transistor amplifier in the circuit.

Oscillating frequency of oscillator is given by $f = \frac{1}{2\pi\sqrt{LC}}$

ADVANTAGES OF SEMICONDUCTOR DEVICES OVER VACUUM TUBES

Advantage

- Semiconductor devices are very small in size as compared to the vacuum tubes. Hence the circuits using semiconductor devices are more compact.

- In vacuum tubes, current flows when the filament is heated an starts emitting electrons. So, we have to wait for some time for the operation of the circuit. One the other hand, in semiconductor devices no heating is required and the circuit begins to operate as soon as it is switched on.
- Semiconductor devices required low voltage for their operation as compared to the vacuum tube. So a lot of electrical power is saved.
- Semiconductor devices do not produce any humming noise which is large in case of vacuum tube.
- Semiconductor devices have longer life than the vacuum tube. Vacuum tube gets damaged when its filament is burnt.
- Semiconductor devices are shock proof.
- The cost of production of semiconductor-devices is very small as compared to the vacuum tubes.
- Semiconductor devices can be easily transported as compared to vacuum tube.

Disadvantages

- Semiconductor devices are heat sensitive. They get damaged due to overheating and high voltages. So they have to be housed in a controlled temperature room.
- The noise level in semiconductor devices in very high.
- Semiconductor devices have poor response in high frequency range.

INTEGRATED CIRCUIT (IC)

An integrated circuit (ICs), sometimes called a chip or microchip, is semiconductor wafer on which thousands or millions of tiny resistors, capacitors and transistors are fabricated. An IC can function as an amplifier, oscillator, timer, counter, computer memory, or microprocessor. ICs can be made very compact, having up to several billion transistors and other electronic components in an area the size of a fingernail. The most widely used technology is the Monolithic Integrated Circuit. The word monolithic is a combination of two Greek words, monos means single and lithos means stone. This, in effect means that the entire circuit is formed on a single silicon crystal (or chip). The chip dimensions are as small 1 mm × 1 mm or it could even be smaller.

Depending upon the level of integration (i.e., the number of circuit components or logic gates), the ICs are termed as Small integration, SSI (logic gates < 10); Medium Scale Integration, MSI (logic gates< 100); Large Scale Integration, LSI (logic gates < 1000) and very Large Scale integration, VLSI (logic gates > 1000). The technology of fabrication is very involved but large scale industrial production has made them very inexpensive.

GOLDEN KEY POINTS

- In transistor, reverse bias is high as compared to forward bias so that the charge carriers move from emitter to base easily enter in collector region so base current is very less.
- CE configuration is widely used because it have large voltage and power gain as compared to other amplifiers.
- CC is used for impdence matching for connecting two transistors in cascade.

ILLUSTRATIONS

Illustrations 14

Explain following these questions :

(i) A transistor is a current operated device. Explain why?

(ii) In a transistor, reverse bias is quite high as compared to the forward bias. Why?

(iii) A transistor is a temperature sensitive device. Explain.

(iv) The use of a transistor in common-emitter configuration is preferred over the common-base configuration. Explain why?

(v) Why we prefer transistor over the vacuum tubes in the portable radio receivers?

(vi) Why a transistor cannot be used as a rectifier?

(vii) Why is a transistor so called?

(viii) The base region of a transistor is lightly doped. Explain why?

or

In a transistor, the base is lightly doped. Explain why?

(ix) Explain why the emitter is forward biased and the collector is reverse biased in a transistor?

Solution

(i) The action of a transistor is controlled by the charge carriers (electrons or holes).That is why a transistor is a current operated device.

(ii) In a transistor, charge carriers (electrons or holes) move from emitter to collector through the base. The reverse bias on collector is made quite high so that it may exert a large attractive force on the charge carriers to enter the collector region. These moving carriers in the collector constitute a collector current.

(iii) In a transistor, conduction is due to the movement of current carriers electrons and holes. When temperature of the transistor increases, many covalent bonds may break up resulting in the formation of more electron, and holes. Thus, the current will increase in the transistor. This current gives rise to the production of more heat energy. The excess heat causes complete breakdown of the transistor.

(iv) The current gain and voltage gain in the common-emitter configuration is more one. So maximum power gain in common emitter configuration.

(v) This is because of two reasons :

(a) Transistor is compact and small in size than the vacuum tube.

(b) Transistor can operate even at low voltage which can be supplied with two or three dry cells.

