Semi-Conductor and Electronic Devices

DISCLAIMER

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Introduction

The word "electronics' is taken from electron plus dynamics which means it is the study of behaviour of an electron under different conditions when externally filled applied.

This field of science deals with electronic devices and their application. In electronic device 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.

KEY POINTS

- Electronics
- Semiconductor
- Rectifier
- Amplifier
- Oscillator

Application of Electronics:

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

- Important application of electronics is computer which is used in every field.
- All electronics equipment require D.C. supply for operation (not A.C. supply)

Concept Reminder

In a vacuum tube, the electrons are provided by a heated cathode and the controlled flow of these electrons in vacuum is obtained by changing the voltage between its electrodes.

Energy Levels And Energy Bands In the Solids

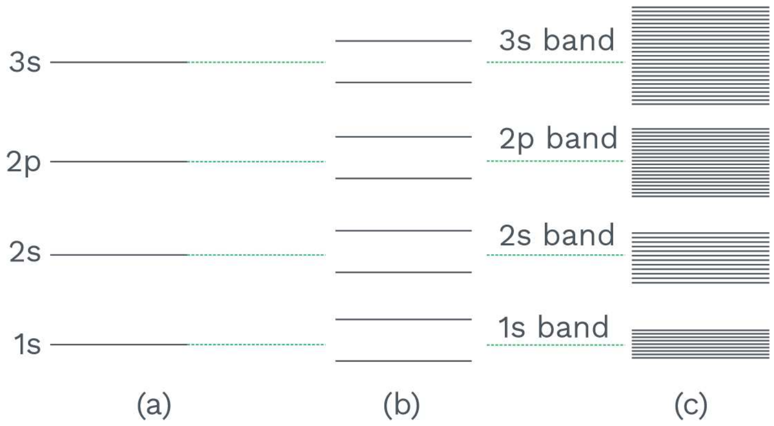
The electrons of an isolated atom are constraint to be in well defined energy levels. The limiting no. of electrons which can be present in any level is given by the Pauli exclusion principle. The electrons that are present in outermost energy level are known as valence electrons. For example, the electronic configuration of sodium

(Z = 11) is $1s^2\ 2s^2\ 2p^6\ 3s^1$, here the electron belongs to the 3s level is the valence electron. Most of solids including metals with which we known about occur in crystalline form. We already know that a crystal is a regular periodic arrangement of atoms separated from each other by very small distance known as lattice constant. The value of the lattice constant is different for non-identical crystalline solids, however it is of the order of linear dimension of atoms {~Å}. Obviously for such a small separation between various neighbouring atoms, electrons in an atom can never be subjected to Coulombic force of the nucleus of this atom but also by Coulombic forces because of nuclei and electrons of the neighbouring atoms. In fact, it is the interaction which gives the bonding between various atoms which further leads to the formation of the crystals. When the atoms are interacting (such as in crystal) then energy level scheme for individual atoms as shown in diagram (a) does not hold good. The interaction between atoms markedly affect the energy levels of electron, as a result there occurs a splitting of energy levels belonging to several atoms.

To understand this phenomenon in more better terms, let us first assume the simplest case of 2 interacting identical atoms. Let us suppose that initially they are far apart that means the forces of interaction between them may be neglected. [If the distance between 2 atoms is much larger (~50Å) in comparison to their linear dimensions (~ 10Å) this assumption is logically correct]. In such a case we can treat there as isolated, having energy level like for the case of an isolated atom as shown in figure(b).

Concept Reminder

The Cathode Ray Tubes (CRT) used in television and computer monitors works on the principle of vacuum tubes are being replaced by Liquid Crystal Display (LCD) monitors with supporting solid state electronics.



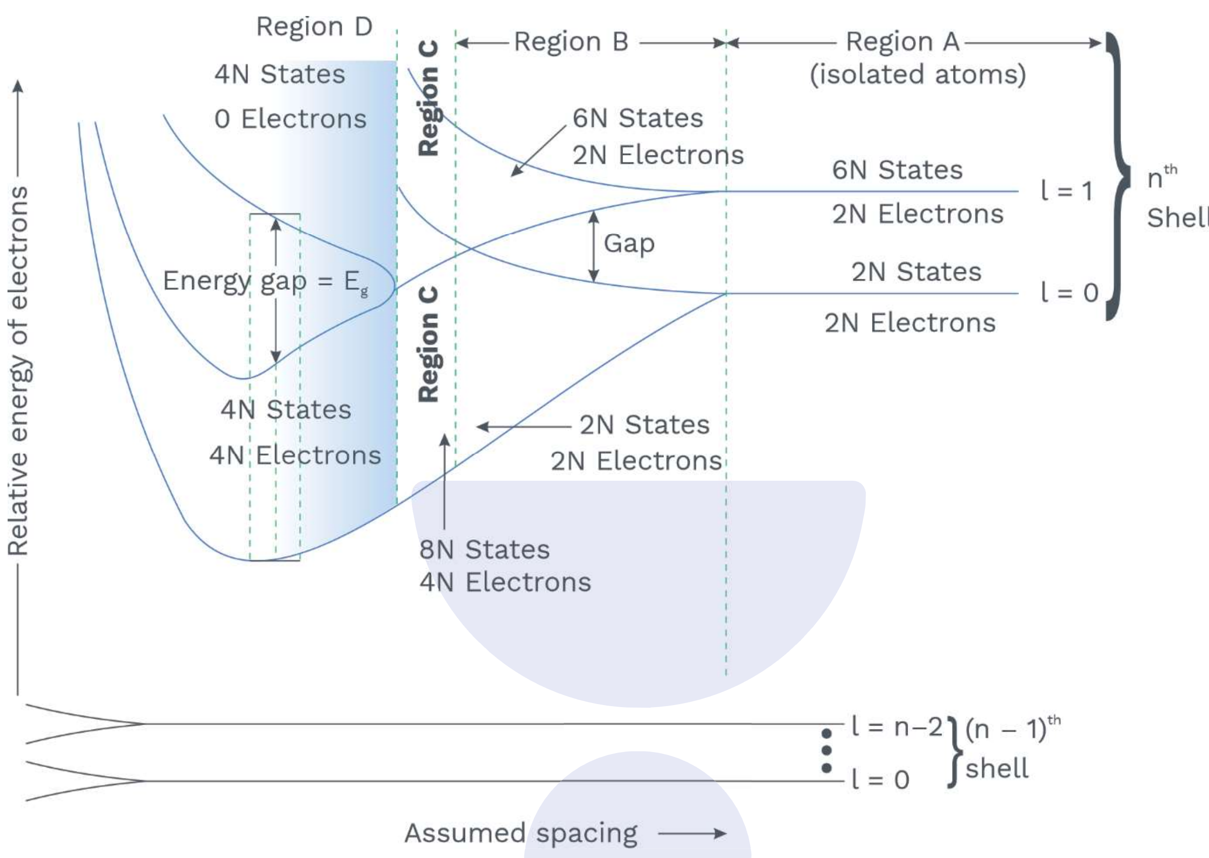
In crystals the no. of atoms, N is very large (order of 10^{22} to 10^{23} per cubic centimetre), so each energy band consists as many levels as the no. of atoms. The spacing between the various levels within a band is hence very small. For example we consider the total thickness of a band of energies as 1 eV and 10^{22} levels are to be fit in within this band, then the average spacing between adjacent levels is about 10^{-22} eV. For all practical purposes, hence, energy within band can be assumed to change continuously. The formation of bands in the solid is shown schematically in given figure (c).

KEY POINTS

- Energy bands
- Valence band
- Conduction band
- Forbidden gap

Energy Bands:

Energy theory is based on Pauli exclusion principle. In an isolated atom the valence electrons can exist only within one of the allowed orbital's each sharply defined energy is known as energy levels. But when two atoms are brought close to each other then there are changes in energy levels and they spread in form of bands.



Energy bands are of the following types:-

(1) **Valence band:** The energy band set up by a series of energy levels consisting of valence electrons is called valence band. At zero Kelvin, the electrons fills the energy levels in valence band starting from lowest one.

- **(i)** This band is always filed with electrons.
- **(ii)** This is a band having maximum energy.
- **(iii)** Electrons are not able to gain energy from an external electric field.
- **(iv)** No flow of current because of electron present in this band.
- **(v)** The maximum energy level which can be occupied by an electron in valence band at zero kelvin is known as Fermi level.

Definitions

The energy band made by a series of energy levels consisting of valence electrons is defined as valence band.

(2) Conduction band: The maximum energy level band is known as conduction band.

- **(i)** It is also known as the empty band of minimum energy.
- **(ii)** This band is partially filled by electrons.
- **(iii)** In this band an electron can gain energy from an external electric field.
- **(iv)** The electrons in this band are called the free electrons. They are able to move anywhere within this volume of the solid.
- **(v)** Current flows due to these electrons.

(3) Forbidden energy gap (ΔE_g): Energy gap between conduction band and valence band

$$\Delta E_g = (C.B.)_{min} - (V.B.)_{max}$$

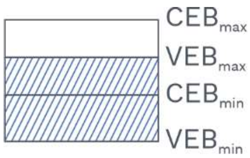
Definitions

Energy gap between conduction band and valence band.

$$\Delta E_g = (C.B.)_{min} - (V.B.)_{max}$$

Types Of Materials On The Basis Of Forbidden Energy Gap

Conductor:

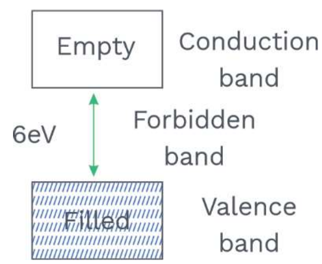


The solid substances in which forbidden energy gap is zero are known as conductors.

Insulator

The solids in which the energy band formation happens in such a manner, that valence band is fully filled while the conduction band is completely empty. Further the valence band and the conduction band are separated by a large forbidden energy gap $\Delta E_g \geq 6\,eV$.

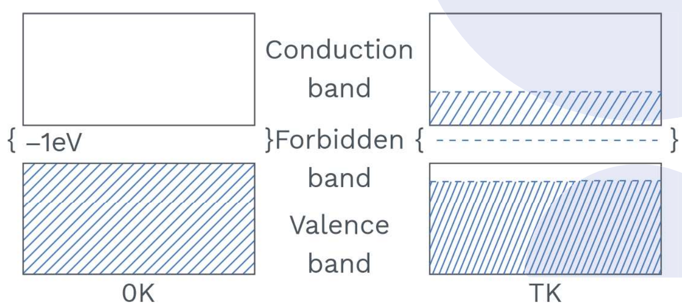
The energy band in diamond is shown in given figure. There present a forbidden band of width 6 eV between conduction band and valence band. No electron can have enough energy to cross forbidden band.



Hence, an electron needs at least 6 eV to reach the empty conduction band. Such an energy cannot be supplied by heat or electric field that are generally used in laboratories. Therefore diamond is an insulator.

Semiconductor

The solids in which the forbidden energy gap between the valence band and the conduction band is small (order of 1eV). At zero Kelvin temperature, valence band is fully filled and the conduction band is fully empty. At zero kelvin, it behaves like an insulator (electron cannot absorb infinitesimal energy because of presence of the forbidden gap just above the top of valence band).



At finite temperature, (room temperature), some electrons gain energy because of thermal motion and jump from the top of valence band to conduction band. These electrons are reason for the conduction of electricity in a semiconductor. The forbidden gap in semiconductor is very small ~ 1eV. At finite temperature, few balance electrons jump to conduction band. Then the formlessly is in middle of this gap.

Forbidden energy gap in some semiconductors is as follows:

E_g (Silicon) = 1.12 eV;

E_g (Germanium) = 0.7 eV

E_g (Indium antimonite) 0.17 eV;

E_g (Gallium arsenide) = 1.43 eV

E_g (Tellurium) = 0.33 eV.

The value of energy gap reduces slightly with increases in temperature.

Rack your Brain

The semiconductors are generally:

(1) Monovalent

(2) Divalent

(3) Trivalent

(4) Tetravalent

Concept Reminder

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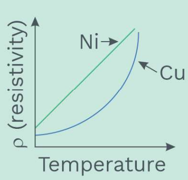
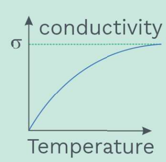
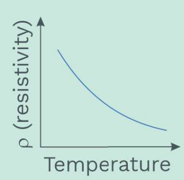
E_g (Indium antimonite) 0.17 eV;

E_g (Gallium arsenide) = 1.43 eV

E_g (Tellurium) = 0.33 eV.

Comparison Between Conductor, Insulator And Semiconductor

	Conductor	Insulator	Semiconductor
1.	Valence band is partially filled or valence band and conduction band overlap	Completely empty conduction band separated from completely filled valence band	At 0K, the conduction band is empty while valence band is full separated by small energy gap
2.	There is no forbidden energy gap	The forbidden gap is large E_g (diamond) ~ 6 eV	Separated by small energy gap E_g (Si) = 1.12 eV
3.	At room temperature, all electrons remains in the partially, filled conduction band or over lapped band	At room temperature, electrons do not get sufficient thermal energy to cross over the forbidden energy band & conduction band remains empty	At room temperature, may electrons have sufficient energy to go to conduction band.
4.	Conducts electric current. Very small resistivity ρ (ohm. meter) ρ (Cu) = 1.7×10^{-8} Ωm ρ (Ag) = 1.6×10^{-8} Ωm The conductively is high $\rho \approx 10^{7}$ to 10^{8} ohm/m (or siemen/m)	Does not conduct electric current (negligible conduction) Very large resistivily (ohm meter) ρ (glass) ~ $10^{11} - 10^{12}$ Ωm ρ (diamond) ~ 10^{14} Ωm Very low conductivity ρ ~ 10^{-10} to 10^{-14} Ωm Very low conductivity ρ ~ 10^{-10} to 10^{-15} ohm/m (or siemen/m)	May conduct electric current but conduction is small. Medium Resistivity and medium conductivity ρ (Si) = 2100 Ωm ρ (Ge) = 0.47 Ωm ρ (Ge) ~ 2.13 ρ (Si) ~ 4.7×10^{-4} (ohm/m).
5.	Only electrons are the current carriers Number of free electrons (in Cu) ~ 10^{28} per m^3	No current carriers (the electric conduction is almost zero for all practical purposes, see σ mentioned before)	Both electrons and holes contribute to current conduction. Number of free electrons (at room temperature) is In Ge ~ 10^{19} per m^3 In Si ~ 10^{18} per m^{3h}
6.	Conductivity decreases with temperature.  The temperature coefficient of resistance of a conductor is positive.	Conductivity negligibly small however increases slightly at very high temperatures.  The temperature coefficient of resistance of an insulator is negative.	Conductivity increases with temperature (the resistivity/ resistance decreases with temperature).  The temperature coefficient of resistance of a semiconductor is negative.

Comment: Band Structure And Optical Properties

The optical properties of a solid are closely related with their energy band structure. The photons of visible light have energies between 1eV and 3 eV. In the case of insulators like mica, diamond, the energy gap is large, then visible light from valence band cannot go to conduction band.

Then such solids are transparent to visible light. In case of semiconductors, since band gap is ~ 1 eV, the visible light is readily absorbed and these are usually opaque, to visible light. Infrared photons have energies less than 1eV and therefore infrared light is not absorbed by Si or Ge.

The metals are usually opaque, because electrons in the partially filled band can readily absorbs visible light photon without leaving the valence band.

The ultraviolet photons energies are large and if they are more than the E_g of insulators, then those insulators will absorb UV radiation. Thus some special glasses are although transparent for visible light but are opaque for UV light.

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

- They have negative temperature coefficient (α). It means with increase in temperature resistance decreases.
- Crystalline structure with covalent bonding [Face centered cubic (FCC)]
- Their conduction properties may change by adding small impurities.
- Position in periodic table → IV group (Generally)
- Forbidden energy gap (0.1 eV to 3 eV)
- They have two charge carriers: electrons and holes.

Concept Reminder

After 1990, a few semiconductor devices using organic semiconductors and semiconducting polymers have been developed signalling the birth of a futuristic technology of polymer electronics and molecular-electronics.

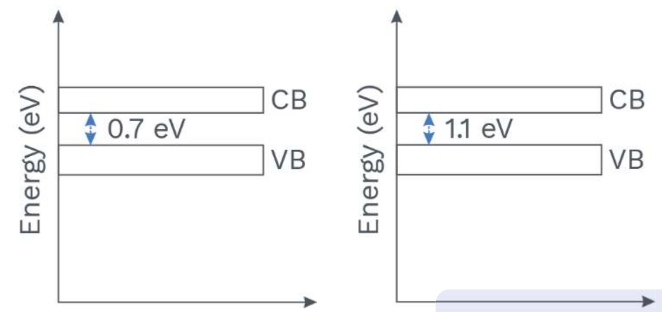
Rack your Brain

A pure semiconductor has:

(1) An infinite resistance at 0°C
(2) A finite resistance which does not depend upon temperature
(3) A finite resistance which increases with temperature
(4) A finite resistance which decreases with temperature

- There are many semiconductors but some of them have practical application in electronics like diodes, transistor and integrated circuits.

Ge^{32} : 2, 8, 18, 4 Si^{14} : 2, 8, 4

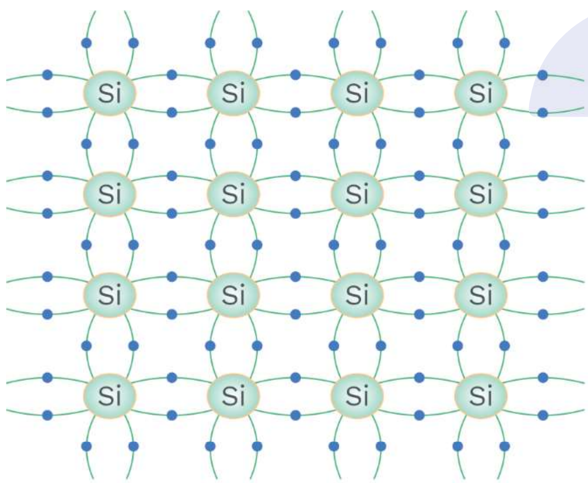


Concept Reminder

Semiconductors have negative temperature coefficient (α) i.e., its resistance decreases as temperature increases.

Effect Of Temperature

- **At absolute zero temperature**
  At 0K temperature covalent bonds are very strong and there are no free electrons thus semiconductor behaves as perfect insulator.



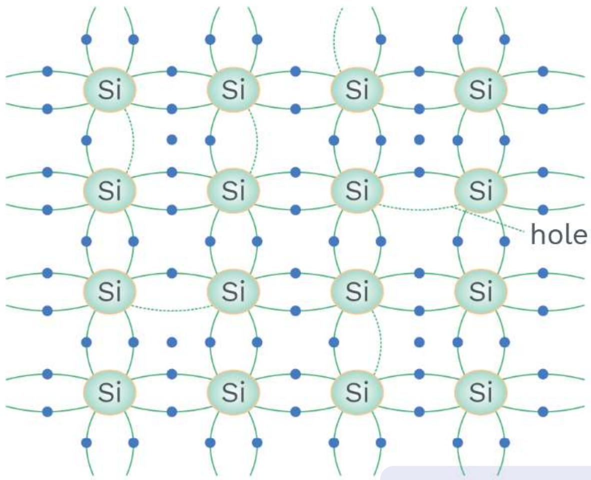
at 0 K

valence band fully filled   conduction band fully empty

Concept Reminder

At zero kelvin, intrinsic semiconductor behaves like an insulator. When temperature increases covalent bands get break and semiconductor starts to behave like poor conductor.

- **Above absolute temperature**
  When temperature increases some covalent bonds are broken and few valence electrons jump to conduction band and hence it behaves as poor conductor.



at higher temperature

valence band partially empty

conduction band partially filled

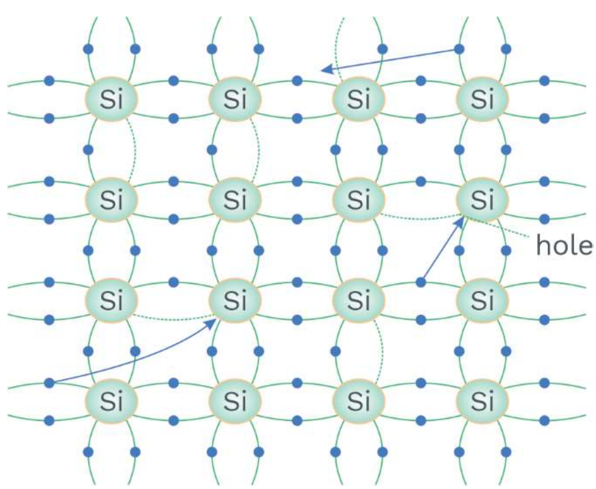
> **Concept Reminder**
>
> If the lowest level in the conduction band happens to be lower than the highest level of the valence band, the electrons from the valence band can easily move into the conduction band.

Concept Of "Holes" in Semiconductors

Due to external energy (temperature or radiation) when electron jump from valence band to conduction band (i.e. bonded electrons gets 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.

> **Concept Reminder**
>
> One can have a metal either when the conduction band is partially filled and the valanced band is partially empty or when the conduction and valance bands overlap.



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.

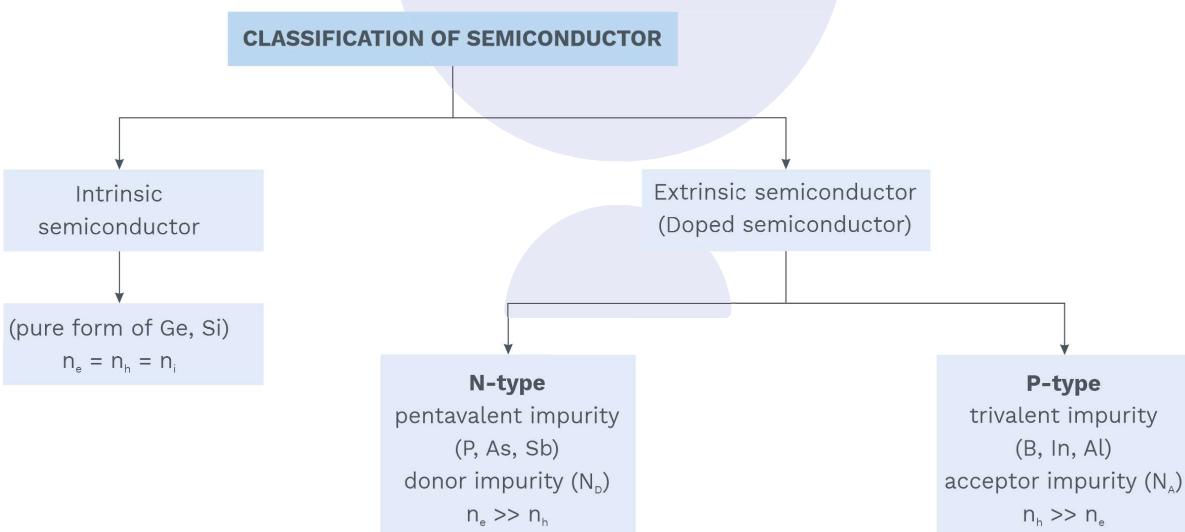
Hole behaves as virtual charge, although there is no physical charge on it.

Concept Reminder

When E_g > 3 eV, there are no electrons in the conduction band, and therefore no electrical conduction is possible. This is a case of insulators.

Effect Of Impurity In A Semiconductor

The addition of desirable impurity atoms to pure semiconductor to increase their conductivity is known as dopping.



Intrinsic Semiconductor

Structure: Most common case of semiconductors is that of Ge and Si whose lattice structures are called the diamond-like structures. In this structure every atom is surrounded by four nearest neighbours. Si and Ge both have four valence electrons. In its crystalline structure, each Si or Ge atom tends to share one of its 4 valence electrons with each of its four closest neighbour atoms. These shared electrons form covalent bond (also called valence bond). The two shared electrons move back and forward between the associated atoms holding them together strongly. Figure shows the schematic two-dimensional representation of Si and Ge structure.

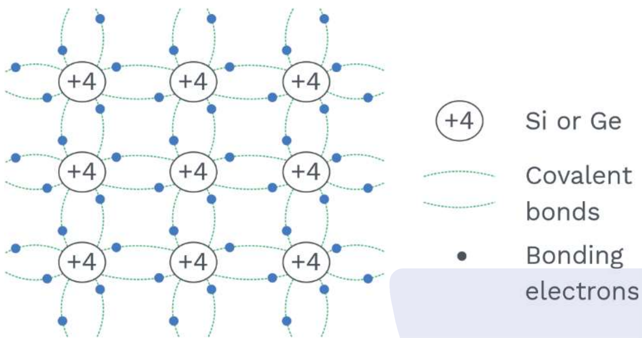
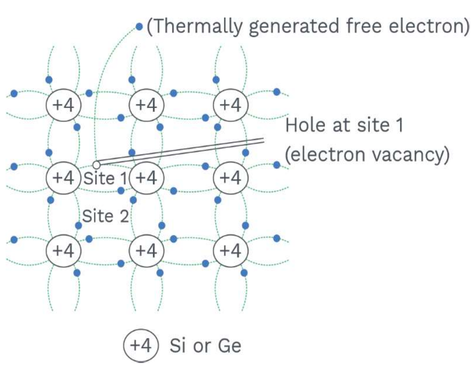


Figure: Schematic 2-dimensional representation of Si or Ge structure showing covalent bonds at low temperature (all bonds are intact). +4 symbol tells about inner cores of Si or Ge.