(vi) If transistor is to be used as a rectifier then either emitter-base or base-collector has to used as diode. For equated working of the said set of diodes, the number density of charge carriers in emitter and base or base and collector must be approximately same. As base is lightly doped and comparatively thin, so transistor cannot work as a rectifier.

(vii) The word Transistor can be treated as short form of two words 'transfer resistor'. In a transistor, a signal is introduced in the low resistance circuit and output is taken across the high resistance circuit. Thus, a transistor helps to transfer the current from low resistance part to the high resistance part.

(viii) In a transistor, the majority carriers (holes or electrons) from emitter region move towards the collector region through base. If base is made thick and highly doped, then majority of carriers from emitter will combine with the carriers in the base and only small number of carriers will reach the collector. Thus the output or collector current will be considerably small. To get large output or collector current, base is made thin and lightly doped so that only few electron-hole combination may take place in the base region.

(ix) In a transistor, the charge carriers move from emitter to collector. The emitter sends the charge carriers and collector collects them. This can happen only if emitter is forward biased and the collector is reverse biased so that it may attract the carriers.

Illustration 15

In a transistor, the value of β is 50. Calculate the value of α.

Solution

$$\beta = \frac{\alpha}{1-\alpha} \quad \Rightarrow \quad 50 = \frac{\alpha}{1-\alpha} \quad \Rightarrow \quad 50 - 50\alpha = \alpha \quad \Rightarrow \quad \alpha = \frac{50}{51} = 0.98$$

Illustrations 16

Calculate the emitter current for which $I_B = 20\ \mu A$, $\beta = 100$

Solution

$I_C = \beta\ I_B = 100 \times 20 \times 10^{-6} = 2000\ \mu A$

$I_E = \beta\ I_B + I_C = 20 + 2000 = 2020\ \mu A = 2.02 \times 10^{-3}\ A = 2.02\ mA$

Illustrations 17

The base current is 100 μA and collector current is 3 mA.

(a) Calculate the values of β, I_E and α.

(b) A charge of 20 μA in the base current produces a change of 0.5 mA in the collector current. Calculate $\beta_{a.c.}$.

Solution

(a) $$\beta = \frac{I_C}{I_B} = \frac{3\times10^{-3}}{100\times10^{-6}} = 30$$

$$\alpha = \frac{\beta}{1+\beta} = \frac{30}{1+30} = \frac{30}{31} = 0.97 \text{ and } I_E = \frac{I_C}{\alpha} = \frac{3\times31}{30} = 3.1\,\text{mA}$$

(b) $\Delta I_B = 20\ \mu A = 0.02$ mA,

$\Delta I_C = 0.5$ mA

$$\therefore \quad \beta_{ac} = \frac{\Delta I_C}{\Delta I_B} = \frac{0.5}{0.02} = 25$$

Illustrations 18

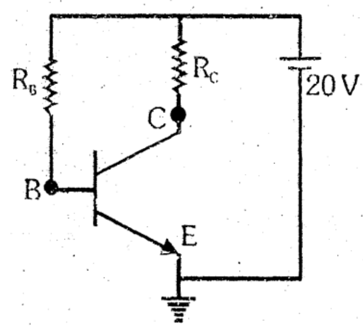
In a transistor connected in common emitter mode $R_0 = 4\ k\Omega$, $R_i = 1\ k\Omega$, $I_C = 1$ mA and $I_B = 20\ \mu A$. Find the voltage gain.

Solution

$$\text{Voltage gain } A_V = \beta\left(\frac{R_0}{R_i}\right) = \left(\frac{I_C}{I_B}\right)\left(\frac{R_0}{R_i}\right) = \left(\frac{1\times10^{-3}}{20\times10^{-6}}\right)\left(\frac{4}{1}\right) = 200$$

Illustrations 19

For given CE biasing circuit, if voltage across collector-emitter is 12 V and current gain is 100 and base current is 0.04 mA then determine the value of collector resistance R_C.