This is an ideal picture in which no bonds are broken and all bonds are intact. Such a situation exists at low temperature.

Conduction process in semiconductors

As the temperature of these semiconductor increases some of these bonded electrons gain thermal energy and become free. These free electrons and vacancy in bond contribute to conduction of electricity in semiconductors. The thermal energy is able to ionize only very few atoms in crystalline lattice and max a vacancy in bond as shown in given figure (a).



Concept Reminder

In case of semiconductor $E_g < 3eV$. Because of the small band gap, at room temperature some electrons from valence band can acquire enough energy to cross the energy gap and enter the conduction band.

KEY POINTS

- Intrinsic semiconductor
- Extrinsic semiconductor
- Holes

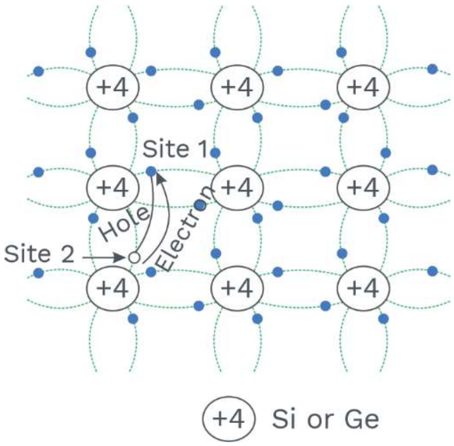


Figure: (a) Schematic model of generation of hole at site one and conduction electron due to thermal energy at medium temperatures. (b) Simplified representation of the possible thermal motion of a hole.

An electron from the lower left hand covalent bond (site 2) goes to the earlier hole site 1,

The leaving a hole at its site indicating a apparent movement of the hole from site 1 to site 2.

The surroundings from which the free electron with charge (–q) has come out leaves a gap or vacancy having an effective charge (+q). This vacancy having an effective positive electronic charge is known as 'hole'. The hole appears to behave as free particle with effective positive charge.

In intrinsic (or pure) semiconductors, the number of free electrons per unit volume (n_e) is same as the number of holes per unit volume (n_h) and it is also equal to the number of intrinsic charge carriers per unit volume (n_i). Here (n_i) is also called intrinsic carrier concentration.

Mathematically, we have the relation $\boxed{n_e = n_h = n_i}$ for intrinsic semiconductors.

Semiconductors have the unique property that apart from electrons, the holes also participate in conduction. Assume, there is a hole at site 1 as shown in figure (b). The movement of holes

Concept Reminder

For intrinsic semiconductor

$\boxed{n_e = n_h = n_i}$ and

the total current I is the sum of electron current I_e and the hole current I_h

$\boxed{I = I_e + I_h}$

Rack your Brain

In semiconductors, which of the following relations is correct at thermal equilibrium?

(1) $n_i = n_e = n_h$

(2) $n_i^2 = n_e n_h$

(3) $n_i = \frac{n_e}{n_h}$

(4) $n_i = n_e + n_h$

is shown through figure (b). An electron from a covalent bond at site 2 may jump to the empty site 1 (hole). Due to such jump, the hole is at site 2 and the site 1 has now an electron. In other words, this is same as if the hole has moved from site 1 to site 2. It is very important to remember here that the electrons originally set free in figure (a) is not involved in this process of motion of hole. Rather the free electron moves independently as conduction electron which produces electron current I_e, if some external electric field is applied. Also remember that the motion of hole is only a convenient way of describing the actual motion of bound electrons. In the action of an electric field, these holes move towards negative potential and this creates the hole current I_h. Hence, the total current I is the sum of electron current I_e and the hole current I_h.

$\therefore \quad \boxed{I = I_e + I_h}$

Note:

Process of Recombination: Apart from the process of generation of conduction electrons and holes, a simultaneous process of recombination also happens in which the electrons recombine with holes. At equilibrium condition, the rate of generation is equal to the rate of recombination of charge carriers. The recombination takes place whenever an electron collides with a hole.

Energy Band Description of Intrinsic Semiconductors

All intrinsic semiconductors behave like an insulator at absolute zero temperature (i.e., at zero kelvin) shown in figure (a). At temperature higher than zero kelvin the thermal energy excites some electrons from the valence band to the conduction band. For an intrinsic semiconductor, energy band diagram is shown in figure (b).

Note that here some electrons have been shown in the conduction band which have come from the valence band creating equal number of holes in valence band.

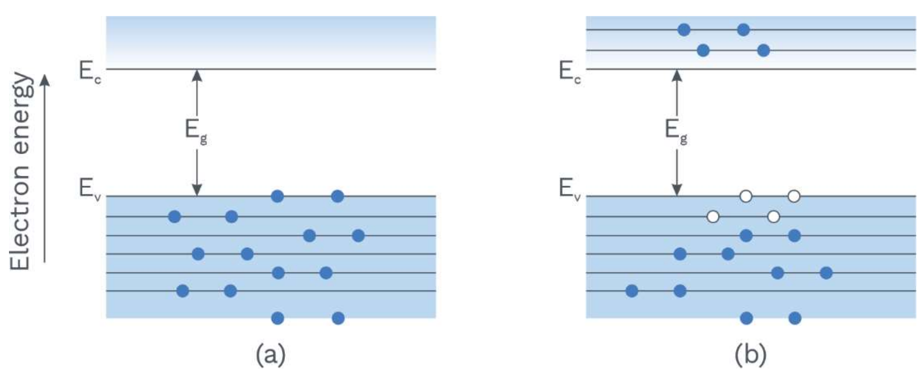


Figure: (a) An intrinsic semiconductor at zero Kelvin behaves like an insulator.
(b) For T > 0 K, four thermally generated electron-hole pairs.
The filled circles (•) represent electrons and empty field (O) represents holes.

Note:-

(1) A pure semiconductor is known as intrinsic semiconductor. It has thermally generated current carries.

(2) Intrinsic semiconductor have four electrons in the outermost orbit of an atom and all atoms are bound together by the covalent bond.

(3) Free electrons and holes both are the charge carriers and n_e (in C.B.) is equal to n_h (in V.B.)

(4) The value of drift velocity of electrons (v_e) is more than that of holes (v_0).

(5) For the level of fermi energy level lies at the conduction band and valence band.

(6) In intrinsic semiconductor, impurity must be less than 1 in 10^8 parts of semiconductor.

(7) In pure semiconductor $n_e = n_h = n_i$; where n_e = Electron density in conduction band, n_h = Hole density in valence band., n_i = Density of intrinsic charge carriers.

(8) The fraction of the electrons of valance band available in conduction band is given by $f \propto e^{-E_g/kT}$; where E_g is Fermi energy or k is Boltzmann's constant and T is absolute temperature.

(9) Because of the less number of charge carriers at the room temperature, intrinsic semiconductor has low conductivity so they have no particle use.

(10) The number of electrons reaching from the valence band to the conduction band $n = AT^{3/2}e^{-E_g/2kT}$ where A is a positive constant.

Concept Reminder

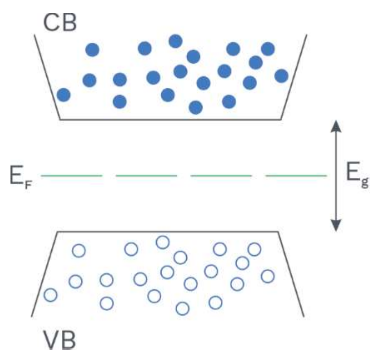
It may be noted that in case of semiconductor apart from the process of generation of conduction electrons and holes, a simultaneous process of recombination occurs in which the electrons recombine with the holes. At equilibrium, the rate of generation is equal to the rate of recombination of charge carriers.

Concept Reminder

Because of less number of charge carriers at room temperature, intrinsic semiconductors have low conductivity so they have no particle use.

(11) Net charge of an intrinsic semiconductor is zero.

(12)

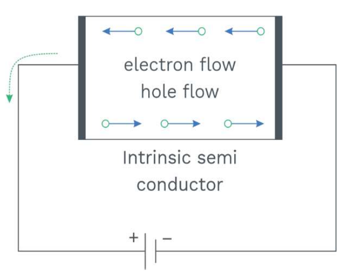


Fermi level is at the middle of ΔE_g.

Conduction In An Intrinsic Semiconductors

An in intrinsic semiconductor, the no. of free electrons and holes are same. Also conduction is because of motion of both electrons and holes. For the purpose of flow of current, a hole, behaves like a positively charged particle having some effective mass. Therefore while the electron moves from negative electrode of the battery to the positive electrode though the semiconductor, the hole moves in opposite side.

The holes exist only within a semiconductor. There are no holes in a metal. Hence, electric conduction through holes takes place inside semiconductor only. Outside the metal wires, the flow of electric current is because of electrons only. (In cell current flow is due to motion of +ve and –ve ions).

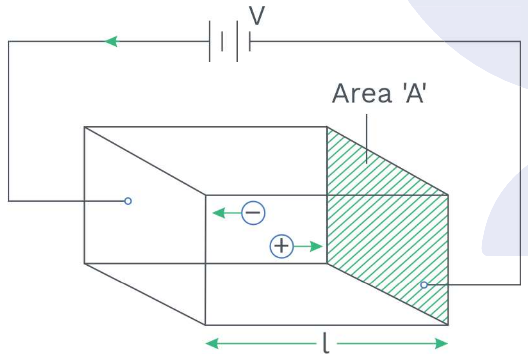


Concept Reminder

The 4 bonding electrons of C, Si or Ge lies in the second, third and fourth orbit respectively. Hence, energy required to take out an electron from these atoms (i.e., ionisation energy E_g) will be least for Ge, followed by Si and highest for C.

In an intrinsic semiconductor the current flows due to the motion of both electrons and the holes. Let e = magnitude of charge on the electrons, n_h = number density of holes, μ_e = mobility of electrons and μ_h = mobility of holes, then the conductivity of intrinsic semiconductor is $\sigma = e(n_e\mu_e + n_h\mu_h)$.

Consider a block of semiconductor of length l, area of cross section A and having density of electron and holes as n_e and n_h respectively when a potential difference say V is applied across it, current I flows through it as shown in fig.
The current I is due to electron current I_e and hole current I_h.



Thus, $I = I_e + I_h$ ....(i)

If v_e represents drift velocity of electrons, then $I_e = en_eAv_e$ ....(ii)

Similarly, the hole current is given by

$$I_h = en_h Av_h \quad ....(iii)$$

Using equations (ii) and (iii), the equation (i) becomes

$$I = eA(n_ev_e + n_hv_h) \quad ....(iv)$$

When R be the resistance offered by a semiconductor to the flow of current, then

$$I = \frac{V}{R} \text{ or } \frac{V}{R} = eA\ (n_ev_e + n_hv_h) \quad ....(v)$$

Concept Reminder

The conductivity of intrinsic semiconductor is,

$$\sigma = e(\mu_en_e + \mu_hn_h)$$

Rack your Brain

In a semiconductor diode, P-side is earthed and N-side is put at potential of –2 V, the diode shall:
(1) Conduct
(2) Not conduct
(3) Conduct partially
(4) Break down

An electric field build across the semiconductor is given by

$$E = \frac{V}{l} \text{ or } V = El$$

Therefore, equation (v) becomes

$$\frac{El}{R} = eA\,(n_e v_e + n_h v_h)$$

or $$\frac{E}{R\frac{A}{l}} = e\,(n_e v_e + n_h v_h)$$

But $R\frac{A}{l} = \rho =$ resistivity of the material of semiconductor

Therefore, $$\frac{E}{\rho} = e(n_e v_e + n_h v_h) \quad \text{......(vi)}$$

The mobility of electrons or holes is defined as drift velocity acquired per unit electric field. So, mobility of electrons and holes is given by

$$\mu_e = \frac{v_e}{E} \text{ and } \mu_h = \frac{v_h}{E}$$

From equation (vi), we have

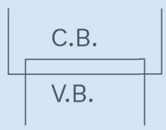
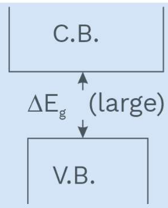
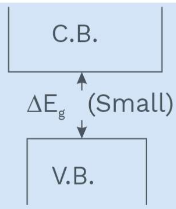
$$\frac{1}{\rho} = e\left\{n_e . \frac{v_e}{E} + n_h . \frac{v_h}{E}\right\}$$

or $$\sigma = e\,(n_e \mu_e + n_h \mu_h) \quad \text{.........(vii)}$$

where $\sigma = \frac{1}{\rho}$ is called conductivity of the material of semiconductor and μ_e and μ_h are electron and hole motilities respectively.

Concept Reminder

When a small amount, say, a few parts per million (ppm), of a suitable impurity is added to the pure semiconductor, the conductivity of the semiconductor is increased manifold.

Properties	Conductors	Insulators	Semiconductors
Electrical conductivity	10^2 to 10^8mho/m	10^{-19} to 10^{-11}mho/m	10^5 to 10^{-8}mho/m
Resistivity	10^{-2} to 10^{-8} Ω-m (negligible)	10^{11} to 10^{19} Ω-m	10^{-5} to 10^6 Ω-m
Band Structure			
Energy gap (E_g)	Zero or very small	Very large : for diamond it is 6 eV	Ge $\rightarrow$ 0.7 eV Si $\rightarrow$ 1.1 eV GaAs $\rightarrow$ 1.3 eV GaF_2 $\rightarrow$ 2.8 eV
Current carriers	Free electrons	–	Free electrons and holes
Condition of V.B. and C.B. at ordinary temperature	V.B. and C.B. are completely filled or C.B. is some what empty	V.B. – Completely field C.B. – Completely unfilled	V.B. – some what empty C.B. – some what filled
Temperature co-efficient of resistance	Positive	Negative	Negative
Effect of temperature on conductivity	Decreases	Increases	Increases
Effect of temperature on resistance	Increases	Decreases	Decreases
Examples	Cu, Ag, Au, Na, Pt, Hg etc.	Wood, plastic, mica diamond, glass etc.	Ge, Si GaAs etc,
Electron density	$10^{29}/m^3$	–	Ge ~ $10^{19}/m^3$ Si ~ $10^{16}/m^3$

Comment

(i) In intrisic semiconductors, at any temperature T, the carrier concentration $n_e = n_h = n$ and the conductivity σ is found by the value of E_g (width of the forbidden band) (see relations given above).

(ii) In metal the value of n is nearly same for different temperatures. The resistance is because of interaction of free (conduction) electrons with the lattice vibrations.

(iii) At absolute zero, n = 0, $\sigma = 0$ i.e., an intrinsic semiconductor behaves like perfect insulator. But as temperature increases both n and s increases. In germanium at T $\approx$ 300 K, $n_e = n_h = 2.5 \times 10^{19} / m^3$. The higher value of temperature means more is the conductivity and lower is the resistivity.

(iv) The temperature coefficient of the resistance of a semiconductor is negative.

(v) Pure semiconductors are of little use (may be used as heat or light sensitive resistance).

Ex. Which one is more sensitive to heat, Ge or Si?

Sol. Ge is more sensitive to heat than Si. Electrons from the valence band of Ge require less energy to move to conduction band.

Concept Reminder

In germanium less energy is required to move electron from valence band to conduction band as compared to silicon.

Extrinsic Semiconductor

Electrical conductivity of intrinsic semiconductors at room temperature is very low. Therefore, no important electronic devices can be developed using these semiconductors. There is a need of improving their conductivity which is temperature dependent. This is done by adding some other substances (called impurities) in the intrinsic semiconductor. Conductivity of a pure semiconductor increases many fold after adding a few parts per million (ppm) of a suitable amount of impurity into it. Such materials are called extrinsic semiconductors or impurity semiconductors.

Doping :-

When desirable impurity is added to intrinsic semiconductors deliberately then this process is called doping and the impurity atoms are called dopants. Such semiconductors are called doped semiconductors.

The sizes of the dopant and the semiconductors atoms should be nearly the same so that the dopant does not distort the original pure semiconductor lattice. A dopant occupies only a very few of the original semiconductor atom sites in the crystal.

Definitions

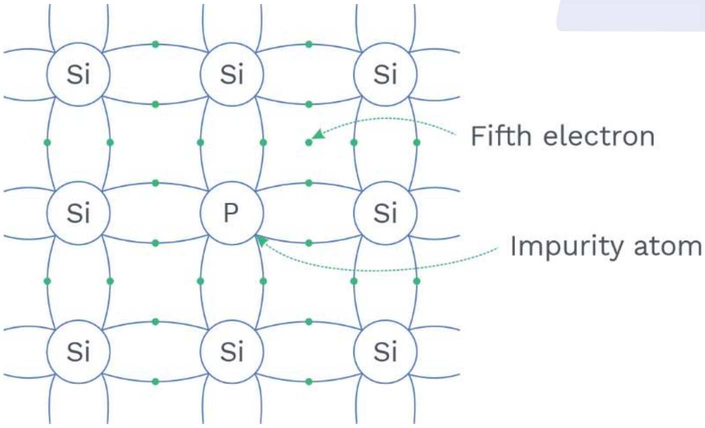
When desirable impurity is added to intrinsic semiconductors deliberately then this process is called doping and the impurity atoms are called dopants. Such semiconductors are called doped semiconductors.

Types of dopants :- There are 2 types of dopants used in doping the tetravalent Si or Ge.

(i) Pentavalent (valency 5) atoms : e.g., Arsenic (As), Antimony (Sb), Phosphorus (P), etc.

(ii) Trivalent (valency 3) atoms : e.g., Indium (in), Boron (B), Aluminium (Al), etc.

N-Type Semiconductor

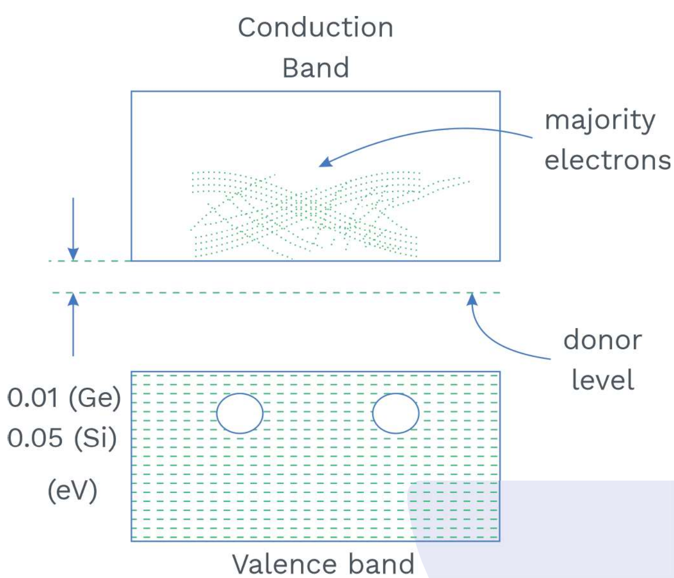


N- Type (n- type) semiconductor is made by mixing a small amount of V group (Pentavalent) impurity to a sample of intrinsic semiconductor. The Pentavalent impurities are P (phosphorus Z = 15), As (Z = 33), Sb (Z = 51), Bi (Z = 83).

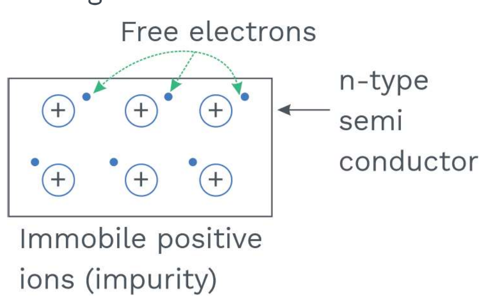
Concept Reminder

(i) Example of pentavalent dopants are Arsenic (As), Antimony (Sb), Phorphorus (P) etc.

(ii) Example of trivalent dopants are Indium (in), Boron (B), Aluminium (Al), etc.



In the energy band picture we see that impurity atoms, produce donor energy levels just below the conduction band. There electrons from these levels move to the conduction band easily by acquiring thermal energies (at room temperature). They may even break some covalent bonds giving electron hole pair, but their number is very small. Hence, in this type of extrinsic semiconductor, there are a large no. of free electrons (donated by impurity atoms) and a negligible no. of holes from covalent bond breaking.



After donating electrons an impurity atom becomes +ve ions. However the over all charge on the semiconductor is zero. The negative charge of the immobile positive charge of the immobile positive ions.

Rack your Brain

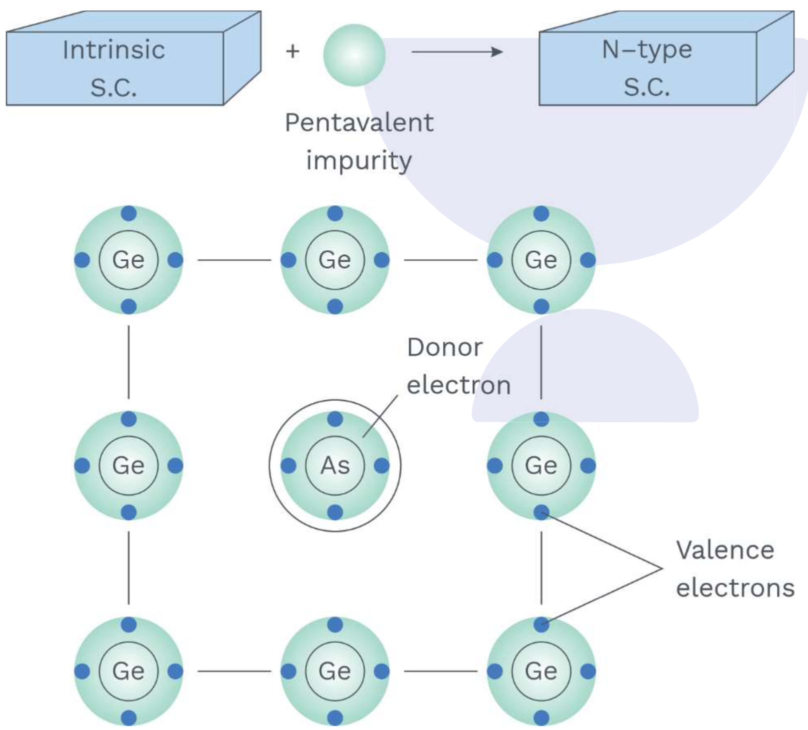
In a n-type semiconductor, which of the following statement is true:

(1) Electrons are minority carriers and pentavalent atoms are dopants.
(2) Holes are minority carriers and pentavalent atoms are dopants
(3) Holes are majority carriers and trivalent atoms are dopants
(4) Electrons are majority carriers and trivalent atoms are dopants.

The majority charge carriers are electrons (negative charge). Therefore, this type of extrinsic semiconductor is called n – type.
The Fermi level which used to lie in the middle of band gap in intrinsic semiconductor, shifts towards the conduction band in N-type semiconductor. The few holes formed by covalent bond breaking are called minority charge carriers.
Amount of impurity atom controls the conductivity of then n-type semiconductors. Since

Note: N-Type Semiconductor

These type of semiconductor are obtained by adding the small amount of Pentavalent impurity to a pure sample of semiconductor (Ge).



(1) Majority charge carriers – electrons
Minority charge carriers – hole

(2) $n_e >> n_h ; i_e >> i_n$

(3) Conductivity $\sigma = n_e \mu_e e$

(4) Donor energy level lies just below conduction band.

(5) **Electrons and hole concentration:** In a doped semiconductor, electron concentration n_e and hole concentration n_h are not equal (as they are in an intrinsic semiconductor). It can be shown that $n_e \approx n_h = n_i^2$

where n_i is intrinsic concentration.

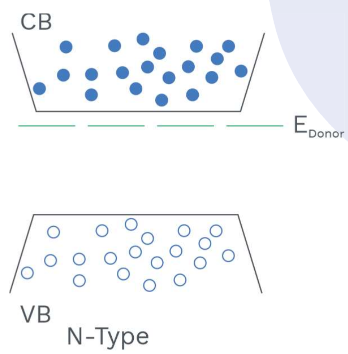
In an n–type semiconductor, concentration of electrons in the conduction band is nearly equal to concentration of the donor atoms (N_d) and very large compared to concentration of holes in valence band. That is

$$n_e \approx n_d >> n_h$$

(6) Impurity atom called donor atom which is elements of V group of periodic table.

(7) Net charge on N-type crystal is zero.

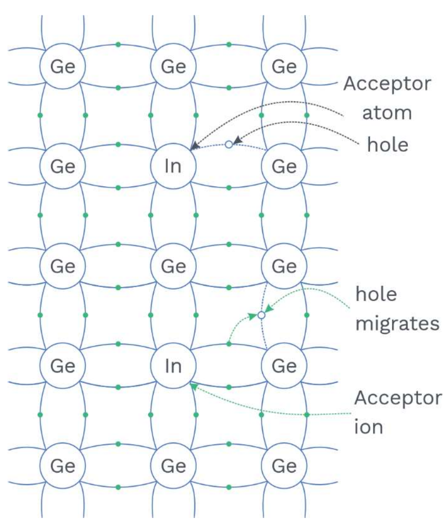
(8) Immobile charge is positive charge.



Concept Reminder

In an n–type semiconductor, the concentration of electrons in conduction band is nearly equal to the concentration of donor atoms (N_d) and very large compared to the concentration of holes in valence band.

P–Type Semiconductor

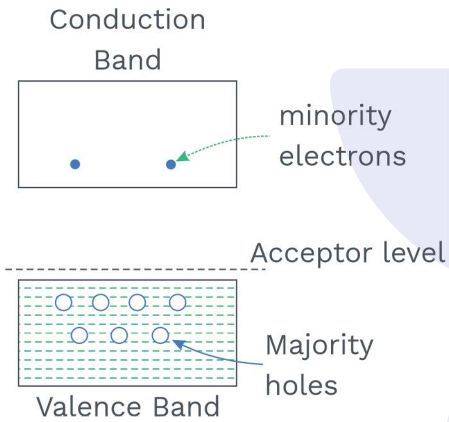


Concept Reminder

The total diode forward current is sum of hole diffusion current and conventional current due to electron diffusion. The magnitude of this current is usually in mA.

By adding a small amount of III group (trivalent) impurity to intrinsic semiconductor, we get P-type of semiconductor. The impurities may be Boron (Z = 5), Al (Z = 13), Ga (Z = 31), In (Z = 49), Tl (Z = 81).

For each acceptor ion there exist a hole in this type of semiconductor, there are a large number of holes present. The majority charge carriers are holes. Therefore, it is called a p-type semiconductor.



In the band picture, we say that acceptor energy level lies just above the valence band. These levels accept electrons from the valence band and create holes. The breaking of covalent bonds may create electron-hole pairs but their number is very little. The majority carriers are holes. The minority carriers are electron.

The conduction takes place mainly through the motion of holes

$$n_h >> n_e$$

$$\sigma_p \approx e\mu_h n_h$$

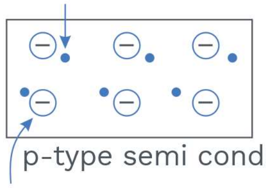
The overall charge on p-type semiconductor is zero. It is represented as shown in Fig. The positive charge of free holes is balanced by the negative charge of immobile impurity ions.

Concept Reminder

In P-type semiconductor, acceptor energy levels lie just above the valence band. These levels accepts electrons from the valence band and creates holes.

Concept Reminder

The direction of applied voltage is same as the direction of barrier potential. As a result, the barrier height increases and the depletion region widens due to the change in the electric field.



Note :-
When temperature is increased, covalent bonds break. This increases minority charge carriers. At very high temperature, it may happen that electron-hole numbers obtained from bond breaking, far exceeds the charge carriers from impurities. Then the semiconductor behaves like intrinsic semiconductor. For germanium and silicon, this critical temperature is 85°C and 200°C respectively.

Ex. Calculate the conductivity and the resistivity of intrinsic silicon crystal at 300 K. It is given that $\mu_e = 1350\, cm^2 / volt - sec,\ \mu_h = 480\, cm^2 / volt - sec$ and at 300 K, the electron-hole pair concentrations 1.072×10^{10} per cm^3.

Sol. The conductivity for intrinsic semiconductor is

$$\sigma = e(n_e\mu_e + n_h\,\mu_h)$$

Given, $n_e = 1.072 \times 10^{10}$ per cm^3

$= 1.072 \times 10^{16}$ per m^3

Also $n_e = n_h$ for intrinsic semiconductor

Further,

$\mu_e = 1350\, cm^2 / volt.sec$

$= 0.1350\, m^2 / volt.sec$

$\mu_h = 0.048\, m^2 / volt - sec$

Therefore,

$\sigma = 1.6 \times 10^{-19} \times 1.072 \times 10^{16} \times (0.135 + 0.048)$

$= 3.14 \times 10^{-4}$ ohm /meter

$= 3.14 \times 10^{-4}$ siemen per meter

The resistivity $\rho = \frac{1}{\sigma} = 10^4 / 3.14$

$= 3185$ ohm. meter

Ex. The concentration of acceptor atoms in a p-type germanium crystal is 4×10^{15} per cm^3. Find the conductivity of the crystal at 300 K. The μ_h for germanium at 300 K is 1900 cm^2/volt sec. It is assumed that all the acceptor atoms are ionized at this temperature.

Sol. For extrinsic semiconductor (p-type)

$$\sigma = n_h e\mu_h$$

Given $n_h = 4 \times 10^{15}$ per cm^3

$= 4 \times 10^{21}$ per m^3

$\mu_h = 1900\ cm^2$ / volt-sec

Thus $\sigma = 4 \times 10^{21} \times 1.6 \times 10^{-19} \times 0.190$

$= 1.216 \times 10^2$ ohm /m

$= 121.6$ siemen/m

Ex. In a pure silicon sample, 10^{13} atoms of phosphorus are doped per cm. If all the donor atoms produce carriers and $\mu_e = 1200$ cm^2/volt-sec then, calculate the resistivity of the sample.

Sol. Given $n_e = 10^{13}$ per cm^3

$= 10^{19}$ per m^3

$\mu_e = 0.12\ m^2$ /volt sec

Therefore, for doped, n-type semiconductor

$$\sigma = e n_e \mu_e$$

$= 1.6 \times 10^{-19} \times 10^{19} \times 0.12$

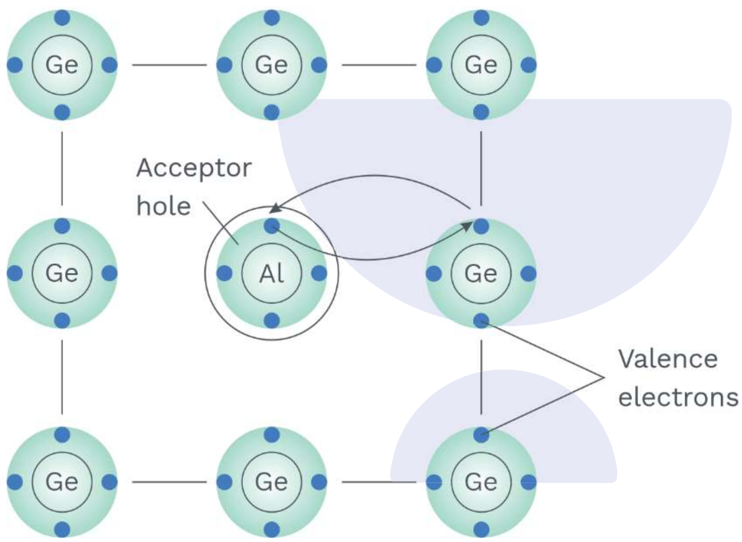
$= 0.192$ ohm m^{-1}

The resistivity is

$$\rho = \frac{1}{0.192} = 5.2\,\text{ohm meter}$$

Note: P-Type Semiconductor

These type of semiconductor are obtained by adding a small amount of trivalent impurity to a pure sample of semiconductor (Ge).



(1) Majority charge carrier – holes
Minority charge carrier – electrons

(2) $n_h >> n_e$; $i_h >> i_e$

(3) Conductivity $\sigma \approx n_h \mu_h e$

(4) P–type semiconductor is also electrically neutral (not positively charged).

(5) Impurity is known as acceptor impurity which is element of III group of the periodic table.

(6) Acceptor energy level lies just above valence band.

(7) **Electron and hole concentration:** In a p–type semiconductor, the concentration of holes in the valence band is nearly equal to concentration of acceptor atoms (N_a) and

Concept Reminder

In a p–type semiconductor, the concentration of holes in valence band is nearly equal to the concentration of acceptor atoms (N_a) and very large compared to the concentration of electron in conduction band.

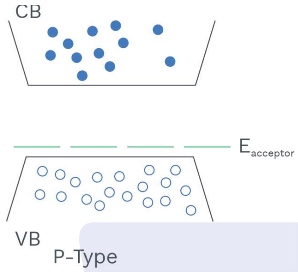
very large compared to concentration of electron in conduction band.
That is

$$n_h = N_a >> n_e$$

(8) Net charge on p-type crystal is zero.

(9) Immobile charge is negative charge.

(10)



Distinction between intrinsic and extrinsic semiconductors:

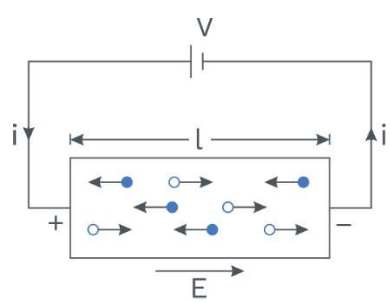
	Instrinsic Semiconductor		Extrinsic Semiconductor
1	It is a pure, natural semiconductor, such as pure Ge and pure Si.	1	It is prepared by adding a small quantity of impurity to a pure semiconductor, such as n- and p-type semiconductors.
2	In it the concentration of electrons and holes are equal.	2	In it the two concentrations are unequal. There is an excess of electrons in n-type semiconductors and an excess of holes in p-type semiconductors.
3	Its electrical conductivity is very low.	3	Its electrical conductivity is significantly high.
4	Its conductivity cannot be controlled.	4	Its conductivity can be controlled by adjusting the quantity of the impurity added.
5	Its conductivity increases exponentially with temperature.	5	Its conductivity also increases with temperature, but not exponentially.

Distribution between n-type and p-type semiconductor :

	n-type semiconductor		p-type semiconductor
1	It is an extrinsic semiconductor obtained by adding a pentavalent impurity to a pure intrinsic semiconductor.	1	It is also an extrinsic semiconductor obtained by adding a trivalent impurity to a pure intrinsic semiconductor.
2	The impurity atoms added provides extra free electrons to the crystal lattice and are called donor atoms.	2	The impurity atoms added create holes in the crystal lattice and are called acceptor atoms because the created holes accept electrons.
3	The electrons are majority carriers and the holes are minority carriers.	3	The holes are majority carriers and the electrons are minority carriers.
4	The electrons concentration is much more than the hole concentration ($n_e >> n_h$).	4	The hole concentration is much more than the electron concentration ($n_h >> n_e$).

Electrical conductivity of extrinsic semiconductors :-

A semiconductor, at room temperature, includes electrons in conduction band and holes in valence band. When the external electric field is applied, electrons move opposite to the field and the hole move in the direction of field, thus constituting current in same direction. The total current is sum of the electron and hole currents.



Let us consider the semiconductor block of length 'l', area of cross-section 'A' and having electrons concentration n_e and hole concentration n_h. A potential difference 'V' applied across the ends of the semiconductor creates an electric field E given by:

Concept Reminder

Both n-type and p-type semiconductors are electrically neutral.

Rack your Brain

If a small amount of antimony is added to germanium crystal
(1) Its resistance is increased
(2) It becomes a p-type semiconductor
(3) The antimony becomes an acceptor atom
(4) There will be more free electrons than holes in the semiconductor.

$E = V/l$ .... (i)

Under the field E, the electrons and holes both drift in the opposite directions and constitute currents i_e and i_h respectively in direction of the field. The total current flowing through the semiconductor is,

$$i = i_e + i_h$$

If v_e, be the drift velocity of electrons in the conduction band and v_h the drift velocity of holes in the valence band, then we have

$$i_e = n_e eA\, v_e \quad \text{and} \quad i_h = n_h eA\, v_h$$

where e is the magnitude of the electron charge

$$\therefore \quad i = i_e + i_h = eA\,(n_e v_e + n_h v_h)$$

$$\text{or} \quad \frac{i}{A} = e(n_e v_e + n_h v_h) \quad \text{....... (ii)}$$

Let 'R' be the resistance of semiconductor block and ρ the resistivity of block material. Then

$$\rho = RA / l \quad \text{....... (iii)}$$

Dividing eq.(i) by the eq.(iii) we have

$$\frac{E}{\rho} = \frac{V}{RA} = \frac{i}{A}$$

Because, V = iR (Ohm's law). Replacing in it the value of i/A from eq.(ii), we get

$$\frac{E}{\rho} = e(n_e v_e + n_h v_h) \quad \text{....... (iv)}$$

Let us introduce a quantity μ known as mobility which is defined as drift velocity per unit field and is expressed in the metre^2/volt-second. Thus, the mobilities of electrons and the hole are given by:

$$\mu_e = \frac{v_e}{E} \quad \text{and} \quad \mu_h = \frac{v_h}{E}$$

Concept Reminder

Due to the applied voltage, electrons from n-side cross the depletion region and reach p-side (where they are minority carries). Similarly, holes from p-side cross the junction and reach the n-side (where they are minority carries). This process under forward bias is known as minority carrier injection.

Introducing μ_e and μ_h in eq. (iv), we get

$$\frac{1}{\rho} = e(n_e\mu_e + n_h\mu_h)$$

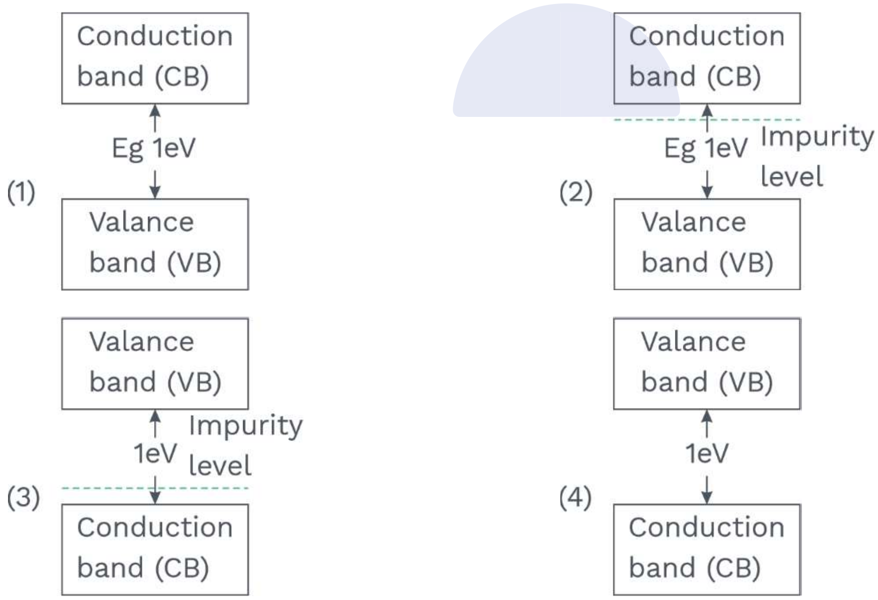
The electrical conductivity σ is reciprocal of the resistivity ρ. Thus, electrical conductivity of the semiconductor is given by

$$\sigma = e(n_e\mu_e + n_h\mu_h)$$

This is the needed expression. It shows that electrical conductivity of a semiconductor depends upon electron and hole concentrations (number densities) and their mobilities. The mobility of electrons is higher than hole mobility. As temperature rises, both concentration n_e and n_h increases due to breakage of more covalent bonds. The mobilities μ_e and μ_h however, slightly decrease with the rise in temperature but this decrease is offset by much greater increase in n_e and n_h. Hence, conductivity of a semiconductor, increases (or the resistivity decreases) with rise in the temperature.

Ex. Which of following energy band diagram shows the N-type semiconductor

Sol.



(2) In N-type of semiconductor impurity energy level lies just below conduction band.

Ex. The mean free path of the conduction electrons in copper is about 4×10^{-8} m. For the copper block, find the electric field which can give, on an average, 1eV energy to a conduction electron.

Sol. Let the electric field be E. The force on the electron is eE. As the electron moves through a distance 'd', the work done on it is eEd. This is equal to energy transferred to electron. As the electron travels average distance of 4×10^{-8} m before the collision, the energy transferred is eE(4×10^{-8} m). To get 1 eV energy from electric field, eE(4×10^{-8} m) = 1 eV or E = 2.5×10^{7} V/m.

Ex. The band gap in germanium is $\Delta E = 0.68$ eV. Assuming that number of hole-electron pairs is proportional to $e^{-\Delta E/2kT}$, find percentage increase in the number of charge carries in pure germanium as the temperature is increased from 300 K to 320 K.

Sol. The number of the charge carries in an intrinsic semiconductor is double no. of hole-electron pairs. If N_1 be no. of charge carries at the temperature T_1 and N_2 at T_2, we have

$$N_1 = N_0 e^{-\Delta E/2kT_1}$$

and $$N_2 = N_0 e^{-\Delta E/2kT_2}$$

The percentage increase as temperature is raised from T_1 to T_2 is

$$f = \frac{N_2 - N_1}{N_1} \times 100 = \left(\frac{N_2}{N_1} - 1\right) \times 100 = 100\left[e^{\frac{\Delta E}{2k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} - 1\right]$$

Now $\dfrac{\Delta E}{2k}\left(\dfrac{1}{T_1} - \dfrac{1}{T_2}\right)$

$$= \frac{0.68\,\text{eV}}{2 \times 8.62 \times 10^{-5}\,\text{eV/K}}\left(\frac{1}{300\,\text{K}} - \frac{1}{320\,\text{K}}\right) = 0.82$$

Thus $f = 100 \times [e^{0.82} - 1] \approx 127$.

Thus, the number of the charge carries increase by about 127%.

Ex. A Si specimen is made into a p-type semiconductor by doping on an average 1 indium atom per 5×10^{7} silicon atoms. If the number density of the atoms in the Si specimen is 5×10^{28} atoms/m^3. Calculate the number of acceptor atoms in silicon per cubic centimetre.

Sol. The doping of 1 indium atoms in Si semiconductor will produce one acceptor atom in the p-type semiconductor. Since one In atom has been dopped per 5×10^{7} silicon atoms, so number density of acceptor atoms in silicon $= \dfrac{5 \times 10^{28}}{5 \times 10^{7}} = 10^{21}\,\text{atom/m}^3 = 10^{15}\,\text{atoms/cm}^3$.

Ex. Pure Si at temperature of 300 K has same electron (n_e) and hole (n_h) concentrations of $1.5 \times 10^{16}\ m^{-3}$. Doping by 'In' increases n_h to $3 \times 10^{22}\ m^{-3}$. Calculate n_e in the doped Si.

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

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5 \times 10^{16})^2}{3 \times 10^{22}} = 7.5 \times 10^9 m^{-3}$$

Ex. Pure Si at temperature of 300 K has equal electron (n_e) and hole (n_h) concentrations of $1.5 \times 10^{16}\ m^{-3}$. Doping by 'In' increases n_h to $4.5 \times 10^{22}\ m^{-3}$. Calculate n_e in the doped Si-

Sol. $n_e n_h = n_i^2$

$n_h = 4.5 \times 10^{22} m^{-3}$

so, $n_e = 5.0 \times 10^9 m^{-3}$

Ex. The energy of a photon of 'Na' light (λ = 589 nm) equals the band gap of a semiconducting material. (a) Find out the minimum energy E required to create a hole-electron pair. (b) Find out the value of E/kT at a temperature of 300 K.

Sol. (a) The energy of the photon is $E = \frac{hc}{\lambda}$

$$= \frac{1242\, eV - nm}{589\, nm} = 2.1 eV$$

Thus, band gap is 2.1 eV. This is also the minimum energy 'E' required to push an electron from valence band into conduction band. Hence, the minimum energy required to create the hole-electron pair is 2.1 eV.

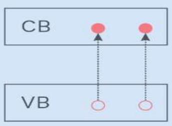
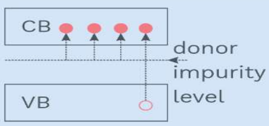
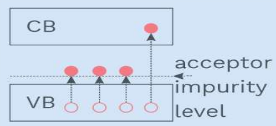
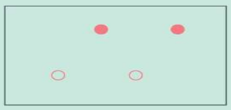
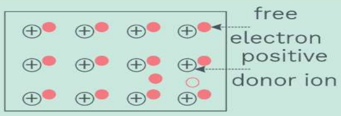
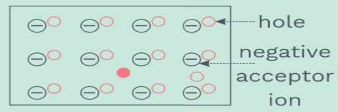
(b) At $T = 300 K$,

$$kT = (8.62 \times 10^{-5} eV / K)(300 K)$$

$$= 25.86 \times 10^{-3}\ eV$$

Thus, $\frac{E}{kT} = \frac{2.1 eV}{25.86 \times 10^{-3} eV} = 81$

So it is difficult for thermal energy to create the hole-electron pair but a photon of light can do it easily.

S.No.	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.	$n_e = n_h = n_i$	$n_e >> n_h$ ($N_D \simeq n_e$)	$n_h >> n_e$ ($N_A \simeq n_h$)
5.	$I = I_e + I_h$	$I \simeq I_e$	$I \simeq I_h$
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 acceptor atoms get ionised leaving holes in valence band. Thus at room temperature density of holes in the valence band is predominantly due to impurity in the extrinsic semiconductor. The electron and the hole concentration in a semiconductor in thermal equilibrium is given by

$$n_e n_h = n_i^2$$

Through the above description is clearly approximate and hypothetical, it helps in understanding difference between the 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

$I = neAv_d$ where n = number of electron in per unit volume

Concept Reminder

The electron and hole concentration in a semiconductor in thermal equilibrium is given by

$$n_e n_h = n_i^2$$

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

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

$\therefore$ conductivity $\sigma = ne\mu = 1/\rho$

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

Concept Reminder

- $J = nev_d$
- $J = \sigma E$
- $\sigma = ne\mu_e$
- $\rho = \frac{1}{ne\mu_e}$

- **Conduction in Semiconductor**

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

Note:-

- Number of electrons reaching from the valence band to the conduction band at temperature 'T' is given by

$$n = A\,T^{3/2} e^{-\frac{\Delta E_g}{2kT}}$$

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

- In 'Si' at room temperature, out of 10^{12} 'Si' atoms only one electron goes from the valence band to the conduction band.
- In 'Ge' at room temperature out of 10^9 'Ge' atoms only one electron goes from the valence band to the 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

Concept Reminder

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

$$n = A\,T^{3/2} e^{-\frac{\Delta E_g}{2kT}}$$

almost independent of applied field.

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

Concept Reminder

The size of dopant (impurity atom) should be almost the same as that of crystal atom. So that crystalline structure of solid remain unchanged.

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

Sol. $E = \frac{hc}{\lambda}$

$$\Rightarrow \quad \lambda = \frac{hc}{E} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{57 \times 10^{-3} \times 1.6 \times 10^{-19}} = 217700 \text{ Å}$$

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

Sol. The doping of one 'In' atom in 'Si' semiconductor will produce one acceptor atom in p-type semiconductor. Since one 'In' atom has been dopped per 5 × 10^7 Si atoms, so number density of acceptor atoms in silicon

$$= \frac{5 \times 10^{28}}{5 \times 10^{7}} = 10^{21} \text{atom} / m^3 = 10^{15} \text{atoms} / cm^3$$

Ex. Pure Si at 300 K has same 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.

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

$$n_e = \frac{n_i^2}{n_h} = \frac{(1.5 \times 10^{16})^2}{3 \times 10^{22}} = 7.5 \times 10^9 m^{-3}$$

Ex. What will be conductance of pure 'Si' crystal at 300 K temperature. If the electron hole pairs per cm^3 is 1.072 × 10^{10} at this temperature, $\mu_e = 1350\,cm^2 / volt - s$ & $\mu_h = 480\,cm^2 / volt - s$

Sol. $\sigma = n_i e \mu_e + n_i e \mu_h = n_i e(\mu_e + \mu_h)$

$= 1.072 \times 10^{10} \times 1.6 \times 10^{-19} \times (1350 + 480)$

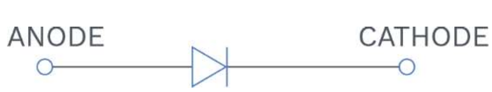
$= 3.14 \times 10^{-6} mho / cm$

Junction Diode:-

A junction diode is a simple semiconductor device. It is a semiconductor crystal having the acceptor impurities in one region (P-type crystal) and the donor impurities in the other region (n-type crystal). The boundary between two regions is known as ‘p-n junction’.

Circuit Symbol for a p-n Junction Diode:-

In electronic circuits, the semiconductor devices are represented by their symbols. The symbol for basic device, p-n junction diode, is shown below. The arrow-head represents "p-region" and the bar represents "n-region" of the diode. The direction of the arrow is from 'p' to 'n' and indicates the direction of the conventional current flow under forward bias. The p-side is known as ‘anode’ and the n-side is called ‘cathode’.



Definitions

It is a semiconductor crystal having acceptor impurities in one region (P-type crystal) and donor impurities in the other region (n-type crystal). The boundary between the two regions is called ‘p-n junction’.

Concept Reminder

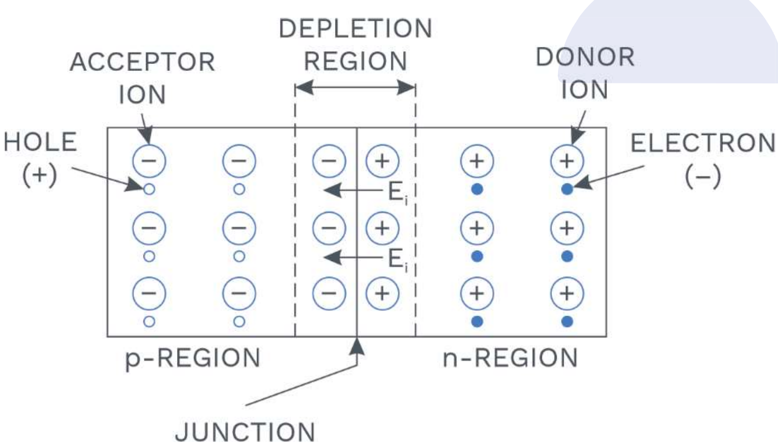
In symbol of diode:
The direction of the arrow is from p to n and indicates the direction of conventional current flow under forward bias.