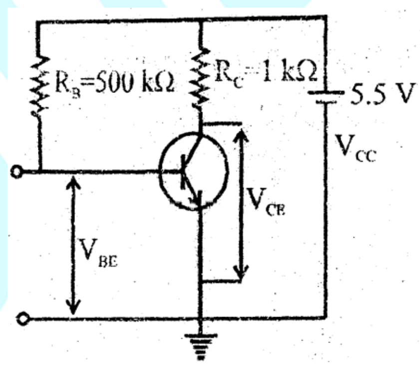
Solution

Q $\quad V_{CE} = V_{CC} - I_C \times R_C$

$$\therefore \quad R_C = \frac{V_{CC} - V_{CE}}{I_C} = \frac{V_{CC} - V_{CE}}{\beta I_B} = \frac{20-12}{100\times0.04\times10^{-3}} = 2k\Omega$$

Illustrations 20

For given transistor circuit; the base current is 10 μA and the collector current is 5.2 mA. Can this transistor circuit be used as a voltage amplifier. Your answer must be supported with proper calculations: **[AIPMT (Mains) 2008]**



Solution

No, it can't be used as an amplifier.

Explanation :

$V_{BE} = 5.5 - I_BR_B = 5.5 \times 10 \times 10^{-6} \times 500 \times 10^3 = 0.5$ V

$V_{CE} = 5.5 - I_CR_C = 5.5 - 5.2 \times 10^{-3} \times 1 \times 10^3 = 0.3$ V

It can't be used as an amplifier as both the emitter-base function and collector function are forward bias.

Illustrations 21

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

Solution

Q $A = A_1 \times A_2 = 10 \times 20 = 200$

∴ Output signal = A × input signal = 200 × 0.01 = 2V

BEGINNER'S BOX-4

1. For a common emitter amplifier, current gain = 50. The emitter current is 6.6 mA calculate the collector and base current. Also calculate current gain, when emitter is working as common base amplifier.

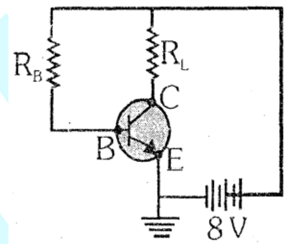
2. Transistor with $\beta = 75$ is connected to common-base configuration. What will be the maximum collector current for an emitter current of 5 rnA ?

3. In npn transistor circuit, the collector current is 10 mA. If 95% of the electrons emitted reach the collector, what is the base current ?

4. In an NPN transistor 10^{10} electrons enter the emitter in 10^{-6} s and 2% electrons recombine with holes in base, then current gain a and p are :

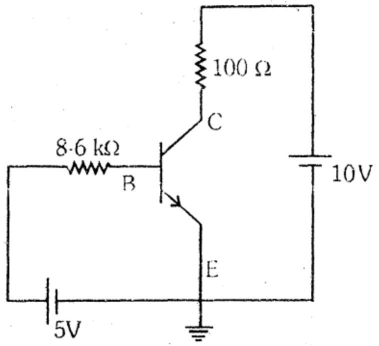
5. For a CE amplifier, current gain is 69. If the emitter current is 7 mA then calculate the base current and collector current. **[AIPMT (Mains) 2008]**

6. An n-p-n transistor in a common emitter mode is used as a simple voltage amplifier with a collector connected to load resistance R_L and to the base through a resistance R_B. The collector-emitter voltage $V_{CE} = 4$ V, the base-emitter voltage $V_{BE} = 0.6$ V. Current through collector is 4 mA and the current amplification factor $\beta = 100$. Calculate the values of R_L and R_B.



7. A common emitter amplifier has a voltage gain of 50, an input impedance of 200 Ω and an output impedance of 4000 Ω. Calculate the power gain of the amplifier.

8. A silicon transistor amplifier ckt. is given here. If $\beta = 100$ then determine



(a) Base current I_B (b) Collector current I_C (c) V_{CE}

Take the voltage drop between base and emitter as 0.7 V.

ANSWERS

BEGINNER'S BOX-1

1. Value of R should be increased because with the increase in temperature of semiconductor as circuit resistance decreases and current tends to increase.