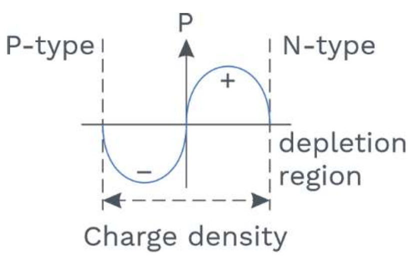
(a) Formation of p-n Junction:-

A p-n junction is not interface between p -type & n - type semiconductor crystals pressed together. It is a single piece of the semiconductor crystal having an excess of the acceptor impurities into one side and of the donor impurities into the other. P-type semiconductor is grown on one side of metallic film while n-type is grown on other side.

(b) Potential Barrier at the Junction : Formation of Depletion Region:-

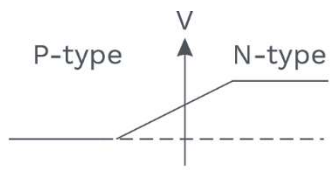
A p-n junction is shown in diagram The p-type region has (positive) holes as the majority charge-carriers, and an same number of fixed negatively-charged acceptor ions. Material as a whole is thus neutral). Same as, the n-type region has (negative) electrons as majority charge-carriers, and an equal number of fixed positively-charged donor ions.



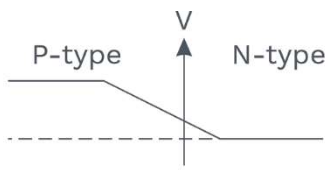


KEY POINTS

- p-n junction
- Diode
- Donor ion
- Acceptor ion
- Depletion region
- Potential barrier
- Diffusion current
- Drift current



Electrostatic potential
energy barrier for holes
(potential barrier for holes)



Potential barrier for electrons

The region on either of junction which becomes depleted (free) of mobile charge-carriers is known as the 'depletion region'. The width of depletion region is of the order of 10^{-6} m. The potential difference developed across depletion region is known as the 'potential barrier'. It is near about 0.3 volt for Ge p-n junction and about 0·7 volt for 'Si' p-n junction. It, however, depends upon dopant concentration in the semiconductor.
The magnitude of barrier electric field for a silicon junction is

$$E_i \approx \frac{V}{d} = \frac{0.7}{10^{-6}} = 7 \times 10^5 \, Vm^{-1}$$

Diffusion & Drift Current: Due to concentration difference hole try to diffuse from 'p' side to 'n' side but due to the depletion layer only those hole are able to diffuse from 'p' to 'n' side which have high kinetic energy. Similarly electron of high kinetic energy also diffuse from 'n' to 'p' so diffusion current flow from 'p' to 'n' side. Due to thermal collision or increase in temperature some valence electron comes in conduction band. If these occurs in depletion region then hole move to 'p' side & electron move to 'n' side so a current produce from 'n' to 'p' side it is called drift current and in steady state both are equal & opposite.

Definitions

The region on either of the junction which becomes depleted (free) of the mobile charge-carriers is called the 'depletion region'.

Concept Reminder

The width of depletion region is 10^{-6} m.

Ex. A potential barrier of 0.5 V exists throughout a P-N junction. If depletion region is 5.0 × 10^{-7} m wide, the intensity of the electric field in this region is

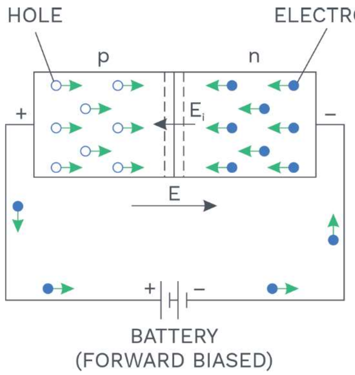
Sol. $E = \frac{V}{d} = \frac{0.5}{5 \times 10^{-7}} = 10^6 \, Vm$

(c) Forward and Reverse Biasing of Junction Diode:-

The junction diode may be connected to an external battery in the two ways, named as 'forward biasing' and 'reverse biasing' of the of diode. It means way of connecting emf source to the P-N junction diode. It is of following two types

(i) Forward Biasing :-

A junction diode is said to be forward-biased when the positive terminal of the external battery is connected to the p-region and the negative terminal to the n -region of the diode.



Forward-Biased Characteristics:- The circuit for this has been shown in diagram. The positive terminal of battery is connected to the p -region and the negative terminal to the n-region of the junction diode through the potential-divider arrangement which enables to change applied voltage.

Definitions

A junction diode is said to be forward-biased when the positive terminal of the external battery is connected to the p-region and the negative terminal to the n-region of the diode.

Rack your Brain

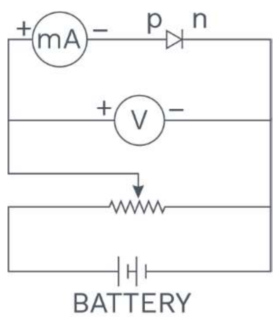
Which of the following statement is False?

(1) The resistance of intrinsic semiconductor decreases with increase of temperature

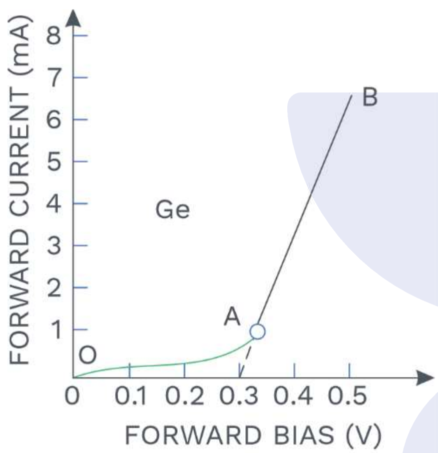
(2) Pure Si doped with trivalent impurities gives a p-type semiconductor

(3) Majority carriers in a n-type semiconductors are holes

(4) Minority carriers in a p-type semiconductor are electrons



(a)



(b)

KEY POINTS

- Forward biasing
- Reverse biasing
- Knee voltage

The voltage is read by the voltmeter 'V' and the current by the millimetre 'mA'. Starting with a low value, forward bias voltage start to increase step by step and corresponding forward current is noted. A graph is then plotted between the voltage and current. The resulting curve OAB (figure b) is the forward characteristic of diode.

In the beginning, when applied voltage is low, the current through junction diode is nearly zero.

It is because of potential barrier (about 0·3 V for the "Ge p-n junction" and about 0·7 V for the "Si junction") which opposes applied voltage. With increase in the applied voltage, current increases very slow and non-linearly until applied voltage exceeds potential barrier. This is represented by portion OA of characteristic curve. With further increase in applied voltage, current increases very rapidly and almost linearly now diode behaves as an ordinary conductor. This is represented by straight-line part AB of the characteristic. If this straight line is projected back. it intersects voltage-axis at barrier potential voltage.

Note :

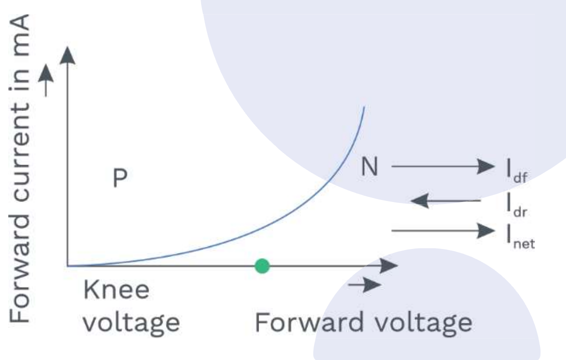
(i) In forward biasing width of the depletion layer decreases.

(ii) In forward biasing resistance offered $R_{Forward} \approx 10\Omega - 25\Omega$

(iii) Forward bias opposes potential barrier and for $V > V_B$ a forward current is set up across the junction.

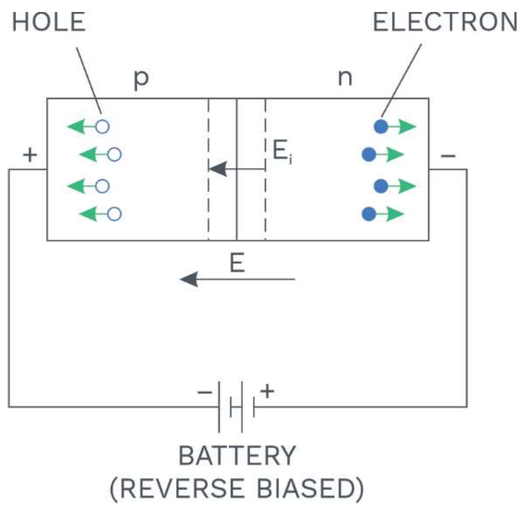
(iv) Cut-in (Knee) voltage: The voltage at which current starts to increase rapidly. For "Ge" it is 0.3 V and for "Si" it is 0.7 V.

(v) d_f-diffusion and d_r-drift



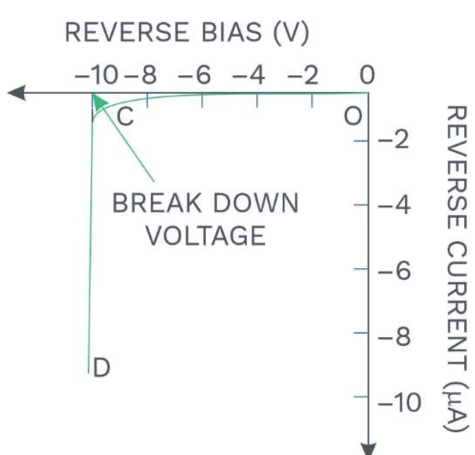
(ii) Reverse Biasing:-

A junction diode is called to be reverse-biased when the positive terminal of external battery is connected to the "n -region" and the negative terminal to the "p-region" of the diode. (Fig.)



In this condition, the external field 'E' is directed from 'n' toward 'p' and thus aids internal barrier field E_i. Hence holes in "p-region" and electrons in "n-region" are both pushed away from junction, that is, they can't combine at the junction. Thus, there is almost no current because of the flow of majority carriers.

Reverse-Biased Characteristic:-
The circuit connections are shown in dia. (a) in which positive terminal of the battery source is connected to n-region and the negative terminal to p-region of the junction diode. In reverse-biased diode, a very low current (of the order of micro Ampere) flows across junction because of the motion of few thermally-generated minority-carriers (electrons in p-region and holes in n-region) whose motion is aided by applied voltage. The small reverse current remains almost uniform over a sufficiently long range of the reverse bias (applied voltage), increasing very little with the increasing bias. This is represented by the part 'OC' of the reverse characteristic curve (dia. b).



(b)

Definitions

A junction diode is said to be reverse-biased when the positive terminal of the external battery is connected to the n-region and the negative terminal to the p-region of the diode.

Concept Reminder

The current under reverse bias is essentially voltage independent upto a critical reverse bias voltage, known as breakdown voltage (V_{br}).

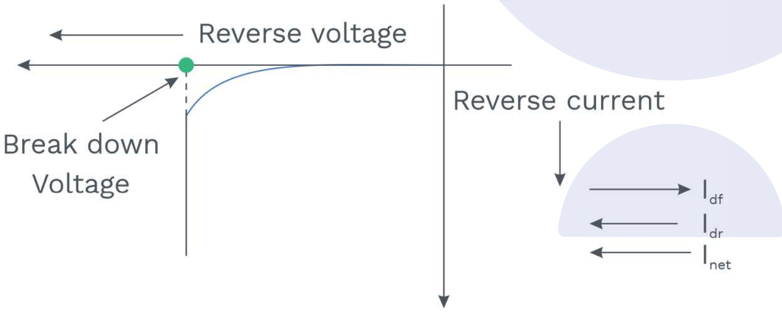
Note:

(i) In reverse biasing width of the depletion layer increases.

(ii) In reverse biasing the resistance offered $R_{Reverse} \approx 10^5 \Omega$

(iii) Reverse bias supports potential barrier and no current flows across the junction because of the diffusion of the majority carriers. (A very small reverse currents can exist in the circuit due to the drifting of the minority carriers across junction).

(iv) **Break down voltage:** It is defined as reverse voltage at which break down occurs for semiconductor. For 'Ge' it is 25 V and for 'Si' it is 35 V.



(v) Reverse saturation current is temperature sensitive and nearly doubles for every 10°C rise.

Concept Reminder

If the reverse current is not limited by an external circuit below the rated value (specified by the manufacturer) the p-n junction will get destroyed. Once it exceeds the rated value, the diode gets destroyed due to overheating. This can happen even for the diode under forward bias, if the forward current exceeds the rated value.

Avalanche Breakdown

The kind of breakdown occurs in a reverse bias of lightly doped p-n junction. When p-n junction is lightly doped, the width of depletion region is large. Hence, when reverse bias is applied, some covalent bonds get broken in the depletion region and electron holes pairs are produced. Under the effect of barrier electric field these free electrons move towards n side which again collides with atoms producing more electron hole pairs. This gives a continuous flow of current carriers in reverse bias and these newly generated charged carriers are also accelerated by used electric field in reverse bias leading to avalanche breakdown.

Zener Breakdown

This breakdown occurs in a highly dopped p-n junction in which width of depletion region is small. When reverse bias voltage is increased, electric field across depletion region also increases (which is the sum of barrier electric field and applied electric field) and if we go on increasing reverse bias voltage, at a particular value (called Zener voltage) a large number of electrons and holes are produced. This is called Zener breakdown.

Concept Reminder

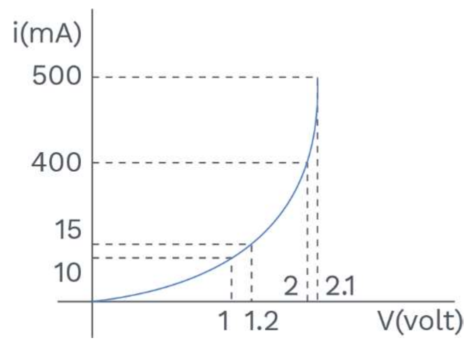
For the diode in reverse bias, the current is very small (~ μA) and almost remains constant with change in bias. It is called reverse saturation current.

Dynamic Resistance of a Junction Diode:-

The current-voltage curve of junction diode appears that the current does not change linearly with the voltage, that is, Ohm's rule is not obeyed. In such condition, a quantity known as 'dynamic resistance' (or a.c. resistance) is defined. The dynamic resistance of a junction diode is defined as the ratio of a small change in applied voltage ( ) to the corresponding small change in current ( ), that is

In the forward characteristic of p-n junction diode, beyond the turning point (knee), however, the current varies almost linearly with voltage. In this region, R_d is almost independent of V and Ohm's law is obeyed.

Ex. The i-V characteristic of a p-n junction diode is shown in figure. Find the approximate dynamic resistance of the p-n junction when (a) a forward bias of 1 volt is applied, (b) a forward bias of 2 volt is applied



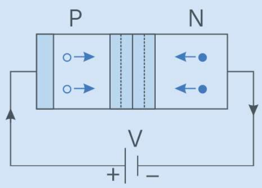
(a) The current at 1 volt is 10 mA and at 1.2 volt it is 15 mA. The dynamic resistance in this region is $R = \frac{\Delta V}{\Delta i} = \frac{0.2\,\text{volt}}{5\,\text{mA}} = 40\,\Omega$

(b) The current at 2 volt is 400 mA and at 2.1 volt it is 800 mA. The dynamic resistance in the region is $R = \frac{\Delta V}{\Delta i} = \frac{0.1\,\text{volt}}{400\,\text{mA}} = 0.25\,\Omega$

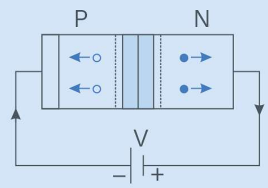
Breakdown are of two types:

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 aquire 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 stablizer zener phenomena is used".	• Here P–N junction damages permanently due to abruptly increment of minorities repetitive collisions.

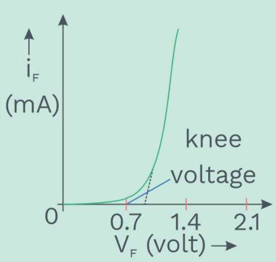
<table>
<tr><th></th><th>Forward Bias</th><th>Reverse Bias</th></tr>
<tr><td></td><td>P → positive
N → negative



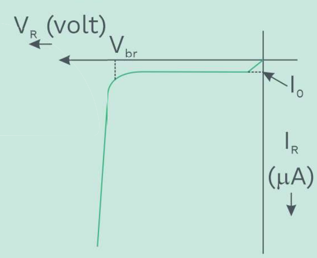
</td><td>P → negative
N → positive



</td></tr>
<tr><td>1.</td><td>Potential Barrier reduces.</td><td>Potential Barrier increases.</td></tr>
<tr><td>2.</td><td>Width of depletion layer decreases.</td><td>Width of depletion layer increases.</td></tr>
<tr><td>3.</td><td>P–N Junction provides very small resistance.</td><td>P–N Junction provides high resistance.</td></tr>
<tr><td>4.</td><td>Forward current flow in circuit.</td><td>Reverse current flow in circuit.</td></tr>
<tr><td>5.</td><td>Order of forward current is milli ampere.</td><td>Order of current is micro ampere (Ge) or Nano ampere (Si).</td></tr>
<tr><td>6.</td><td>Mainly majority current flows.</td><td>Mainly minority current flows.</td></tr>
<tr><td>7.</td><td>Forward characteristic curve

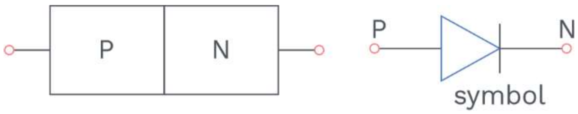


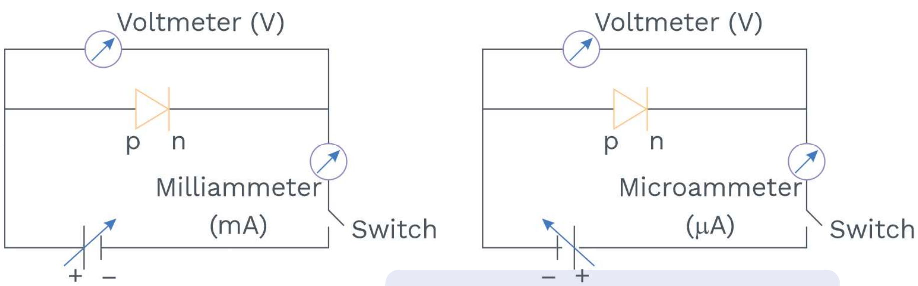
</td><td>Reverse characteristic curve



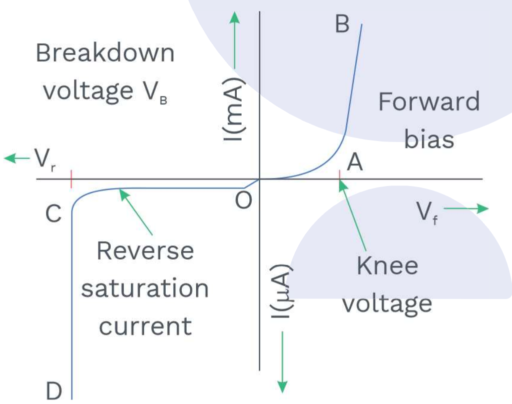
</td></tr>
<tr><td>8.</td><td>Forward resistance
$R_f = \frac{\Delta V_f}{\Delta I_f} \cong 100\Omega$</td><td>Reverse resistance
$R_r = \frac{\Delta V_r}{\Delta I_r} \cong 10^6\Omega$</td></tr>
<tr><td>9.</td><td>Knee or cut in voltage
Ge → 0.3 V, Si → 0.7 V</td><td>Breakdown voltage
Ge → 25 V, Si → 35 V</td></tr>
<tr><td>10.</td><td>Forward current Equation
$I = I_0\left[e^{+\frac{qV}{kT}} - 1\right]$
$\because \frac{R_B}{R_F}$
$\therefore I \cong I_0 e^{\frac{qV}{kT}}$ (exp. increment)
For Ge $\frac{R_r}{R_F} = 10^3 : 1$</td><td>Reverse current equation
$I = I_0\left[e^{-\frac{qV}{kT}} - 1\right]$
$\because e^{-\frac{qV}{kT}} << 1$
$\therefore I \simeq -I_0$
For Si $\frac{R_r}{R_F} = 10^4 : 1$</td></tr>
</table>

Characteristic Curve of P-N Junction Diode





(a) forward bias (b) reverse bias



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, called knee voltage. At this voltage, barrier potential is completely eliminated and diode offers a low resistance.

In reverse bias a micro ammeter has been used as current is very very small. When reverse voltage is increased from 0 V 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_B, called breakdown voltage, current increases very sharply.

For Ideal Diode

In forward bias

$R = 0\,\Omega$

on switch

In reverse bias

$R = \infty\,\Omega$

off switch

Note :-

- Width of depletion layer $\cong 0.1\ \mu m$

  (a) As doping increases, width of depletion layer decreases.

  (b) P-N junction $\rightarrow$ nonohmic, due to nonlinear relation between I and V.

- Potential Barrier or contact potential for $Ge \rightarrow 0.3\,V$, for $Si \rightarrow 0.7\,V$

- Strength of junction field $E = \dfrac{\Delta V}{\Delta d} = \dfrac{0.5}{10^{-7}} \Rightarrow E \cong 5 \times 10^{6}\,V/m$

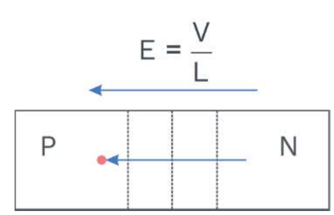
  This field prevents the respective majority carriers from crossing barrier region.

- In reverse bias, current is very small and nearly constant with bias (termed as reverse saturation current). However interesting behavior results in some special cases if the reverse bias is increased further beyond a certain limit, breakdown of depletion layer takes place.

Ex. 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 move towards the p-n junction from n-side. With what speed will it enter p-side?

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

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

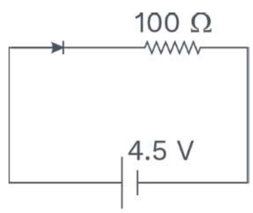


(ii) Work energy theorem $\frac{1}{2}Mv_i^2 = eV + \frac{1}{2}Mv_f^2$

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

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

Sol.



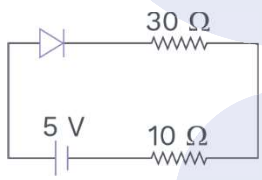
$E = 4.5\,V, R = 100\,\Omega$

voltage drop across p-n junction = 0.5 V
effective voltage voltage in the circuit $V = 4.5 - 0.5 = 4.0\,V$

current in the circuit

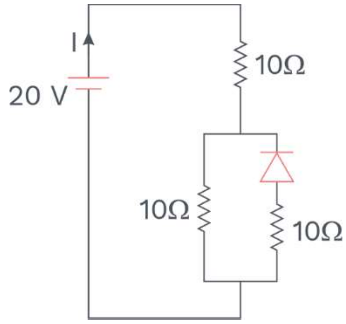
$$I = \frac{V}{R} = \frac{4.0}{100} = 0.04\text{ A} = 0.04 \times 1000\,\text{mA} = 40\,\text{mA}$$

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



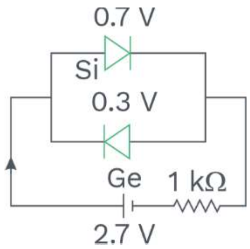
Sol. Let resistance of PN junction be R then $I = \dfrac{5}{R + 30 + 10} = 0.1 \Rightarrow R = 10\,\Omega$

Ex. What is the amount of current I in given circuits



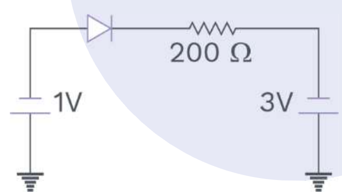
Sol. $I = \dfrac{20}{10 + 10} = 1\text{A}$

Ex. What is the amount of current I in given circuits.

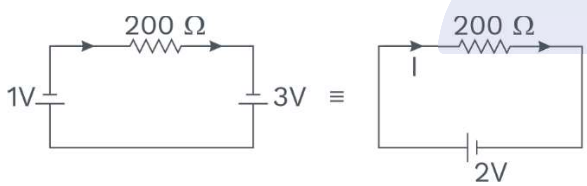


Sol. $I = \dfrac{27 - 0.7}{1 \times 10^3} = 2\,mA$

Ex. In the giving circuit, if P-N junction is ideal, then calculate current flowing through it.



Sol. In given condition



$\Rightarrow I = \dfrac{2V}{200} = 0.01\ A$

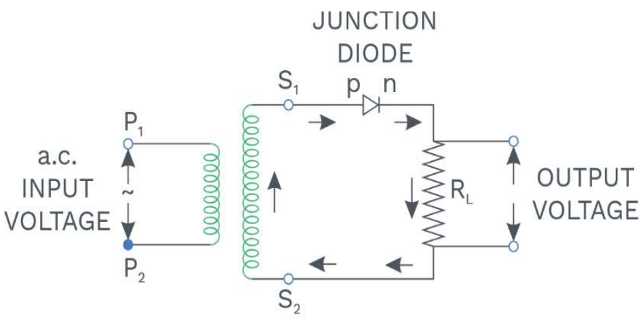
$\Rightarrow I = \dfrac{2V}{200} = 0.01A$

p-n Junction Diode as a Rectifier:-

An electronic apparatus which converts alternating current (AC) / voltage into direct current/voltage is called 'rectifier'. A p-n junction diode offers a low resistance for the current to flow, when forward-biased, but a very high resistance, when reverse-biased. It thus passes current only in one direction and acts as a rectifier. The junction diode can be used either as an half-wave rectifier, when it allows current only through the positive half-cycles of the input a.c. supply; or as a full-wave rectifier when it allows current in the same direction for both half-cycles of the input a.c.

(a) p-n Junction Diode as Half-wave Rectifier:-
The half-wave rectifier circuit is display in Fig. (a) and the input and output wave forms in Fig. (b). The a.c. input voltage is utilized across the primary P_1P_2 of a transformer. S_1S_2 is the secondary coil of the even transformer. S_1 is attached to the p-type crystal of the junction diode and S_2 is attached to the n-type crystal through a load resistance R_L.

Through the first half-cycle of the a.c. input, when the terminal S_1 of secondary is consider positive and S_2 is negative, the junction diode is forward-biased. Therefore it conducts and current flows through with the load R_L in the direction indicated by arrows. The current produces through the load an output voltage of the identical shape as the half-cycle of the input voltage. Through the second half-cycle of the a.c. input, the terminal S_1 is negative and S_2 is positive. The diode is now reverse-biased. Therefore there is almost zero current and zero output voltage across R_L. The procedure is repeated. Thus, the output current is unidirectional, but intermittent and pulsating, as shown in lower part of Fig. (b).



(a)

Definitions

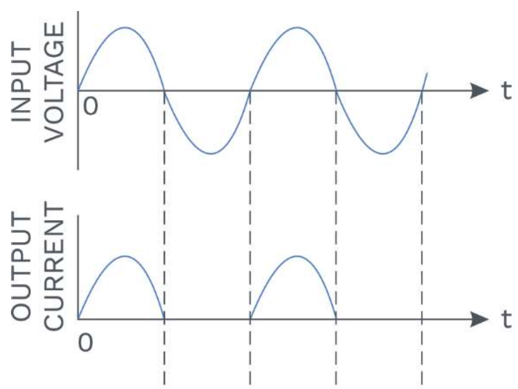
An electronic device which converts alternating current / voltage into direct current/ voltage is called 'rectifier'.

Concept Reminder

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

KEY POINTS

- Rectifier
- Half-wave rectifier
- Full-wave rectifier



(b)

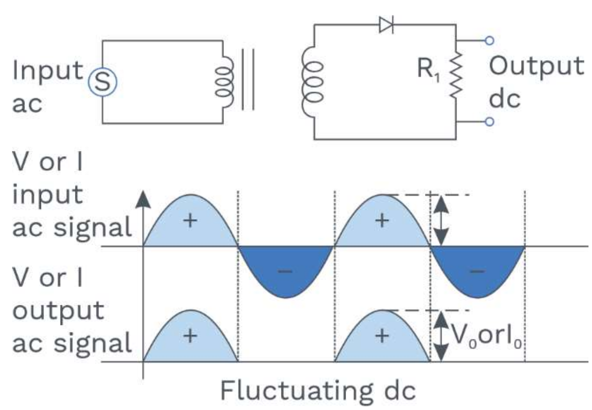
While the output- current corresponds to one half of the input voltage wave, the other half being missing, the method is called half-wave rectification.

The use of the transformer is to supply the essential voltage to the rectifier. But direct current at high voltage is to be found from the rectifier, as is essential for power supply, then a step-up transformer is used, as indicated in Fig. (a). In many solid-state equipment, however, direct current of low voltage is needed. In that case, a step-down transformer is utilised in the rectifier.

Concept Reminder

The purpose of the transformer is to supply the necessary voltage to the rectifier. If direct current at high voltage is to be obtained from the rectifier, as is necessary for power supply, then a step-up transformer is used.

Note :



(i) Through positive half cycle

Diode $\longrightarrow$ forward biased

Output signal $\longrightarrow$ obtained

(ii) Through negative half cycle

Diode $\longrightarrow$ reverse biased

Output signal $\longrightarrow$ not obtained

(iii) Output voltage is noted across the load resistance R_L. It is not constant but pulsating (mixture of ac and dc) in nature.

(iv) Average output in one cycle

$$I_{dc} = \frac{I_0}{\pi} \text{ and } V_{dc} = \frac{V_0}{\pi}; I_0 = \frac{V_0}{r_f + R_L}$$

(r_f = forward biased resistance)

(v) r.m.s. output: $I_{rms} = \frac{I_0}{2}, V_{rms} = \frac{V_0}{2}$

(vi) The ratio of the useful alternating component of the output voltage or current of the dc component is known as ripple factor.

$$r = \frac{I_{ac}}{I_{dc}} = \left[\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1\right]^{1/2} = 1.21$$

(vii) Peak inverse voltage (PIV):- The maximum reverse biased voltage that can be utilized before commencement of Zener region is named the PIV. When diode is not performing PIV across it = V_0

(viii) Efficiency: It is given by%

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{40.6}{1 + \frac{r_f}{R_L}}$$

If $R_L >> r_f$ then $\eta = 40.6\%$

If $R_L = r_f$ then $\eta = 20.3\%$

(ix) Form factor $= \frac{I_{rms}}{I_{dc}} = \frac{\pi}{2} = 1.57$

(x) The ripple frequency (ω) for the half wave rectifier is same as that of a.c.

Rack your Brain

Zener breakdown takes place if:

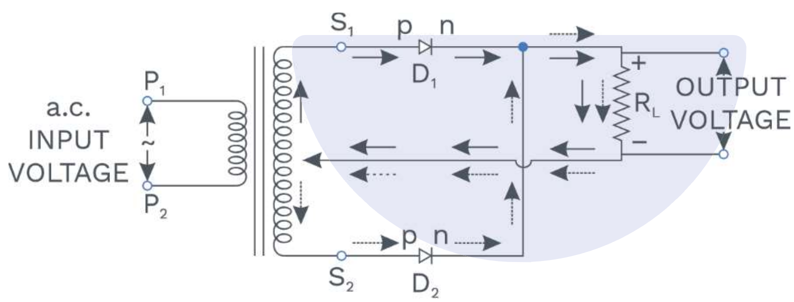
(1) Doped impurity is low

(2) Doped impurity is high

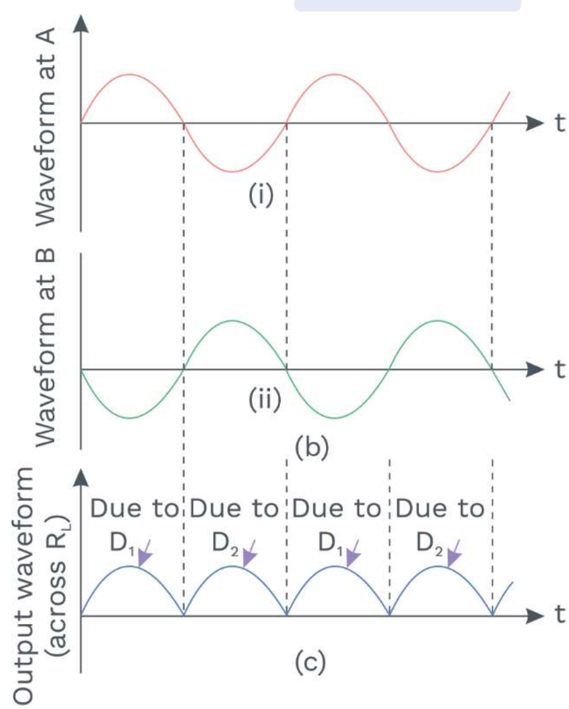
(3) Less impurity in N-part

(4) Less impurity in p-type

(b) p-n Junction Diode as Full-wave Rectifier: In the a full-wave rectifier, an unidirectional, pulsating output current is found for both halves of the a.c. input voltage. Essentially, it requires two junction diodes so connected such that one diode rectifies one half and 2nd diode rectifies the 2nd half of the input. The circuit for the full-wave rectifier is shown in Fig. (a) and the input and the output wave forms in Fig. (b). The a.c. input voltage is applied across primary P_1P_2 of the transformer. The terminals S_1 and S_2 of secondary are connected to the p -type crystals of the junction diodes D_1 and D_2 whose n–type crystals are connected to each other. A load resistance of R_L is connected across the n-type crystals and the central-tap T of the secondary S_1S_2.

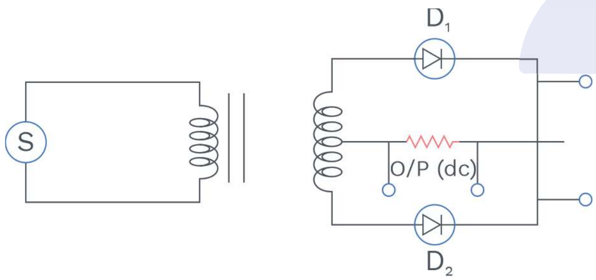


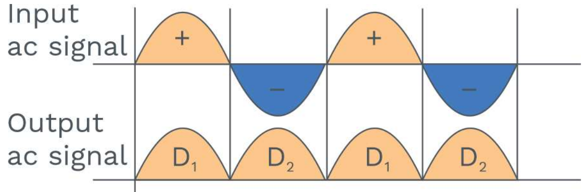
(a)



During the 1st half-cycle of the a.c. input voltage, terminal S_1 is suppose positive relative to T and S_2 is negative. In this situation, junction diode D_1 is forward-biased and D_2 is reverse-biased. Therefore, D_1 conducts while D_2 doesn't. The conventional current flows through the diode D_1, load R_L and the upper half of secondary winding, as shown by solid arrows. During the 2nd half-cycle of the input voltage, S_1 is negative relative to T and S_2 is positive. Now, D_1 is reverse-biased and doesn't conduct while D_2 is forward-biased and conducts. The current now flows across D_2, load R_L and the lower half of the secondary, as shown by the dotted arrows. It can be seen that the current in load R_L flows in the same direction for both half-cycles of the a.c. input voltage. Thus, output current is a continuous series of the unidirectional pulses. However, it may be made fairly steady by means of smoothing filters.

Note :-





(i) During positive half cycle

Diode: $D_1 \longrightarrow$ forward biased

$D_2 \longrightarrow$ reverse biased

Output signal obtained due to D_1 only

Concept Reminder

- If half wave rectifier ripple frequency is same as ac source.
- In full wave rectifier ripple frequency is double as of ac source.

(ii) During negative half cycle

Diode: $D_1 \longrightarrow$ reversed biased

$D_2 \longrightarrow$ forward biased

Output signal $\longrightarrow$ obtained due to D_2 only

(iii) Fluctuating dc $\longrightarrow$ Filter $\longrightarrow$ constant dc.

(iv) Output voltage is obtained through the load resistance R_L. It is not constant but they pulsating in nature.

(v) Average output: $V_{av} = \frac{2V_0}{\pi}, I_{av} = \frac{2I_0}{\pi}$

(vi) r.m.s. output = $V_{rms} = \frac{V_0}{\sqrt{2}}, I_{rms} = \frac{I_0}{\sqrt{2}}$

(vii) Ripple factor: r = 0.48 = 48%

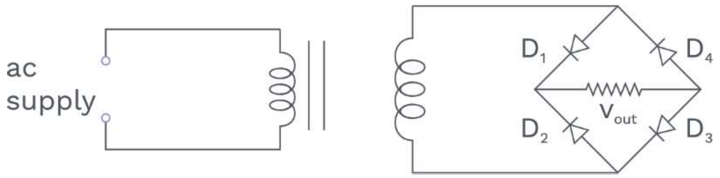
(viii) Ripple frequency: The ripple frequency of full wave rectifier = 2 × (Frequency of input ac)

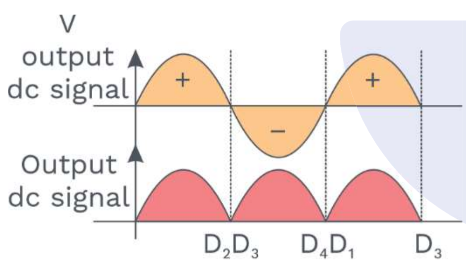
(ix) Peak inverse voltage (PIV): Its value is $2V_0$.

(x) Efficiency: $\eta\% = \frac{81.2}{1+\frac{r_1}{R_L}}$ for $r_f << R_L, \eta = 81.2\%$

S.No.	Half wave rectifier	Full wave rectifier
1.	$I_{av} = I_{dc} = \frac{I_0}{\pi}$	$I_{av} = \frac{2I_0}{\pi}$
2.	$E_{av} = E_{dc} = \frac{V_0}{\pi}$	$E_{av} = \frac{2V_0}{\pi}$
3.	$r = 1.21 \therefore I_{ac} > I_{dc}$	$r = 0.48 \therefore I_{ac} < I_{dc}$
4.	$\eta = \frac{0.406}{1+\frac{r_P}{R_L}}$	$\eta = \frac{0.812}{1+\frac{r_P}{R_L}}$
5.	Form factor = 1.57	1.11
6.	Ripple frequency = ω	2ω
7.	Pulse frequency = $\frac{\text{input pulse frequency}}{2}$	Pulse freq = Input pulse frequency

- **Full wave bridge rectifier:** 4 diodes D_1, D_2, D_3 and D_4 are used in a circuit. During the positive half D_1 and D_3 are in forward biased and D_2 and D_4 are reverse biased. During the negative half cycle D_2 and D_4 are in forward biase and D_1 and D_3 are reverse biased.





Filter Circuit

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

- **Capacitor Filter :-**

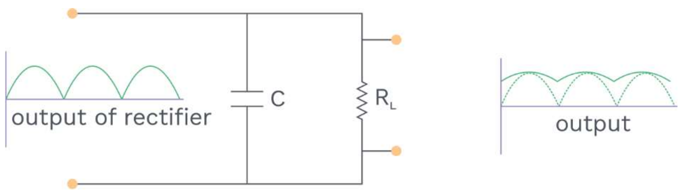
When the voltage across capacitor is rising, it gets charge. If there is no any external load, it remains charged to peak voltage of rectified output. When there is a load, it will get discharged through load and the voltage across it starts to fall. In the next half-cycle of the rectified output it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

Rack your Brain

In a full wave rectifier circuit operating from 50 Hz mains frequency, the fundamental frequency in the ripple would be

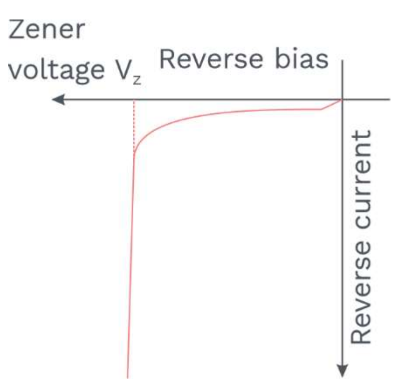
(1) 25 Hz (2) 50 Hz

(3) 70.7 Hz (4) 100 Hz



Special Purpose p-n Junction Diodes:-
Junction diodes are of many types and calculate a wide range of applications in electronics. Some of them are discussed below.

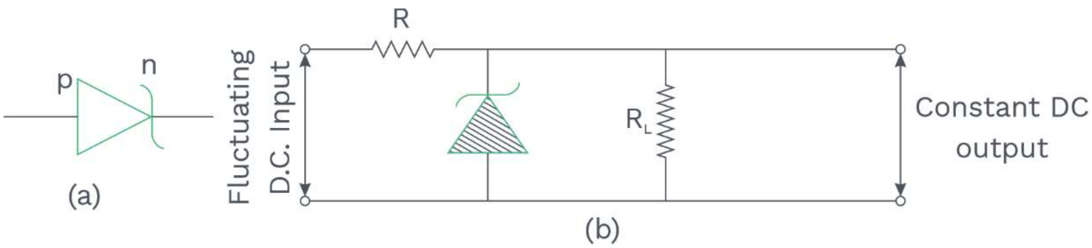
Zener diode:-
In the usual junction diodes, the reverse current increases rapidly at large reverse breakdown voltage. The junction diodes of low power rating are destroyed by reverse breakdown voltage. The specially constructed junction diodes which can operate in the reverse breakdown voltage region continuously without being scratched, are called Zener diodes. These are normally highly doped Silicon diodes. Silicon is favoured over germanium because of its higher thermal stabilities



A Zener diode is symbolized by the symbol shown in figure (a).

Definitions

The specially designed junction diodes which can operate in the reverse breakdown voltage region continuously without being damaged, are called Zener diodes.



Zener diode as a voltage regulator:-

An important function of Zener diode is that it can be used as a voltage regulator. The regulating activity takes place because of the fact that in reverse breakdown region, minor change in voltage produces a very larger change in current. In the Zener zone, the resistance of the Zener diode drops noticeably. Now we consider a Zener diode and a dropping resistor R attached to a varying dc source supply such that Zener diode is reverse biased (figure (b)). When the utilised voltage is such that the voltage through Zener is less than Zener voltage, the diode will not conduct. Therefore, the output voltage will be proportional to the input voltage and is given by $V_{out} = \frac{R_L}{R + R_L} V_{in}$, but when input voltage is such that voltage developed around the Zener is more than Zener voltage, the diode will conduct and will offer very slight resistance.

Therefore, it will allow all the extra current and the output voltage will be equal to Zener voltage i.e., $V_{out} = V_z$. But each Zener diode has a certain value of current limit and comparable power limit. If current in the Zener diode exceeds this limit, the diode will burn out. Note that Zener diode is always used in reverse bias.

Ex. A zener diode having breakdown voltage equal to 15 V, is used in a voltage regulator circuit shown in figure. Find the current through the diode.

Concept Reminder

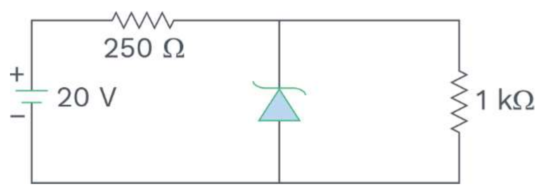
An important application of Zener diode is that it can be used as a voltage regulator.

KEY POINTS

- Zener diode
- Breakdown region

Concept Reminder

A Photodiode is again a special purpose p-n junction diode fabricated with a transparent window to allow light to fall on the diode. It is operated under reverse bias.



Sol. Current through $250\,\Omega$ is

$$I_1 = \frac{\text{Net voltage}}{\text{Resistance}} = \frac{(20-15)\text{V}}{250\,\Omega} = 20\times10^{-3}\,\text{A} = 20\,\text{mA}$$

Current through 1 kΩ is

$$I_2 = \frac{15\text{ V}}{1\text{k}\Omega} = 15\times10^{-3}\,\text{A} = 15\,\text{mA}$$

So, current through diode is

$$I_1 - I_2 = 20\,\text{mA} - 15\,\text{mA} = 5\,\text{mA}$$

Concept Reminder

The magnitude of the photocurrent depends on the intensity of incident light (photocurrent is proportional to incident light intensity).

Optoelectronic Junction Devices

So far we discussed how a semiconductor diode behaves under applied electrical inputs. In this section, we will discuss those semiconductor diodes in which current carriers are generated by photons (a process called photo-excitation). Hence, these devices are called optoelectronic devices. They are:

(i) Photo diodes which are used for detecting optical signals and hence they are also called photo detectors.

(ii) Light-emitting diodes which convert the electrical energy into light.

(iii) Photovoltaic devices which convert the optical radiation into electricity e.g., solar cells.

Concept Reminder

The emission of electrons from the host atoms due to the high electric field is known as internal field emission or field ionisation. The electric field required for field ionisation is of the order of 10^6 V/m.

(i) **Photo diode:** In semiconductors, current carriers are produced when energy is supplied to release electrons from valence band. In photo diodes this energy is supplied in the form of light energy. A junction diode created from photosensitive semiconductor is called a photo diode. It is represented by the symbol as shown in figure. In photo diode one region is made so thin that incident light may reach the depletion region.

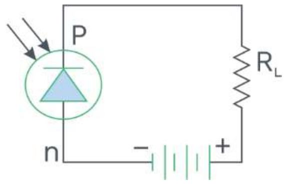
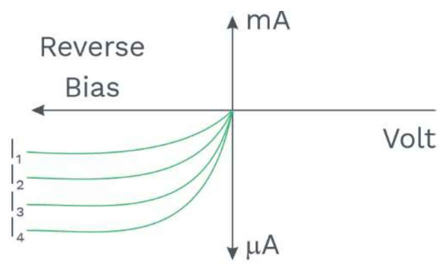


Photo diode is operated under reverse bias. When the photo diode is illuminated with energy greater than the energy gap (E_g) of the semiconductor, when electron-hole pairs are generated. The construction of photo diode is such that electron-hole pairs are created in or near the depletion region of the diode. Inside diode, electric field is such that electrons are collected on the N-side and holes are collected on the P-side giving rise to an emf. Therefore, when an external resistance is connected then current flows through it. The photo-current is proportional to incident light intensity.

If a photo diode will be forward-biased then photo current will be more, still a photo diode is connected in reverse bias because fractional change in reverse-biased current is easier to observer when light intensity falling on it changes. Thus photo diodes can be used as photo detector to detect optical signals. The typical I-V characteristics of photo diode is shown below.



$(I_4 > I_3 > I_2 > I_1)$

Ex. A p-n junction diode is prepared of a material with the band gap of 2 eV. Find the minimum frequency of radiation that can be absorbed by the material?

Sol. Use energy E = hf

$$\therefore \quad f = \frac{E}{h} = \frac{2 \times 1.6 \times 10^{-19}\,J}{6.6 \times 10^{-34}\,J-s} \approx 5 \times 10^{14}\,Hz$$

(ii) When a junction diode is forward-biased, energy is released at the junction due to recombination of electrons and holes. In case of silicon and germanium diodes, the energy released is in infrared region. In the junction diode made of gallium arsenide or indium phosphide, the energy is released in visible region. Forbidden energy gap for GaAs is 1.4 eV which gives infrared radiation when recombination of electrons and holes takes placed but when this is doped with Al, the width of depletion region increases, so it gives visible light in forward bias.

Light-emitting diode is a strongly doped p-n junction encapsulated with a transparent cover so that emitted light can come out. When the forward current of diode is small intensity of light emitted is small. As the forward current increases, intensity of the light increases and reaches a maximum. Further increase in forward current results in decrease of the light intensity. LEDs are biased such that light-emitting efficiency is maximum.

Rack your Brain

In a transistor the base is very lightly doped as compared to the emitter because by doing so

(1) The flow across the base region is mainly because of electrons

(2) The flow across the base region is mainly because of holes

(3) Recombination is decreased in the base region

(4) Base current is high

Concept Reminder

The generation of emf by a solar cell, when light falls on, it is due to the following three basic processes: generation, separation and collection.

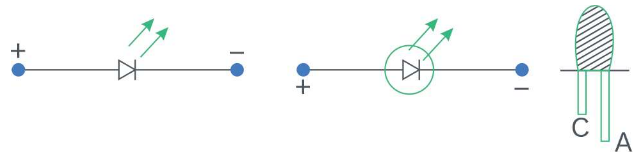
The V-I characteristics of an LED is similar to that of a silicon junction diode but threshold voltages are much high and slightly different of each colour. The reverse breakdown voltages of the LEDs are very low, approximately around 5 V. So high reverse voltages should not appear across them.

LEDs are used in the remote control system, optical communication system, burglar alarm system etc. Advantages of LEDs over low power conventional incandescent lamps is that they have less operational voltages, less power consumption, fast action with no ward up time, are nearly monochromatic, have ruggedness and long life have quick switching on-off capability.

Concept Reminder

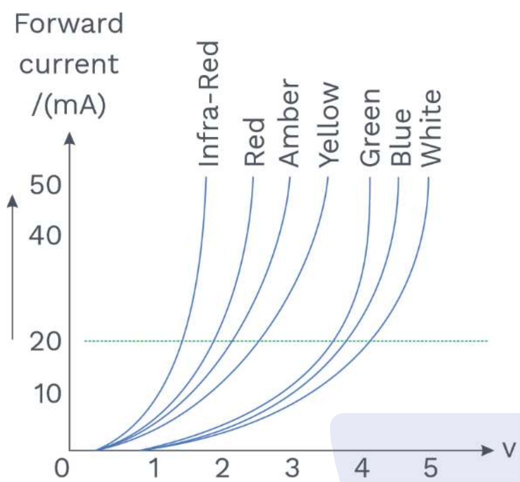
The semiconductor used for fabrication of visible LEDs must at least have a band gap of 1.8 eV (spectral range of visible light is from about 0.4 μm to 0.7 μm, i.e., from about 3 eV to 1.8 eV).

The I-V characteristics of a light-emitting diode (LED): The light-emitting diode, represented by either of two symbols shown here, is basically same as the conventional p-n junction diode. Its actual shapes is also shown here. The shorter, of its 2 leads, corresponds to its 'n' (or cathode side) while longer lead corresponds to its 'p' (or anode side).