2. $n_e = 5 \times 10^9\ m^{-3}$

3. $n_e = 5 \times 10^{22}\ m^{-3}$, $n_h = 4.5 \times 10^9\ m^{-3}$

4. $\frac{n_e}{n_h} = \frac{6}{5}$

BEGINNER'S BOX-2

1. (a) 0.2 eV (b) 0.1 eV (c) 0.3 eV

2. 200 Ω

3. $I_1 = 0$ and $I = I_2 = 5$ mA

4. 0.25 A

5. (a) $V_0 = 11.7$ V, I = 2.34 mA
(b) $V_0 = 11.3$ V, I = 2.26 mA

BEGINNER'S BOX-3

1. (1)

2. $I_S = 30$ mA, $I_L = 6$ mA, $I_Z = 24$ mA, $P_Z = 0.144$ W

3. 40 mA

4. 8671.33 A

BEGINNER'S BOX-4

1. $I_C = 6.47$, $I_B = 0.13$ mA, $\alpha = 0.98$

2. 4.93 mA

3. 0.53 mA

4. $\alpha = 0.98$, $\beta = 49$

5. $I_B = 0.1$ mA; $I_C = 6.9$ mA

6. 1 kΩ, 185 kΩ

7. 1250

8. (i) 0.5 mA, (ii) 50 mA, (iii) 5V

Logic Gates

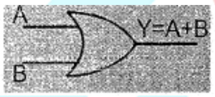
INTRODUCTION

- A logic gate is a digital circuit which is based on certain logical relationship between the input and the output voltages of the circuit.
- The logic gates are built using the semiconductor diodes and transistors.
- Each logic gate is represented by its characteristic symbol.
- The operation of a logic gate is indicated in a table, known as truth table. This table contains all possible combinations of inputs and the corresponding outputs.
- A logic gate is also represented by a Boolean algebraic expression. Boolean algebra is a method of writing logical equations showing how an output depends upon the combination of inputs. Boolean algebra was invented by George Boole.

BASIC LOGIC GATES

There are three basic logic gates. They are (1) OR gate (2) AND gate, and (3) NOT gate.

- **The OR gate** : The output of an OR gate attains the state 1 if one or more inputs attain the state1.

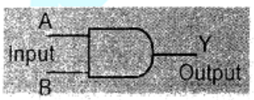
  Logic symbol of OR gate 

  The **Boolean expression** of OR gate is Y = A + B, read as Y equals A ORing B.

  Truth table of a two-input OR gate

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

- **The AND gate** : The output of an AND gate attains the state 1 if and only if all the inputs are in state 1.

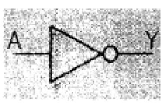
  Logic symbol of AND gate 

  The **Boolean expression** of AND gate is Y = A.B.
  It read as Y equals A ANDing B.

  Truth table of a two-input AND gate

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

- **The NOT gate** : The output of a NOT gate attains the state 1 if and only if the imput does not attain state 1.

  Logic symbol of NOT gate 

  The **Boolean expression is** $Y = \overline{A}$, read as Y equals NOT A.

Truth table of NOT gate

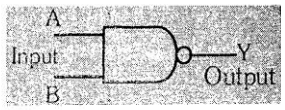
A	B
0	1
1	0

COMBINATION OF GATES

The three basis gates (OR, AND and NOT) when connected in various combinations give us logic gates such as NAND, NOR gates, which are the universal building blocks of digital circuits.

- **The NAND gate** :

  Logic symbol of NAND gate



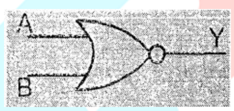
  The **Boolean expression** of NAND gate is $Y = \overline{A.B}$

  Truth table of a NAND gate

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

- **The NOR gate** :

  Logic symbol of NOR gate



  The **Boolean expression** of NOR gate is $Y = \overline{A + B}$

  Truth table of a NOR gate

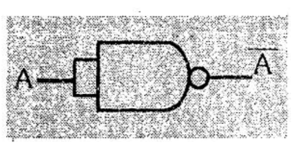
True table of a single input NAND gate

A	B = (A)	Y
0	0	1
1	1	0

UNIVERSE GATE

The NAND or NOR gate is the universal building block of all digital circuits. Repeated use of NAND gates (or NOR gates) gives other gates. Therefore, any digital system can be achieved entirely from NAND or NOR gates. We shall show how the repeated use of NAND (and NOR) gates will gives us different gates.

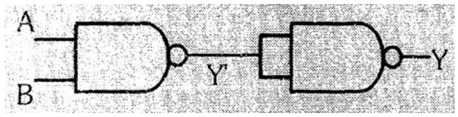
- **The NOT gate from a NAND gate :** When all the inputs of a NAND gate are connected together, as shown in the figure, we obtain a NOT gate.



True table of a single input NAND gate

A	B = (A)	Y
0	0	1
1	1	0

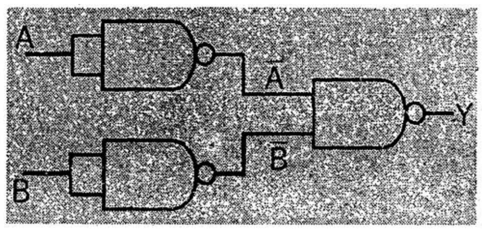
- **The AND gate from a NAND gate :** If a NAND gate is followed by a NOT gate (i.e. a single input NAND gate), the resulting circuit is an AND gate as shown in figure and truth table given show how and AND gate has been obtained from NAND gates.



True table

A	B	Y′	Y
0	0	1	0
0	1	1	0
1	0	1	0
1	1	0	1

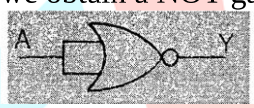
- **The OR gate from NANB gates** : If we invert the inputs A and B and then apply them to the NAND gate, the resulting circuit is an OR gate.



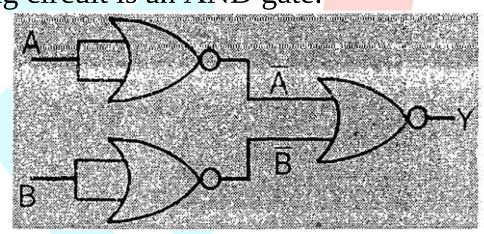
True table

A	B	$\bar{A}$	$\bar{B}$	Y
0	0	1	1	0
0	1	1	0	1
1	0	0	1	1
1	1	0	0	1

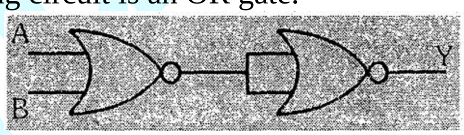
- **The NOT gate from NOR gates :** When all the inputs of a NOR gate are connected together as shown in the figure, we obtain a NOT gate



- **The AND gate from NOR gates** : If we invert the inputs A and B and then apply them to the NOR gate, the resulting circuit is an AND gate.



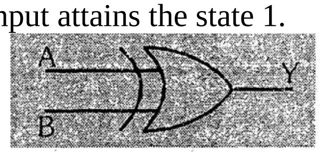
- **The OR gate from NOR gate :** If a NOR gate is followed by a single input NOR gate (NOT gate), the resulting circuit is an OR gate.



XOR and XNOR gates

- **The Exclusive-OR gate (XOR gate) :** The output of a two-input XOR gate attains the state 1 if one and only one input attains the state 1.

Logic symbol of XOR gate

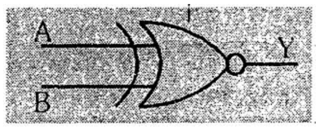


The Boolean expression of XOR gate is $Y = A\bar{B} + \bar{A}.B$ or $Y = A \oplus B$

Truth table of a XOR gate

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

- **Exclusive-NOR gate (XNOR gate) :** The output is in state 1 when its both imputs are the same that is both 0 or both 1.

Logic symbol of XNOR gate 

The Boolean expression of XNOR gate is $Y = A.B + \bar{A}.\bar{B}$ or $Y = \overline{A \oplus B}$ or A e B

Truth table of a XNOR gate

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

Laws of Boolean Algebra

Basics OR, AND and NOT operations are given below :

Truth Table

A	B	$\bar{A}$	$\bar{B}$	Y
0	0	1	1	0
1	0	0	1	1
0	1	1	0	1
1	1	0	0	1

Boolean algebra obeys commutative, associative and distributive laws as given below :