The general shape, of I-V characteristics of a LED, is related to that of a conventional, p-n junction diode. However, 'barrier potential' veries slightly with the colour.

The colour of light emitted by a given LED, depends on its band-gap energy. The energy of photons emitted, is same to (or slightly) less than this band gap energy. The other main characteristic, of emitted light, its intensity, is calculated by the forward current conducted by the junction.



LEDs usually use a low-voltage DC supply for their operation. A particular LED has a 'safe value' of forward current that it can carry. This value is around 5.0 mA for the usual simple LEDs and can go up to 30 mA, or more, for LEDs needed for offering a high brightness output light. In exercise, it is usual to have a (proper) series resistor, connected to the LED, so that forward current is limited to within its 'safe value'.

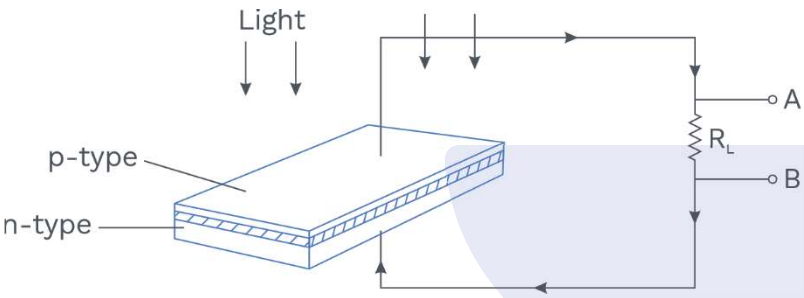
(iii) **Solar cell:** A junction diode, in which one of the p or n-regions is made very thin (so that light energy falling on the diode is not greatly absorbed before reaching the junction), can be used to convert light energy into electrical energy.

In a solar cell, one zone is made very thin so that most of the light incident on it reaches the depletion region. In this diode (selenium is used as semiconductor) when photons of visible light event to depletion region, electrons leave from valence band to conduction band and generating electron-hole pairs. These free electrons under the effect of barrier electric field moves to

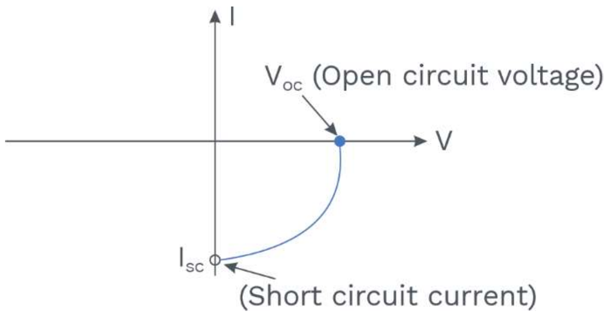
Concept Reminder

To create an e-h pair, we spend some energy (photoexcitation, thermal excitation, etc.). Therefore, when an electron and hole recombine the energy is released in the form of light (radiative recombination) or heat (non-radiative recombination).

n-region and holes move to p-region, so the potential of p-region increases and that of n-region decreases. A net potential difference extends across the junction. Hence, when a load resistance is connected to p-n junction, electrons flow in the resistor from B to A resulting into a net current from A to B as shown in figure.



Note that the I-V characteristics of solar cell is drawn in the fourth quadrant of the co-ordinate axes. This because a solar cell does not draw current but supplies the same to the load.



Concept Reminder

The I–V characteristics of solar cell is drawn in the fourth quadrant of the coordinate axis. This is because a solar cell does not draw current but supplies the same to the load.

Since solar radiation spectrum has maximum intensity of 1.5 eV, therefore, semiconductors with band gap close to 1.5 eV are ideal resources for solar cell fabrication. Materials used are Si, GaAs, CdTe, $CuInSe_2$ etc. Materials should have high optical absorption, electrical conductivity, low cost and availability. Solar cells are extensively used to power electronic devices in satellites and space vehicles, in calculators etc.

Ex. A light-emitting diode (LED) has the voltage drop of 2 V across it and passes the current of 10 A , when it operates with the 6 V battery with a limiting resistor 'R'. What is the value of R ?

Sol. $I = \frac{V}{R}$ or $R = \frac{V}{I}$

$$R = \frac{(6-2)V}{10 \times 10^{-6} A} = 400\,k\Omega$$

Concept Reminder

The V-I characteristics of a LED is similar to that of a Si junction diode. But the threshold voltages are much higher and slightly different for each colour.

Junction Transistor:-

Transistor structure and action:

A transistor has 3 doped regions forming 2 p-n junctions between them. There are 2 types of transistors, as shown in diagram.

(i) **n-p-n transistor:** Here two segments of n-type semiconductor (emitter and collector) are separated by the segment of p-type semiconductor (base).

(ii) **p-n-p transistor:** Here 2 segments of p-type semiconductor (termed as the emitter and collector) are separated by the segment of n-type semiconductor (termed as base). The schematic representations of the n-p-n and the p-n-p configuration are shown in diagram. All the 3 segments of a transistor have different thickness and their doping levels are also different. In schematic symbols used for representing the p-n-p and n-p-n transistors (figure b) the arrowhead shows direction of conventional current in transistor. A brief description of the 3 segments of a transistors is given as follows:

Concept Reminder

Three segments of a transistors are:

(a) Emitter

(b) Base

(c) Collector

Emitter: This is segment on one side of transistor shown in fig.(a). It is of small size and heavily doped. It supplies the large number of the majority carriers for the current flow through transistor.

Base: This is central segment. It is very thin & lightly doped.

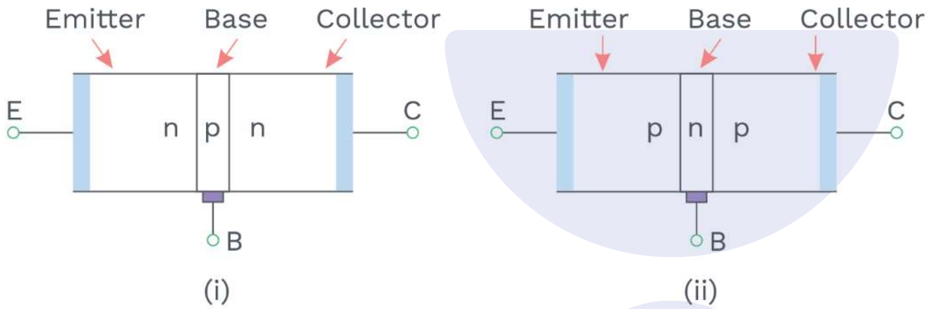
Collector: This segment collects the major portion of majority carries supplied by the emitter. The collector side is moderately dopping and larger in size as compared to the emitter.

In case of a p-n junction, there is a formation of depletion region through the junction. In example of a transistor, depletion regions are constructed at the emitter base-junction and the base collector junction.

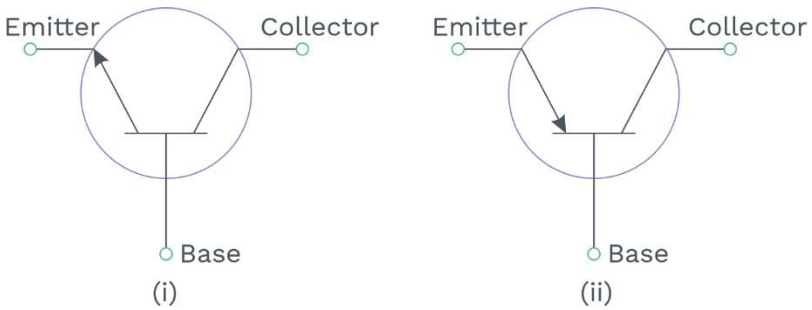
Concept Reminder

In transistor,

$I_E = I_C + I_B$.



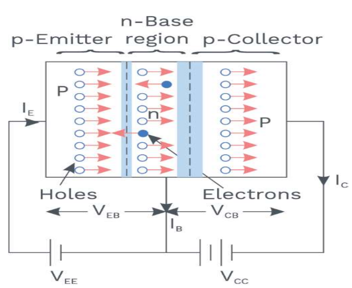
(a) Schematic representations of n–p–n transistor and p–n–p transistor



(b) Symbols for n–p–n and p–n–p transistors.

The transistor used as an amplifier, with its emitter-base junction forward biased and base-collector junction reverse biased. This situation is shown in diagram, where V_{CC} and V_{EE} are used for creating respective biasing. When transistor is biased in this way it is said to be in the active state. We represent the voltage between

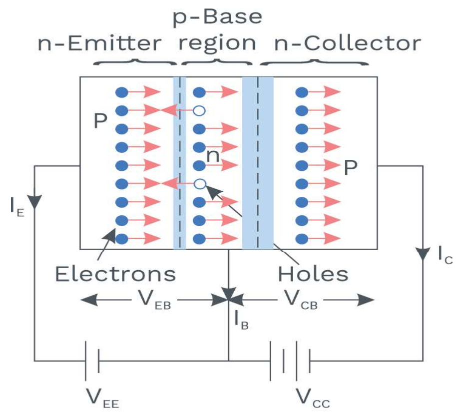
the emitter and base as V_{EB} and that between collector and base as V_{CB}.
In figure, base is a common terminal for the 2 power supplies whose other terminals are connected to the emitter and collector, respectively. So, two power supplies are represented as V_{EE}, and V_{CC}, respectively. In circuits, where emitter is common terminal, the power supply between the base and emitter is denoted as V_{BB} and that between collector and emitter as V_{CC}. The heavily dopping emitter has a high concentration of the majority carriers, which will be holes in a p-n-p transistor and the electrons in an n-p-n transistor. These majority carriers enter base region in large numbers. The base region is thin and lightly doped. Thus, the majority carriers there would be few. In a p-n-p transistor the majority carries in the base are electrons since the base is of the n-type semiconductor. The large number of the holes entering the base from emitter swamps the small number of electrons there. As the base collector-junction is reverse biased, these holes, which appear as the minority carriers at the junction, can easily cross junction and enter the collector. The holes in base could move either towards the base terminal to combine with electrons move in from outside or cross the junction to enter into the collector and reach collector terminal. The base is create thin so that most of the holes locate themselves near the reverse-biased base-collector junction and thus cross the junction instead of moving to the base terminal.



(a)

Rack your Brain

The input signal given to a CE amplifier having a voltage gain of 150 is $V_i = 2\cos\left(15t + \frac{\pi}{3}\right)$. Find the corresponding output signal.



(b)

Note: Due to the forward bias a large current enters emitter-base junction, but most of it is diverted to the adjacent reverse-biased base-collector junction and current coming out of the base becomes a very small fraction of current that entered the junction. If we represent hole current and the electron current crossing the forward biased junction by the sum $I_h + I_e$. We see that emitter current $I_E = I_h + I_e$ but base current $I_B << I_h + I_e$, because a major part of I_E goes to the collector instead of coming out of the base terminal. So, the base current is a small fraction of emitter current.

It is obvious from above description and also from a straight forward application of Kirchhoff's law to figure(a) that emitter current is sum of collector current and base current :

$$I_E = I_C + I_B$$

We also see that $I_C \approx I_E$,

Our description of direction of motion of the holes is identical with direction of the conventional current. But the direction of motion of the electrons is just opposite to that of current. Thus in a p-n-p transistor current enters from the emitter into base whereas in a n-p-n transistor it

Concept Reminder

The transistor can be connected in either of the following three configurations:
Common Emitter (CE), Common Base (CB), Common Collector (CC).

enters from base into the emitter. The arrowhead in emitter shows direction of the conventional current. We can conclude that in active state of the transistor the emitter-base junction acts as a low resistance while base collector acts as a high resistance.

In a transistor, only 3 terminals are available viz emitter (E), base (B) and collector (C). Therefore in a circuit input/output connections have to be such that the one of these (E, C or B) is common to both input and output. Therefore, the transistor can be connected in either of following 3 configurations:

Common Emitter (CE), Common Collector (CC), Common Base (CB).

Working of Transistor:-

(1) There are 4 possible ways of biasing two P-N junctions (emitter junction and collector junction) of transistor.

(i) Active mode : Also known as the linear mode operation.

(ii) Saturation mode : Max. collector current flows and transistor acts as a closed switch from the collector to the emitter terminals.

(iii) Cut-off mode : Represents operation like an open switch where only the leakage current flows.

(iv) Inverse mode : The collector and emitter are inter changed.

Different modes of operation of a transistor

Operating mode	Emitter base bias	Collector base bias
Active	Forward	Reverse
Saturation	Forward	Forward
Cut off	Reverse	Reverse
Inverse	Reverse	Forward

(2) A transistor is mostly used in active region of operation i.e., the emitter base junction is forward biased and the collector base junction is reverse biased.

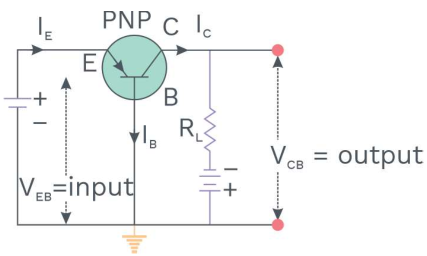
(3) From the operation of the junction transistor it is found that when the current in the emitter circuit changes. There is corresponding change in the collector current

(4) In each state of transistor there is an input port and an output port. In general every electrical quantity (V or I) obtained at output is controlled by the input.

Transistor Configurations

A transistor may be connected in a circuit in following 3 different configurations.

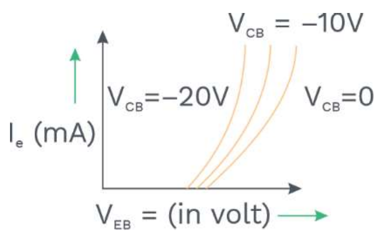
(1) **CB configurations :** Base is common to the both emitter and collector.



(i) Input current = I_e
(ii) Input voltage = V_{EB}
(iii) Output voltage = V_{CB}
(iv) Output current = I_C

With small increase in the emitter-base voltage V_{EB}, the emitter current I_e increases rapidly because of the small input resistance.

(v) **Input characteristics**: If V_{CB} = constant, curve between I_e & V_{EB} is known as input characteristics. It is also known as the emitter characteristics:



Input characteristics of NPN transistor are also similar to the above figure but I_e and V_{EB} both are negative and V_{CB} is positive. Dynamic input resistance of a transistor is given by

$$R_i = \left(\frac{\Delta V_{EB}}{\Delta I_e}\right)_{V_{CB=constant}}$$

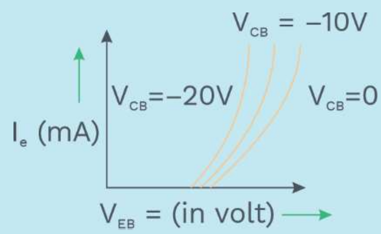
{R_i is of the order of 100 Ω}

(vi) **Output characteristics:** Taking the emitter current I_e constant, the curve drawn between I_C and V_{CB} are known as output characteristics of CB configuration.

Dynamics output resistance

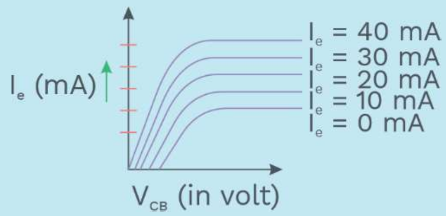
Concept Reminder

Input characteristics of CB configuration,

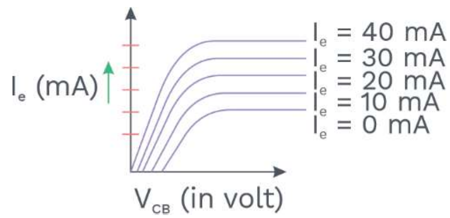


Concept Reminder

Output characteristics of CB configuration,



$$R_0 = \left(\frac{\Delta V_{CB}}{\Delta i_C}\right)_{i_e = \text{constant}}$$



Note:- Transistor as CB amplifier

(i)

$$\text{ac current gain } \alpha_c = \frac{\text{Small change in collector current } (\Delta I_c)}{\text{Small change in collector current } (\Delta I_e)}$$

(ii)

$$\text{dc current gain } \alpha_{dc} (\text{or } \alpha) = \frac{\text{Collector current } (I_c)}{\text{Emitter current } (I_e)}$$

value of α_{dc} lies between 0.95 to 0.99

(iii) Voltage gain

$$A_v = \frac{\text{Change in output voltage } (\Delta V_0)}{\text{Change in input voltage } (\Delta V_i)}$$

$$\Rightarrow A_v = \alpha_{ac} \times \text{Re sis tance gain}$$

(iii) Power gain $= \dfrac{\text{Change in output voltage } (\Delta P_0)}{\text{Change in input voltage } (\Delta P_C)}$

$$\Rightarrow \text{Power gain} = \alpha_{ac}^2 \times \text{Re si tance gain}$$

Common Emitter (CE):-

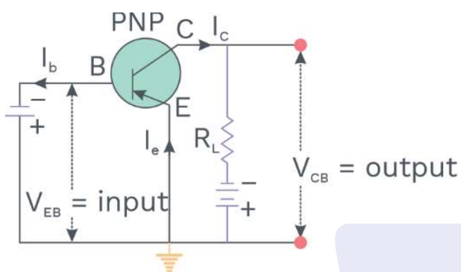
The transistor is very widely used in the CE configuration. When a transistor is utilised in CE configuration, the input is between the emitter and the base and output is between the collector and the emitter. The variation of base current I_B with base-emitter voltage V_{BE} is named the input characteristic. The output characteristics are monitored by the input characteristics. This implies that the collector the current varies with

Concept Reminder

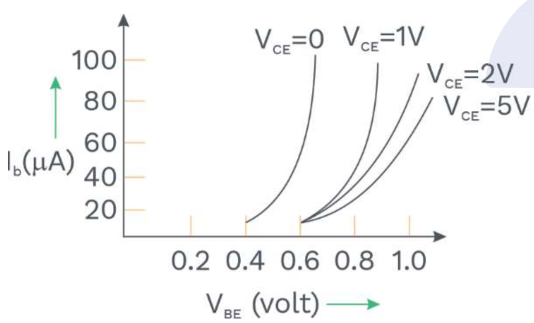
- $\alpha = \dfrac{I_c}{I_e}$
- $\beta = \dfrac{I_c}{I_B}$

Concept Reminder

Input characteristics of CB configuration, base current. CE configurations : Emitter is common to both the base and collector. The graphs between voltages and currents when the emitter of a transistor is common to input and output circuits are known as CE characteristics of a transistor.



Input characteristics : Input characteristics curve is drawn between base current I_b and emitter base voltage V_{EB}, at constant collector emitter voltage V_{CE}

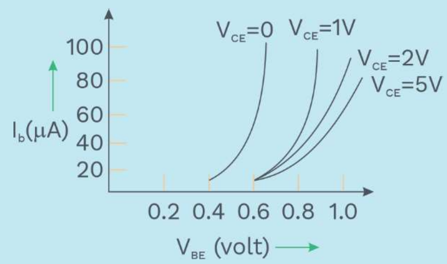


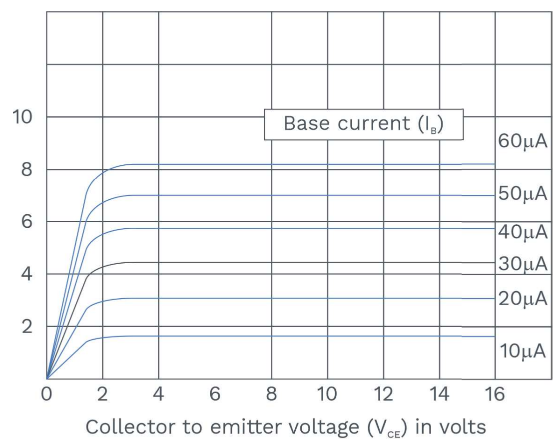
Dynamic input resistance $R_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE} \rightarrow \text{constant}}$

Output characteristics: Variation of collector current I_C with V_{CE} can be noticed for V_{CE} between 0 to 1 V only. The value of V_{CE} up to which the I_C changes with V_{CE} is called knee voltage. The transistor are operated in region above knee voltage.

Concept Reminder

Input characteristics of CE configuration,





Dynamic output resistance $R_0 = \left(\dfrac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B \to \text{constant}}$

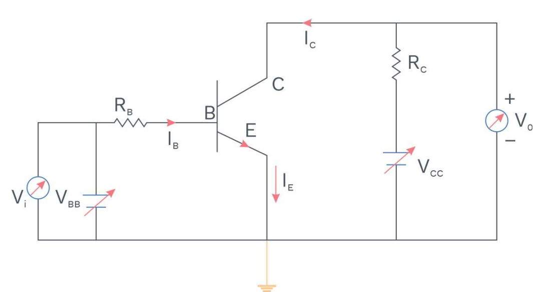
(b) Transistor as a device:-

The transistor may be used as a device application depending on configuration used (namely CB, CC and CE), biasing of the E-B and B-C junction and the operation region namely the cutoff, active region and saturation. When the transistor is used in cutoff or saturation state it behaves as a switch. On the other side for using transistor as an amplifier, it has to operate in active region.

(i) Transistor as a switch:

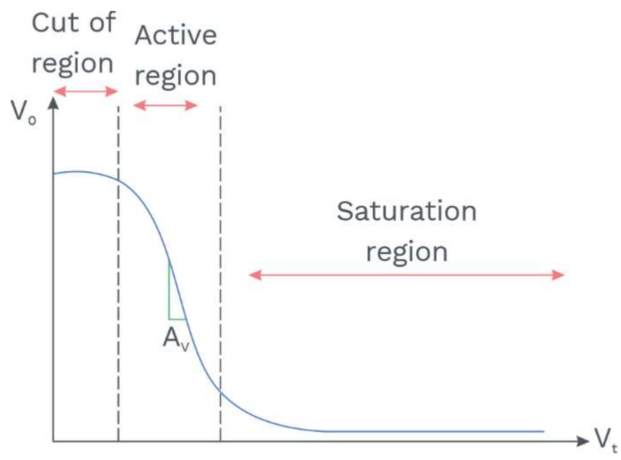
We shall try to understand operation of the transistor as a switch by analysing the behavior of the base-biased transistor in the CE configuration as shown in dia. (a). Applying Kirchhoff's voltage rule to the input and output sides of this circuit, we get

$V_{BB} = I_B R_B + V_{BE}$ and $V_{CE} = V_{CE} = V_{CC} - I_C R_C$



(a)

We shall treat V_{BB} as the dc input voltage V_i and V_{CE} as dc output voltage Vo. So, we have $V_i = V_B R_B + V_{BE}$ and $V_0 = V_{CC} - I_C R_C$



(b)

Let us see how V_0 varies as V_i increases from zero onwards. In the case of the Si transistor, as long as input V_i is less than 0.6 V, transistor will be in cut off state and the current I_C will be zero. Therefore $V_O = V_{CC}$.

When V_i becomes greater than 0.60 V transistor is in active state with a few current I_C in the output path and output V_0 decrease as the term I_CR_C increases. With increase of V_i, I_C both increases almost linearly and so V_0 decreases linearly till its value becomes less than about 1 V. Beyond this, the change becomes non-linear and transistor goes into the saturation state. With more increase in V_i the output voltage is notice to decrease further towards zero though it may never become zero. If we plot the V_0 vs V_i curve, [also called the transfer characteristics of the base-biased transistor (figure b], we see that between active state and cut off state and also between active state and saturation state there are zones of non-linearity showing that the transition from cut-off state to active state and from the active state to the saturation state are not sharply defined. As long as V_i is low and unable to forward-bias the transistor, the V_0 is high (at V_{CC}). If V_i is high enough to drive transistor into saturation very near to zero. When transistor is not conducting it is said to be switched off and when it is driven into the saturation it is said to be switched on. This shows that if we define the low and high states as below and above certain voltage levels corresponding to cut-off and saturation of the transistor, then we can tell that a low input switches the transistor turn-off and a high input switches it on.

(ii) **Transistor as an Amplifier (CE-Configuration):-** To operate the transistor as an amplifier it is essential to fix its operating point someplace in the middle of its active region. If we fix the amount of V_{BB} equivalent to a point in the middle of linear part of the transfer curve then dc base current I_B would be constant and resultant collector current I_C will be constant.

The dc (direct current) voltage, $V_{CE} = V_{CC} - I_C R_C$ would remain constant. The operating values of V_{CE} and I_B define the operating point, of the amplifier. If a slight sinusoidal voltage with amplitude v_s is superimposed on the dc base bias by connecting source of that signal in series with V_{BB} supply, then the base current will have sinusoidal variations superimposed on the amount of I_B. As a consequence collector current also will have sinusoidal variants superimposed on the value of collector current (I_C) producing in turn corresponding change in the value of V_0. We can determine the ac variations across the input and output terminals by blocking the dc voltages by larger capacitors.

In the description of the amplifier given above we have not studied any ac signal. In common, amplifiers are applied to amplify alternating signals. Currently let us superimpose an ac input signal v_i (to be amplified) on the bias V_{BB} (dc) as shown in Figure. The output is chosen between the collector and ground. The working of an amplifier be able to easily recognized, if we first think that $v_i = 0$. Then using Kirchhoff's law to the output loop, we get

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

Likewise, the input loop gives

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

when v_i is not zero, we get

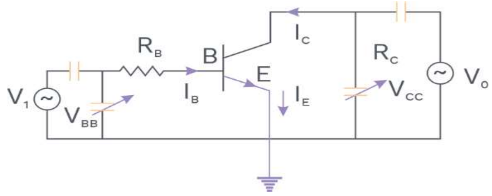
$$V_{BE} + v_i = V_{BE} + I_B R_B + \Delta I_B \ (R_B + r_i)$$

The variation in V_{BE} can be related to input resistance r_i and the change in I_B. Hence

$$v_i = \Delta I_B (R_B + r_i) = r\Delta I_B$$

The change in I_B affects a change in I_C. We define a parameter β_{ac}, which is similar to the β_{dc} defined in equation as

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B} = \frac{I_c}{I_b}$$



Which is also called as the ac current gain A_i. Usually β_{ac} is close to d_{ac} in the linear zone of the output characteristics. The change in current, I_C due to a change in current, I_B causes a change in V_{CE} and voltage drop across the resistor R_L because V_{CC} is fixed. These changes can be given by Eq. as

$\Delta V_{CC} = \Delta V_{CE} + R_L \Delta I_C = 0$ or $\Delta V_{CE} = -R_L \Delta I_C$

The change in V_{CE} is the output voltage v_0.

From equation we get $v_0 = \Delta V_{CE} = -\beta_{ac} R_L \Delta I_B$

The voltage gain of the amplifier is

$$A_v = \frac{v_0}{v_i} = \frac{\Delta V_{CE}}{r \Delta I_B} = \frac{-\beta_{ac} R_L}{r}$$

The negative sign signifies that output voltage is opposite with phase with the input voltage. From the conversion of the transistor characteristics, you have seen that there is a current gain β_{ac} in the CE configuration. Here we have also notice the voltage gain A_v. Hence, the power gain A_p can be expressed as the product of the current gain and voltage gain. Mathematically

$$A_p = \beta_{ac} \times A_v$$

Since β_{ac} and A_v are greater than 1, we get the ac power gain. However, it should be realised that the transistor is not the power generating device. The energy for higher ac power at output is supplied by the battery.

Concept Reminder

the power gain Ap can be expressed as the product of the current gain and voltage gain. Mathematically

$$A_p = \beta_{ac} \times A_v$$

Note: Transistor as CE amplifier:

(i) ac current gain

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_b}\right) \quad (V_{CE} = \text{constant})$$

(ii) dc current gain $\beta_{dc} = \frac{I_C}{I_b}$

(iii) Voltage gain:

$$A_v = \frac{\Delta V_0}{\Delta V_i} = \beta_{ac} \times \text{Resistance gain}$$

(iv) Power gain $= \frac{\Delta P_0}{\Delta P_i} = \beta_{ac}^2 \times \text{Resistance}$

(v) Trans conductance (g_m):

The ratio of the variation in the collector current to the change in the emitter base voltage is known as transconductance. i.e. $g_m = \frac{\Delta I_c}{\Delta V_{EB}}$.

Also $g_m = \frac{A_v}{R_L}$;

R_L = Load resistance

Relation between α and β:

$$\beta = \frac{\alpha}{1-\alpha} \text{ or } \alpha = \frac{\beta}{1+\beta}$$

CB current gain (α)

CB current gain (α) is the ratio of output current to the input current in common base configuration of a transistor.

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

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

CE current gain (β)

Concept Reminder

Relation between α and β:

$$\beta = \frac{\alpha}{1-\alpha} \text{ or } \alpha = \frac{\beta}{1+\beta}$$

CE current gain (β) is the ratio of the output current to the input current in emitter configuration of the transistor.

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

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}$$

The CB current gain α and CE current gain β are related by the following relations.

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

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

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

The above relations are applicable for both dc and ac current gains.

Comment: The value or α is always less than 1. α ~ 0.9 to 0.99 or more. The value of β is always much greater than 1. (β ~ 95 to 999 or so).

Ex. In a common base transistor amplifier, the input and the output resistance are $500\,\Omega$ and $40\,\Omega$, and the emitter current is 1.0 mA. Find the input and the output voltages. Given $\alpha = 0.95$

Sol. The input voltage is emitter current multiplied by input resistance, that is,

$$V_{in} = i_E \times R_{in} = (1.0 \times 10^{-3}\,A) \times 500\,\Omega = 0.5\,V$$

Similarly, the output voltage is

$$V_{out} = i_C \times R_{out} = \alpha\, i_E \times R_{out}$$

$$= 0.95(1.0 \times 10^{-3}\,A) \times (40 \times 10^{3}\,\Omega) = 38\,V$$

Ex. A P-N-P transistor is used in the CE mode in an amplifier circuit. A change of $40\,\mu A$ in base current brings a change of 2 mA in collector current and 0.04 V in base-emitter voltage. Find the:

(i) input resistance ($R_{inp.}$), and

(ii) the base current amplification factor (β).

If a load of $6\,k\Omega$ is used, then also find the voltage gain of the amplifier.

Sol. Given $\Delta I_B = 40\,\mu A = 40 \times 10^{-6}\,A$

$$\Delta I_C = 2mA = 2 \times 10^{-3}\,A$$

$\Delta V_{BE} = 0.04\ \text{volt}, R_L = 6k\Omega = 6 \times 10^3 \Omega$

(i) Input Resistance,

$$R_{inp.} = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{0.04}{40 \times 10^{-6}} = 10^3 \Omega = 1k\Omega$$

(ii) Current amplification factor,

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{2 \times 10^{-3}}{40 \times 10^{-6}} = 50$$

(iii) Voltage gain in common-emitter configuration,

$$A_v = \beta \frac{R_L}{R_{inp.}} = 50 \times \frac{6 \times 10^3}{1 \times 10^3} = 300$$

Ex. In an N-P-N transistor 10^{10} electrons enter the emitter in 10^{-6} s. 2.0% of the electrons are lost in the base. Determine the current transfer ratio and current amplification factor.

Sol. We know that current = charge/time

$$I_E = \frac{Ne}{t} = \frac{10^{10}(1.6 \times 10^{-19})}{10^{-6}} = 1.6\,\text{mA}$$

The emitter current (I_E) is given by

$$I_B = \frac{2}{100} \times 1.6 = 0.032\,\text{mA}$$

The base current (I_B) is given by

In a transistor, $I_E = I_B + I_C$

$$I_C = I_E - I_B = 1.6 - 0.032 = 1.568\,\text{mA}$$

Current transfer ratio $= \frac{I_C}{I_E} = \frac{1.568}{1.6} = 0.98$

Current amplification factor $= \frac{I_C}{I_B} = \frac{1.568}{0.032} = 49$

Ex. A transistor is used in the CE mode in an amplifier circuit. When a signal of 20 mV is added to the base-emitter voltage, the base current changes by $20\,\mu A$ and the collector current changes by 2 mA. The load resistance is $5k\Omega$. Calculate (a) the factor β, (B) the input resistance R_{BE}, (C) the trans-conductance and (D) the voltage gain.

Sol. (A) $\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{2mA}{20\ \ A} = 100$

(B) The input resistance $R_{BE} = \frac{\Delta I_{BE}}{\Delta I_B} = \frac{20\,mA}{20\,\mu A} = 1k\Omega$

(C) Transconductance = $\frac{\Delta I_c}{\Delta I_{BE}} = \frac{2\,mA}{20\,mV} = 0.1$ mho

(D) The change in output voltage is $R_L \Delta I_c = (5\,k\Omega)(2mA) = 10\,V$

Thus, the voltage gain is, = $\frac{10\ V}{20\,mV} = 500$

Ex. The a-c current gain of the transistor is $\beta = 19$. In its common-emitter configuration, what will be the change in the collector-current for a change of 0.4 mA in the base-current ? What will be the change in the emitter current ?

Sol. By definition, the a.c. current gain β is given by

$$\beta(a.c.) = \frac{\Delta I_c}{\Delta I_B}$$

$$\therefore \quad \Delta I_c = \beta \times \Delta I_B = 19 \times 0.4\,mA = 7.6\,mA$$

The emitter-current is the sum of the base-current and the collector-current $(I_E = I_B + I_C)$

Ex. A transistor is connected in common-emitter (C-E) configuration. The collector-supply is 8 V and the voltage drop across a resistor of 800 Ω in the collector circuit is 0.5 V. If the current gain factor (α) is 0.96, find the base-current?

Sol. The alternating-current gain is

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$

The collector-current is

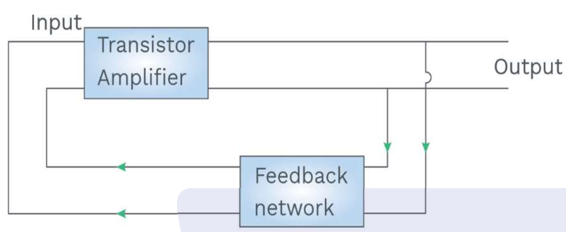
$$I_c = \frac{\text{voltage} - \text{drop across resistor}}{\text{resistance}} = \frac{0.5V}{800\,\Omega} \times 10^{-3}\,A$$

But $\beta = \frac{I_C}{I_B}$, where I_B is base-current.

$$I_B = \frac{I_C}{\beta} = \frac{0.625 \times 10^{-3}\,A}{24} = 26 \times 10^{-6}\,A - 26\,\mu A$$

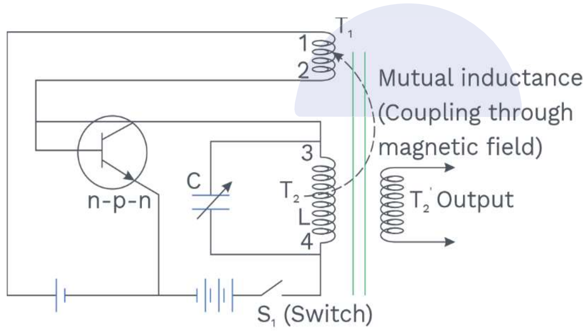
Feedback amplifier and transistor oscillator:

In an oscillator, we get ac output without any external input signal. A portion of the output power is returned back (feedback) to the input in phase with starting power (this process is termed the positive feedback) as shown in Diagram(a). The feedback may be achieved by inductive coupling (through mutual inductance) or LC or RC networks.



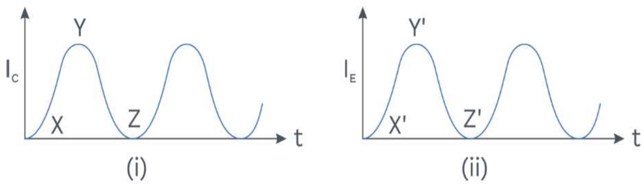
(a)

Assume switch S_1 is put on to apply the proper bias for the first time. Obviously, a surge of the collector current flows in transistor. This current flows through coil T_2 where terminals are numbered 3 and 4 (Figure- b).



(b)

This current does not achieve full amplitude rapidly but increases from X To Y, as shown in figure(c). The inductive coupling between the coil T_2 and coil T_1 right now causes a current to flow in emitter circuit (note that this really is the 'feedback' from input to output). By result of this positive feedback, this current (in T_1 emitter current) also increases from 'X' to 'Y' in figure (c) (ii).



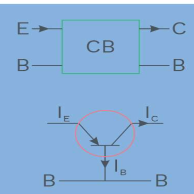
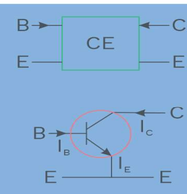
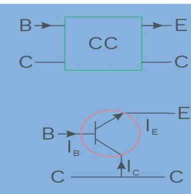
(c)

The current in coil T_2 (collector current), connected in collector circuit acquires the value 'Y' when the transistor becomes saturated. This means that the maximum collector current is flowing and may increase no further. Since there is no further change in the collector current, the magnetic field around coil T_2 ceases to grow. Quickly the field becomes static, there will be no further feedback from coil T_2 to coil T_1. Without continued feedback, emitter current begins to fall. Consequently, collector current decreases causes magnetic field to decay around the coil T_2. Thus, coil T_1 is now seeing a decaying field in coil T_2 (opposite from what it saw when the field was growing at initial start operation). This causes the further decrease in means that the both I_E and I_C cease to flow. Therefore, transistor has reverted back to its original state (when the power was first switched on). The complete process now repeat itself. The transistor is driven to the saturation, then to cut-off, and then back to the saturation. The time for change from saturation to the cut-off and back is calculated by the constant of the tuned circuit or tank circuit (inductance 'L' of Coil T_2 and 'C' connected in parallel to it). The resonance frequency (v) of this tuned ckt determines frequency at which the oscillator will oscillate. $\nu = \frac{1}{2\pi\sqrt{LC}}$

Comparative study of transistor configuration

1. Common Base (CB) **2.** Common Emitter (CE)

3. Common Collector (CC)

Properties	1. Common Base	2. Common Emitter	3. Common Collector
			
Input Resistance	Low (100 Ω)	High (750 Ω)	Very High ≅ 750 kΩ
Output resistance	Very High	High	Low
Current Gain	(α) $\alpha = \frac{I_C}{I_E} < 1$	(β) $\beta = \frac{I_C}{I_B} > 1$	(γ) $\gamma = \frac{I_E}{I_B} > 1$
Voltage Gain	$A_V = \frac{V_o}{V_i} = \frac{I_C R_L}{I_E R_i}$ $A_v = \alpha \frac{R_L}{R_i}$	$A_p = \frac{P_o}{P_i}$ $A_p = \beta \frac{R_L}{R_i}$	$A_p = \frac{P_o}{P_i}$ $A_p = \gamma \frac{R_L}{R_i}$
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
$I_E = I_B + I_C$	$I_E = I_B + I_C$	$I_E = I_B + I_C$
divide by I_C	divide by I_B	$\because \ \gamma = 1 + \beta$
$\frac{I_E}{I_C} = \frac{I_B}{I_C} + 1$	$\frac{I_E}{I_B} = 1 + \frac{I_C}{I_B}$	$\gamma = 1 + \frac{\alpha}{1 - \alpha}$
$\frac{1}{\alpha} = \frac{1}{\beta} + 1$	$\gamma = 1 + \beta$	$\gamma = \frac{1}{1 - \alpha}$
$\beta = \frac{\alpha}{1 - \alpha}, \alpha = \frac{\beta}{1 + \beta}$		$\alpha \cdot \gamma = \beta$

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 identified as negative feedback. It is used to get constant gain amplifier.

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

Advantages Of Semiconductor Devices Over Vacuum Tubes:-

Advantages:

- SEMICONDUCTOR devices are very small in the size as compared to vacuum tubes. Hence the circuits using semiconductor devices are more compact.
- In vacuum tubes, current flows when the filament is heated and starts emitting electrons. So, we must wait for sometime for the operation of the circuit. On the other hand, in semiconductor devices no heating is required and the circuit begins to operate quickly 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 produced any humming noise which is large in case ofthe vacuum tube.
- Semiconductor devices have longer life than vacuum tube. Vacuum tube gets damaged when its filament is burnt.

Concept Reminder

Voltage gain in positive feedback

$$A_f = \frac{A}{1 - A\beta}$$

Voltage gain in negative feedback

$$A_f = \frac{A}{1 + A\beta}$$

Rack your Brain

For a common emitter circuit if $\frac{I_C}{I_E} = 0.98$ then current gain for common emitter circuit will be:

(1) 49×10^{-2} (2) 98

(3) 4.9×10^{1} (4) 25.5

- Semiconductor devices are shock proof.
- The cost of production of semiconductor-devices is very small as compared to 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 is 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 the tiny resistors, capacitors and transistors are fabricated. An IC may function as an amplifier, oscillator, timer, counter, computer memory, or microprocessor. ICs may be made very compact, having up to the several billion transistors and other the electronic components in an area size of a fingernail. The most widely used technology is Monolithic Integrated Circuit. The word monolithic is a combination of 2 Greek words, monos implies single and lithos implies stone.

This, in cause means that the entire circuit is produced on a single silicon crystal (or chip). The chip dimensions are as small 1 mm × 1 m or it could even be smaller.

Depending upon 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 > 1000). The technology of fabrication is very expensive but large scale

Concept Reminder

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.

KEY POINTS

- Logic gates
- Integrated circuit

Concept Reminder

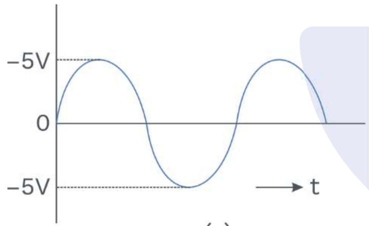
A binary number has only two digits '0' (say, 0V) and '1' (say, 5V). In digital electronics we use only these two levels of voltage. Such signals are called Digital Signals.

industrial production has made them very inexpensive.

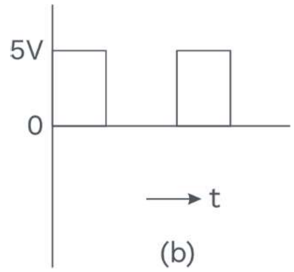
Analogue Circuits and Digital Circuits and signal:

There are 2 types of electronic circuits: analogue circuits and digital circuits:

In analogue circuits, the voltage (or current) changes continuously with time (figure a). Such a voltage (or current) signal is known as an 'analogue signal'. Diagram shows a typical voltage analogue signal changing sinusoidally between 0 and 5V.



(a)

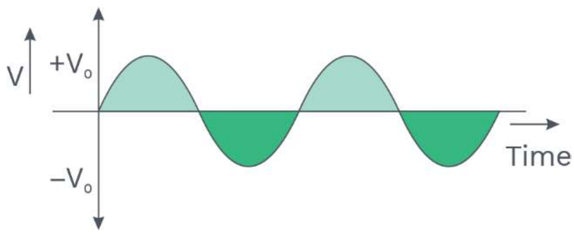


(b)

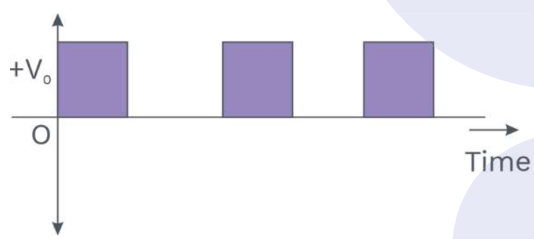
On the other hand, in digital circuits, voltage (or current) has only 2 levels, either zero or some constant value of the voltage (figure b). A signal having only 2 levels of voltage (or current) is knowns as a 'digital signal'. Digram shows a typical digital signal in which voltage at any instant is either 0 or 5V. In digital circuits, binary number system is used, according to which the two levels of (digital) signal are represented by the digits 0 and 1 only. The digital circuits are basis of calculators, computers, etc.

Voltage Signal:

(a) Analogue voltage signal: The signal which represents the continuous variation of voltage with time is known as analogue voltage signal.



(b) Digital voltage signal : The signal which has only two values i.e., either a constant high value of voltage or zero value is called digital voltage signal.



Decimal and Binary Number System:-

(1) Decimal number system:- In a decimal number system, we get ten digits i.e. 0,1,2,3,4,5,6,7,8,9

A decimal number system has a base of ten (10)

e.g.

1971 = 1000 + 900 + 70 + 1

$= 1 \times 10^3 + 9 \times 10^2 + 7 \times 10^1 + 1 \times 10^0$

MSD LSD

LSD = Least significant digit

MSD = Most significant digit

(2) Binary number system:- A number system which has only 2 digits i.e. 0 (Low) and 1

Definitions

The signal which has only two values. i.e., either a constant high value of voltage or zero value is called digital voltage signal.

Concept Reminder

A gate is a digital circuit that follows certain logical relationship between the input and output voltages. Therefore, they are generally known as logic gates — gates because they control the flow of information.

(High) is called binary system. The base of the binary number method is 2.

(i) Each digit in the binary system is known as a bit and a group of bits is known as the byte.

(ii) The electrical circuit which works only in these 2 state i.e. 1 (On or High) and 0 (Off or Low) are known as digital circuits.

State code	1	0
	On	Off
	Up	Down
	Close	Open
Name for the State	Excited	Unexcited
	True	False
	Pulse	No pulse
	High	Low
	Yes	No

(3) Decimal to binary conversion:-

(i) Divide the certain decimal number by 2 and the successive quotients by 2 till the quotient becomes zero.

(ii) The sequence of remainders found during divisions gives the binary equivalent of decimal number.

(iii) The really significant digit (or bit) of the binary number so found is the last remainder and least significant digit (or bit) is the first remainder found during the division.

For Example: Binary equivalence of 61

2	61	Remainder
2	30	1LSD
2	15	0
2	7	1
2	3	1
2	1	1
	0	1MSD

$\Rightarrow$ $(61)_{10} = (111101)_2$

Rack your Brain

Which of the conditions must be satisfied to operate a transistor amplifier?

(1) Emitter-base and collector-base junctions are forward biased

(2) Emitter-base junction is forward biased collector-base is reverse biased

(3) Emitter-base and collector-base junctions both are reverse biased

(4) Emitter-base junction is reverse biased collector-base junction is forward biased

(4) **Binary to decimal conversion: The least significant digit in the binary number is the coefficient of 2 with power zero. As we move towards the left side of LSD, the power of 2 goes on increasing.**

For Example : (11111100101) 2 = $1 \times 2^{10} + 1 \times 2^{9} + 1 \times 2^{8} + 1 \times 2^{7} + 1 \times 2^{6} + 1 \times 2^{5} + 0 \times 2^{4} + 0 \times 2^{3} + 1 \times 2^{2} + 0 \times 2^{1} + 1 \times 2^{0} = 2021$

Logic Gates:-

Logic gate is a digital circuit which acts according to various logical relationship between input and output voltages. It moreover allows a signal to pass through or stops it. The logic gates are the building block of digital circuits. There are three basic logic gates.

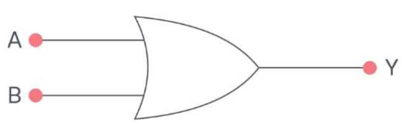
(a) OR gate

(b) AND gate

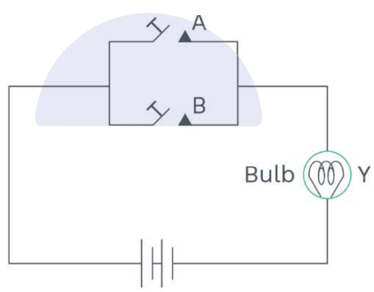
(c) NOT gate

(a) **The OR Gate:-**

The OR gate is a tool that has two input variables A and B and one output variable Y, and follows the Boolean expression, A + B = Y, read as' A OR B equal Y. Its logic symbol is shown in figure.



(a)



(b)

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

(c)

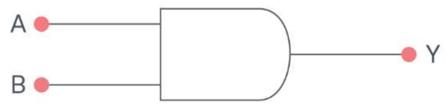
The possible combinations of the inputs 'A' and 'B' and the output Y of the OR gate can be known with the help of an electrical circuit, shown in Diagram. In this circuit, two switches 'A' and 'B' (inputs) are connected in parallel with a battery and a bulb Y (output).

(b) **AND Gate :**

The AND gate is also a two-input and one-output logic gate. It combines the inputs 'A' and 'B' to give the output Y, according to the Boolean expression

$$A.B = Y$$

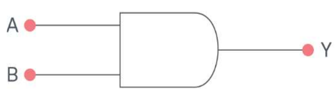
read 'A AND B equals Y'



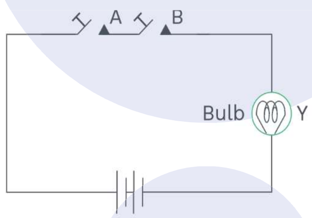
(a)

> **Concept Reminder**
>
> In modern day circuit, many logical gates or circuits are integrated in one single 'Chip'. These are known as Integrated circuits (IC).

The possible combination of the inputs A and B and output Y of AND gate can be known with the help of electric circuit, shown in figure. In this, two switches A and B (inputs) are connected in series with a battery and a bulb 'Y' (output).



(a)



(b)

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

(c)

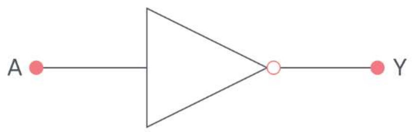
(c) The NOT Gate:-

The NOT gate has only one input and one output. It combines the input 'A' with the output 'Y', according to the Boolean expression

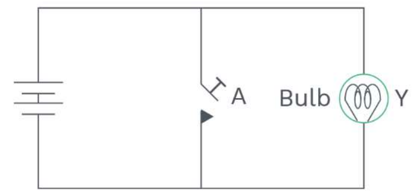
$$\overline{A} = Y,$$

read as 'NOT A equals Y'. It means that 'Y' is negation (or inversion) of 'A'. While there are only two digits 0 and 1 in binary system, we have, Y = 0, if A = 1 and Y = 1 if A = 0. The logic symbol of NOT gate is shown in figure.

> **Rack your Brain**
>
> In a common base transistor circuit, the current gain is 0.98. On changing emitter current by 5.00 mA, the change in collector current is:
>
> (1) 0.196 mA (2) 2.45 mA
>
> (3) 4.9 mA (4) 5.1 mA



(a)



(b)

A	Y(=Ā)
0	1
1	0

(c)

The possible groupings of the input A and the output Y of the NOT gate can be known with the help of electric circuit, shown in figure. In this circuit, a switch A (input) is connected in parallel to a battery and a bulb Y(output). The working of circuit is as follows:

If switch A is open (A = 0), the bulb will shine (Y = 1).

If switch A is closed (A = 1), the bulb will not shine (Y = 0).