- **Commutative Laws :**

  A + B = B + A

  A.B = B.A

- **Associative laws :**

  A + (B + C) = (A + B) + C

  A.(B.C) = (A.B).C

- **Distributive laws :**

  A.(B + C) = A.B + A.C

- **Some other useful identities**

  (i) A + AB = A   **(ii)** A.(A + B) = A

  (iii) $A + (\bar{A}.B) = A + B$ **(iv)** $A.(\bar{A} + B) = A.B$

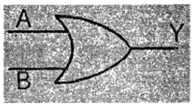
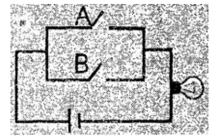
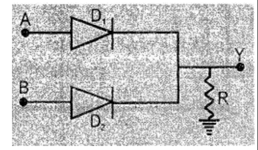
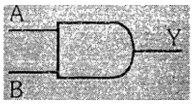
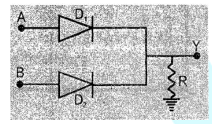
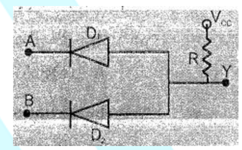
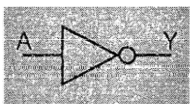
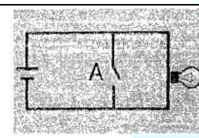
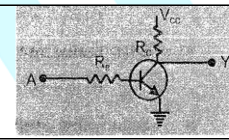
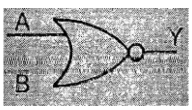
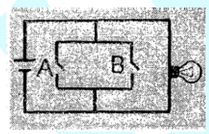
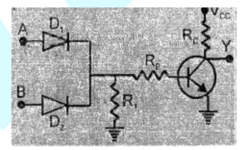
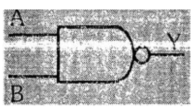
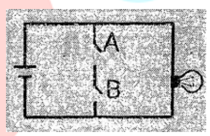
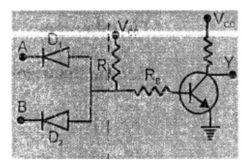
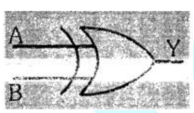
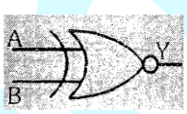
  (v) $A + (B.C) = (A + B).(A + C)$ **(vi)** $(\bar{A} + B).(A + C) = \bar{A}.C + B.A + B.C$ **sssss**

- **De-Morgan's theorem :**

  First theorem : $\overline{A + B} = \bar{A}.\bar{B}$

  Second theorem : $\overline{A.B} = \bar{A} + \bar{B}$

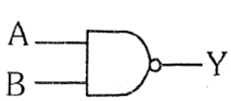
Names	Symbol	Boolean Expression	Truth Table	Electrical Analogue	Circuit diagram (Practical realization)

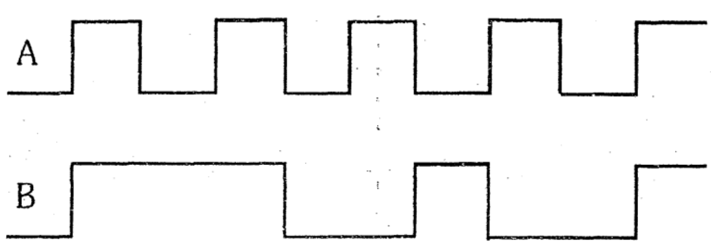
OR		$Y = A + B$	A B Y 0 0 0 0 1 1 1 0 1 1 1 1		
AND		$Y = A.B$	A B Y 0 0 0 0 1 0 1 0 0 1 1 1		
NOT Or Inverter		$Y = \overline{A}$	A B 0 1 1 0		
NOR (OR + NOT)		$Y = \overline{A + B}$	A B Y 0 0 1 0 1 0 1 0 0 1 1 0		
NAND (AND + NOT)		$Y = \overline{A.B}$	A B Y 0 0 1 0 1 1 1 0 1 1 1 0		
XOR (Exclusive OR)		$Y = A \oplus B$ or $Y = \overline{A}.B + A\overline{B}$	A B Y 0 0 0 0 1 1 1 0 1 1 1 0		
XNOR (Exclusive NOR)		Y = A e B or $Y = A.B + \overline{A}.\overline{B}$ or $Y = \overline{A \oplus B}$	A B Y 0 0 1 0 1 0 1 0 0 1 1 1		

ILLUSTRATIONS

Illustrations 1

In the figures below, circuit symbol of a logic gate and two input waveform 'A' and 'B' are shown.





(a) Name the logic gate & Write its Boolean expression.

(b) Write its truth table.

(c) Give the output wave from.

Solution

(a) NAND gate : $Y = \overline{A.B}$

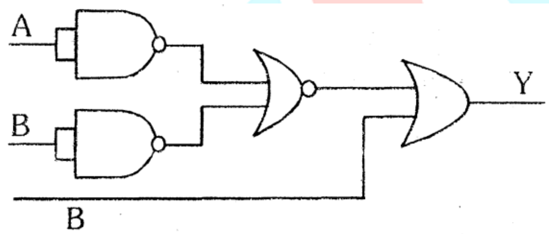
(b) Truth table

Input A	Input B	Output Y
0	0	1
0	1	1
1	0	1
1	1	0

(c) Output waveform

Illustration 2

Write down output Y in terms of inputs A and B.



Solution

$$Y = \overline{\overline{A} + \overline{B}} + B = \overline{\overline{A.B}} + B = A.B + B = (A+1)B = B$$

Illustration 3

By using Boolean Algebra prove that $\overline{A}B + A\overline{B} + AB = A + B$

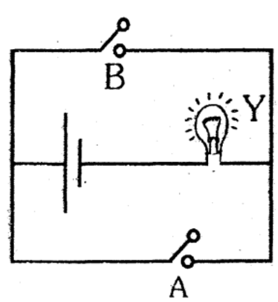
Solution

LHS $= \overline{A}B + A\overline{B} + AB = \overline{A}B + A\overline{B} + AB + AB$

$= A(B+\overline{B}) + B(\overline{A}+A) = A.1 + B.1 = A + B = RHS$

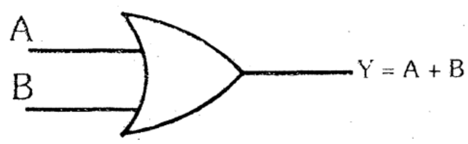
Illustration 4

Given electrical circuit is equivalent to which logic gat, also draw its symbol and truth table.



Solution

OR gate



A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Illustration 5

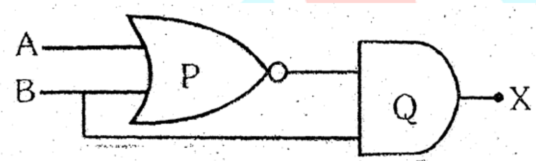
Write the truth table for the logical function D = (A AND B) OR B

Solution

A	B	X = A AND B	D = X OR B
0	0	0	0
0	1	0	1
1	0	0	0
1	1	1	1

Illustration 6

Identify the logic gates P and Q in given circuit. Also write down relation in A, B and X.

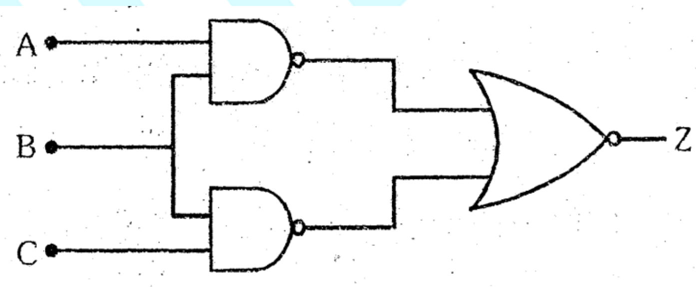


Solution

P is NOR gate and Q is AND, $X = (\overline{A+B}).B = (\bar{A}.\bar{B}).B = \bar{A}.(\bar{B}.B) = \bar{A}.0 = 0$

Illustration 7

Write down the equivalent function performed by given circuit. Explain your answer.

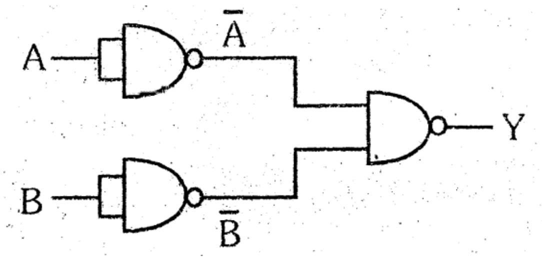


Solution

AND gate, $A = \overline{\overline{A\cdot B}+\overline{B\cdot C}} = \overline{\overline{AB\cdot BC}} = \overline{\overline{ABC}} = ABC$ (Q $\bar{X}+\bar{Y} = \overline{X\cdot Y}$)

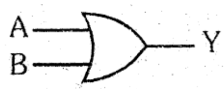
Illustration 8

If inputs A and B are inverted before entering into NAND gate as shown in diagram. Write down the logical symbol and truth table by using $A, B, \bar{A}, \bar{B}, Y$. **[AIPMT 2005, 2007]**



Solution

$Y = \overline{\bar{A}\cdot\bar{B}} = A + B$ so logical symbol



Truth Table

A	B	$\bar{A}$	$\bar{B}$	Y
0	0	1	1	0
1	0	0	1	1
0	1	1	0	1
1	1	0	0	1