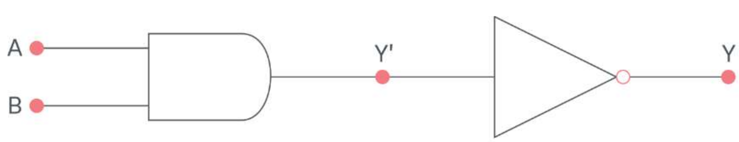
These two possible combinations of input A and output Y are tabulated in figure, which is the truth table of the NOT gate.

Combinations of gates:

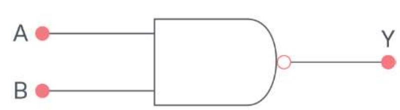
Various combinations of the 3 basic gates, namely, OR, AND and NOT, produce complicated digital circuits, which are also known as 'gates'. The commonly used combinations of basic gates are NAND gate, NOR, gate. These are also known as universal gates.

(i) The NAND gate:-

This gate is a combination of AND and NOT gates. If the output Y' of AND gate is connected to the input of NOT gate, as displayed in figure, the gate so obtained is called NAND gate. The logic symbol of NAND gate is shown in figure.



(a)



(b)

The Boolean expression for the NAND gate is

$$\overline{A \cdot B} = Y$$

read as 'A AND B negated equals Y.

The truth table of the NAND gate can be obtained by logically combining the truth tables of AND and NOT gates. In figure, the output Y' of the truth table of AND gate have been negated (NOT operation) to obtain the corresponding outputs Y for the NAND gate.

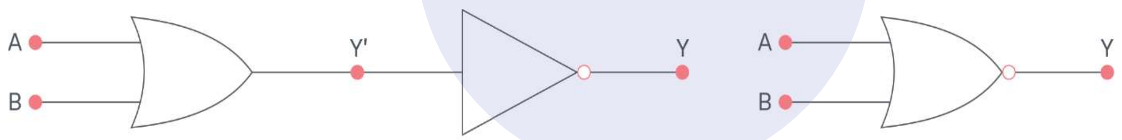
The resulting table is the truth table of the NAND gate is shown in figure.

A	B	Y'(=A.B)	Y(=$\overline{A.B}$)=$\overline{Y'}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

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

(ii) The NOR Gate:-

The NOR gate is a mixture of OR and NOT gates. If the output Y' of OR gate is connected to the input of NOT gate, as shown in diagram, the gate so obtained is NOR gate.



(a) (b)

The Boolean expression for the NOR gate is

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

read as 'A OR B negated equals Y:

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

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

The truth table of NOR gate can be obtained by logically combining the truth tables of OR and NOT gates. In figure(a), the outputs Y' of the truth table of OR gate have been negated to obtain the corresponding outputs Y for the NOR gate.

Universal Gates:

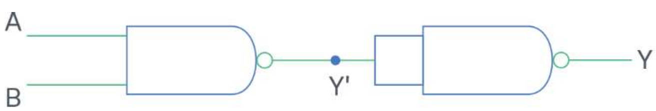
The NAND or NOR gate is the universal building block of all digital circuits. Repeated use of NAND gates (or NOR gates) gives other gates. Therefore, any digital system can be achieved entirely from NAND or NOR gates. We shall show how the repeated use of NAND (and NOR) gates will give other gates.

- **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

Truth table of single-input NAND gate

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

- **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 the table given show how an AND gate has been obtained from NAND gates.



Truth table

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

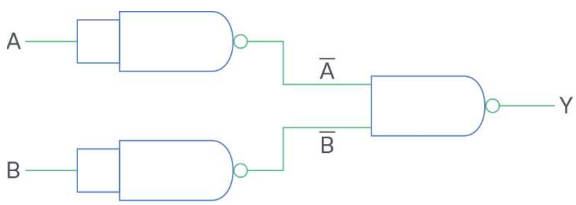
- **OR gate from NAND gate:** If we invert the inputs A and B and then apply them to the NAND gate, the resulting circuit is an OR gate.

Concept Reminder

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.

Rack your Brain

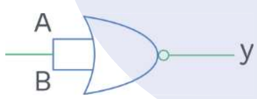
An oscillator is nothing but an amplifier with
(1) Positive feedback
(2) Negative feedback
(3) Voltage gain
(4) No feedback



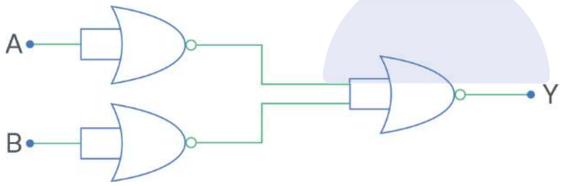
Truth table

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

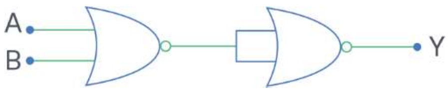
- **NOT gate from NOR gates:** When all the inputs of a NOR gate are connected together as shown in the figure, we obtain a NOR gate.



- **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.



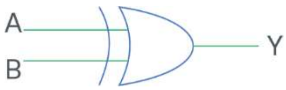
- **OR gate from NOR gate:** If a NOR gate is followed by a single input NOR gate (NOT gate), the resulting circuit is an OR gate.



XOR AND XNOR GATE :

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



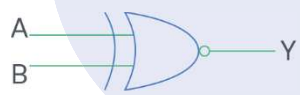
The Boolean expression of XOR gate is $Y = A\overline{B} + \overline{A}B$ or $Y = A \oplus B$

Truth table of a XOR gate

Input		output
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 input are the same that is, both 0 or both 1.

Logic symbol of XNOR gate



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

Truth table of a XNOR gate

Input		output
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

Laws of Boolean Algebra:-

Basic OR, AND, & NOT operations are as follows

OR	AND	NOT
$A + 0 = A$	$A.0 = 0$	$A + \overline{A} = 1$
$A + 1 = 1$	$A.1 = A$	$A.\overline{A} = 0$
$A + A = A$	$A.A = A$	$\overline{\overline{A}}.A = A$

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

Commutative laws :

$A + B = B + A$;

$AB = BA$

Associative laws :

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

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

Distributive laws:

A (B + C) = AB + AC

Some other useful identities:

(i) A + AB = A

(ii) A. (A + B) = A.

(iii) $A + \overline{A}B = A + B$

(iv) $A.(\overline{A} + B) = AB$

(v) A + BC = (A + B) (A + C)

(vi) $(\overline{A} + B)(A + C) = \overline{A}C$

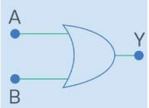
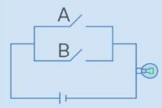
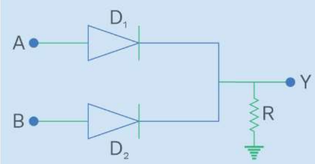
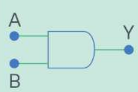
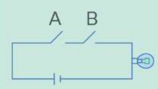
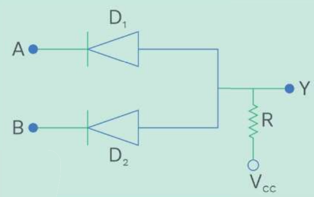
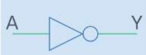
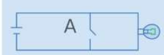
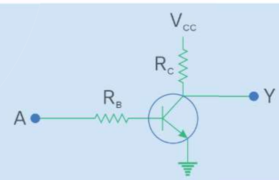
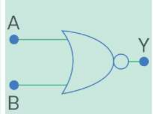
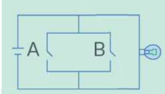
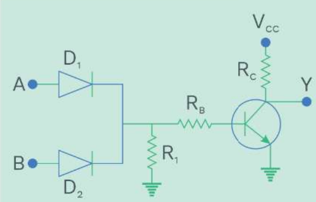
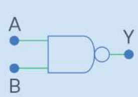
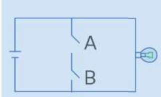
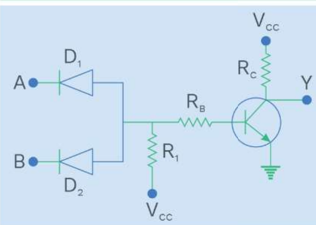
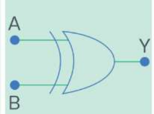
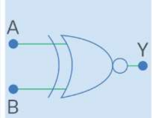
De Morgan's theorem

First theorem:

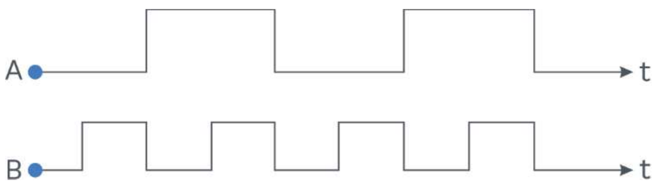
$$\overline{A + B} = \overline{A} \cdot \overline{A}$$

Second theorem:

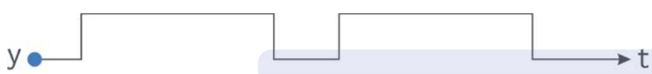
$$\overline{A.B} = \overline{A} + \overline{B}$$

Names	Symbol	Boolean Expression	Truth table	Electrical analogue	Circuit diagram (Practical Realisation)
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 Y 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)		$Y = \overline{A \oplus B}$ or $Y = A.B + \overline{A}.\overline{B}$	A B Y 0 0 1 0 1 0 1 0 0 1 1 1		

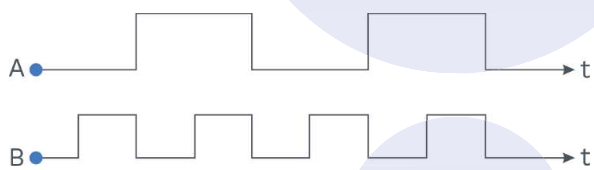
Ex. Show the output waveform of OR gate for the following input waveforms of A and B.



Sol. For OR gate Y = A + B. Hence the output waveform will be as follows.
(0 + 0 = 0, 1 + 0 = 1, 0 + 1 = 1, 1 + 1 = 1)

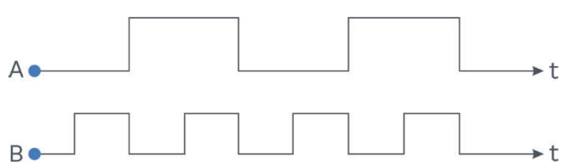


Ex. Show the output waveform of AND gate for the following input waveforms of A and B.

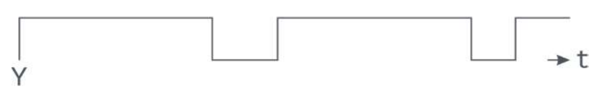


Sol. For AND gate Y = AB
∴ 0.0 = 0, 1.0 = 0, 0.1 = 0, 1.1 = 1
So the output waveform will be as follows.

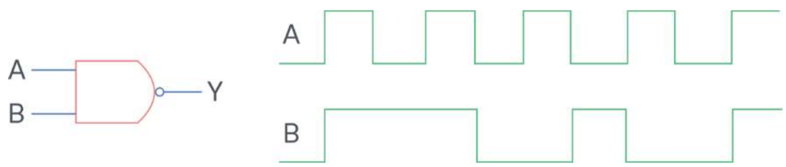
Ex. Sketch the output waveform Y from a NAND gate having following inputs A and B.



Sol. NAND gate has the logic $Y = \overline{AB}$. So, $\overline{0.0} = 1, \overline{0.1} = 1, \overline{1.0} = 1, \overline{1.1} = 0$. Hence, the output waveform will be.



Ex. In the figures below, Circuit symbol of a logic gate and two input waveforms 'A' and 'B' are shown.



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

(b) Write its truth table

(c) Give the output wave form

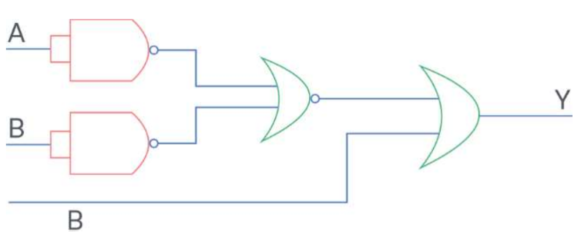
Sol. (a) NAND gate; $Y = \overline{A.B}$

(b) Truth table

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

(c) Output waveform

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



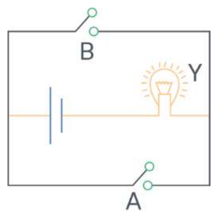
Sol. $Y = \overline{\overline{A}.\overline{B}} + B = \overline{\overline{A.B}} + B + B = (A + 1)B = B$

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

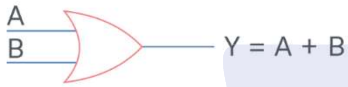
Sol. $LHS = \overline{A}B + A\overline{B} + AB = \overline{A}B + A\overline{B} + AB + AB$

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

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



Sol. OR gate



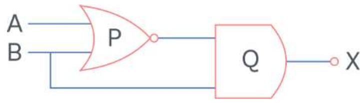
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

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

Sol.

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

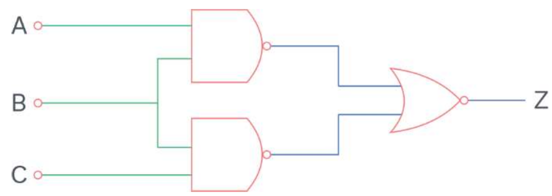
Ex. Identify the logic gates P and Q in given circuit. Also write down relation in A, B and X.



Sol. P is NOR gate & Q is AND gate,

$$X = \left(\overline{A + B}\right).B = (\bar{A}.\bar{B}).B = \bar{A}.(\bar{B}.B) = \bar{A}.0 = 0$$

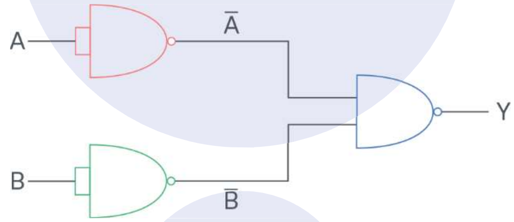
Ex. Write down the equivalent function performed by given circuit. Explain your answer.



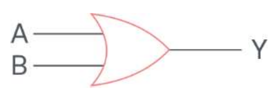
Sol. AND gate, $Z = \overline{\overline{A \cdot B} + \overline{B \cdot C}} = \overline{\overline{AB}} \cdot \overline{\overline{BC}} = \overline{\overline{ABC}} = ABC$

$(\because \overline{X} + \overline{Y} = \overline{X \cdot Y})$

Ex. If inputs A and B are reversed before entering into NAND gate as taken in diagram. Write down the logical symbol and truth table by using $A, B, \overline{A}, \overline{B}, Y$.



Sol. $Y = \overline{\overline{A}.\overline{B}} = A + B$ so logical symbol.



Truth table

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

EXAMPLES

Q.1 **C, Si and Ge all have same lattice structure. Then why is C insulator while Si and Ge intrinsic semiconductors?**

Sol The four bonding electrons of C, Si or Ge lie, respectively, in the 2^{nd}, 3^{rd} and 4^{th} orbit. So, energy needed to take out an electron from these atoms (i.e., ionisation energy E_g) will be less for Ge, followed by Si and more for C. therefore, number of free electrons for conduction in Si and Ge are significant but negligibly for C.

Q.2 **Consider a pure Si crystal has 5×10^{28} atoms per m^3. It has been doped by 1 ppm concentration of pentavalent As. Find the number of electrons and holes. Given that $n_t = 1.5 \times 10^{16}\ m^{-3}$.**

Sol. Note that thermally generated electrons ($n_t \sim 10^{16}\ m^{-3}$) are negligibly small as compared to those produced by doping.

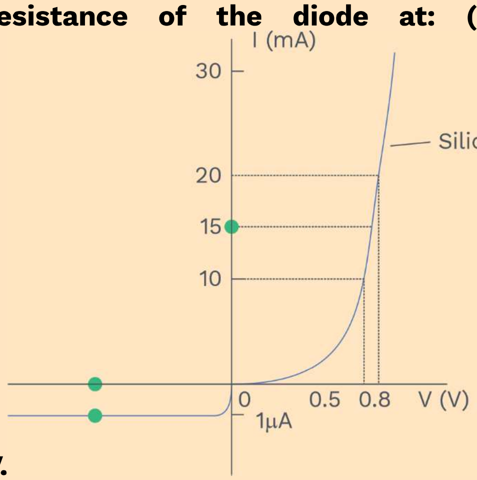
Therefore, $n_e \approx N_D$

Since $n_e n_h = n_i^2$, The number of holes

$n_h = (2.25 \times 10^{32})/(5 \times 10^{22})$

$\sim 4.5 \times 10^9\ m^{-3}$

Q.3 **The V-I characteristic of a silicon diode is shown in the Figure. Find the resistance of the diode at: (a) I_D = 15 mA and (b) V_D = –10**



V.

Sol Considering the diode characteristics as a straight line between I = 10 mA to I = 20 mA passing through the origin, we can calculate the resistance using Ohm's law.

(a) From the curve, at I = 20 mA, V = 0.8 V, I = 10 mA,
$V = 0.7$ V $r_{fb} = \Delta V/\Delta I$ =- 0.1V/10 mA = 10 Ω

(b) From the curve at V = –10 V, I = –1 μA,
Therefore,
R_{rb} = 10 V/1 μA = 1.0×10^7 Ω.

Q.4 **In a Zener regulated power supply a Zener diode with V_z = 6 V is used for regulation. The load current is to be 4 mA and the unregulated input is 10 V. What should be the value of series resistor R_S?**

Sol. The value of R_S should be such that current through the Zener diode is much larger than load current. This is to have good load regulation. Choose Zener current as five times the load current, i.e., I_z = 20 mA.
The total current through RS is, therefore, 24 mA.
The voltage drop across R_S is 10.0 – 6.0 = 4.0 V.
This gives R_S = 4.0 V/(24×10^{-3}) A = 167 Ω.
The nearest value of carbon resistor is 150 Ω. So, a series resistor of 150 Ω is appropriate.
Note that slight variation in the value of the resistor does not matter, what is important is that the current I_z should be sufficiently larger than I_L.

Q.5 **The current in forward bias is known to be more (~ mA) than the current in reverse bias (~ μA). Explain the reason then to operate the photodiodes in reverse bias?**

Sol Take the case of an n-type semiconductor. The majority carrier density (n) is very larger than the minority hole density p (i.e., n >> p). On illumination, Suppose the excess electrons and holes generated be Δn and Δp, respectively

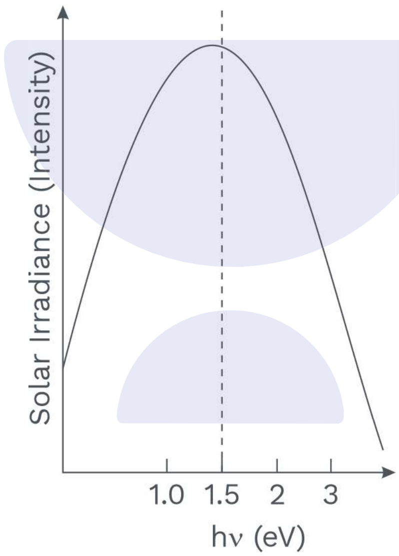
$$n' = n + \Delta n$$

$$p' = p + \Delta p$$

Here n′ and p′ are electron and hole concentrations at some specific illumination and n and p are carriers concentration If there is no illumination. Remember Δn = Δp and n >> p. So, the fractional change in majority carriers (i.e., $\Delta n/n$) would be much less than that in the minority carriers (i.e., $\Delta p/p$). In general, we can say that the fractional change because of the photo-effects on the minority carrier dominated or reverse bias current is more easily measurable than fractional change in the forward bias current. So, photodiodes are preferably used in the reverse bias condition for measuring light intensity.

Q.6 **Why are Si and GaAs are preferred materials for solar cells?**

Sol. The solar spectrum of radiation received by us is as shown in Figure.



The maxima is near 1.5 eV. For photo-excitation, $h\nu > E_g$. So, semiconductor with band gap ~1.5 eV or less is likely to give better solar conversion efficiency. Si has E_g ~ 1.1 eV while for GaAs it is ~ 1.53 eV. Also, GaAs is better (in spite of its large band gap) than Si due to its relatively higher absorption coefficient. If we select materials like CdS or CdSe (E_g ~ 2.4 eV), we can use only high energy component of this solar energy for photo-conversion and a significant part of energy will get in no use.

Then question arises: why don't we use material like PbS (E_g ~ 0.4 eV) which satisfy the condition $h\nu > E_g$ for n maxima corresponding to solar radiation spectra? If we do so, most of solar radiation will get absorbed on top-layer of solar cell and will not be able to reach in or near the depletion region. For effective electron-hole separation, because of the junction field, we want the photo-generation to occur in the junction region only.

Q.7 **From the output characteristics shown in Figure, determine the values of β_{ac} and β_{dc} of the transistor when V_{CE} is 10 V and I_C = 4.0 mA.**

Sol $\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}\bigg|_{V_{CE}}, \beta_{dc} = \frac{I_C}{I_B}$

To determine β_{ac} and β_{dc} at the stated values of V_{CE} and I_C one can proceed as follows. Take any two characteristics for any two values of I_B which lie above and below the given value of I_C. Here I_C = 4.0 mA. (Select characteristics for I_B = 30 and 20 μA.) At V_{CE} = 10 V we cut the two values of IC from graph. Then

ΔI_B = (30 – 20) μA = 10 μA, ΔI_C = (4.5 – 3.0) mA = 1.5 mA

So,

β_{ac} = 1.5 mA/ 10 μA = 150

To determine β_{dc}, either Find the value of I_B corresponding to I_C = 4.0 mA at V_{CE} = 10 V or Determine the two values of β_{dc} for the two characteristics chosen and write their mean.

So, for I_C = 4.5 mA and I_B = 30 μA,

β_{dc} = 4.5 mA/30 μA = 150

and for I_C = 3.0 mA and I_B = 20 μA

β_{dc} = 3.0 mA / 20 μA = 150

So, β_{dc} = (150 + 150) /2 = 150

Q.8 **In figure, the V_{BB} supply can be varied from 0 V to 5.0 V. The Silicon transistor has β_{dc} = 250 and R_B = 100 kΩ, R_C = 1 KΩ, V_{CC} = 5.0 V. Consider that when the transistor is saturated, V_{CE} = 0 V and V_{BE} = 0.8 V.**

(a) determine the minimum base current, for which the transistor will reach saturation.

(b) Find V_1 when the transistor is 'switched on'.

(c) Calculate the ranges of V_1 for which the transistor is 'switched off' and 'switched on'.

Sol. Given at saturation V_{CE} = 0 V, V_{BE} = 0.8 V

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

$I_C = V_{CC}/R_C$ = 5.0 V/1.0 kΩ = 5.0 mA

Therefore $I_B = I_C/\beta$ = 5.0 mA/250 = 20 μA

The input voltage for which the transistor will go into saturation is given by

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

= 20μA × 100 kΩ + 0.8 V = 2.8 V

The input voltage below which the transistor remains cut-off is given by

$V_{IL} = 0.6$ V, $V_{IH} = 2.8$ V

Between 0.0 V and 0.6 V, the transistor will be in the 'switched off' state. Between 2.8 V and 5.0 V, it will be in state of 'switched on' state.

Note that the transistor will be in active state when I_B varies from 0.0 mA to 20 mA. In this range, $I_C = \beta I_B$ is valid. In the saturation range, $I_C \leq \beta I_B$.

Q.9 **For a CE transistor amplifier, the audio signal voltage across the collector resistance of 2.0 kΩ is 2.0 V. Let the current amplification factor of transistor is 100 then what should be the value of resistance R_B in series with V_{BB} supply of 2.0 V when the dc base current has to be 10 times the signal current. Also find the dc drop across the collector resistance.**

Sol. The output ac voltage is 2.0 V.

Therefore, an ac collector current $i_C = 2.0/2000 = 1.0$ mA.

The signal current through the base is,

$i_B = i_C/\beta = 1.0 \text{ mA}/100 = 0.010$ mA

The dc base current has to be 10 × 0.010 = 0.10 mA.

From Equation, $R_B = (V_{BB} - V_{BE})/I_B$.

Assuming $V_{BE} = 0.6$ V, $R_B = (2.0 - 0.6)/0.10 = 14$ kΩ.

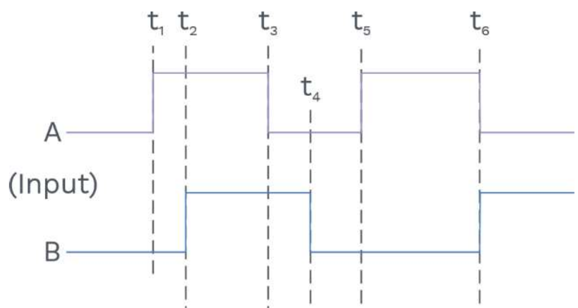
The dc collector current $I_C = 100 \times 0.10 = 10$ mA.

Q.10 **Justify the output waveform (Y) of the OR gate for the following inputs A and B given in Figure.**

Sol Note following points:

- For $t < t_1$; A = 0, B = 0; Hence Y = 0
- For t_1 to t_2; A = 1, B = 0; Hence Y = 1
- For t_2 to t_3; A = 1, B = 1; Hence Y = 1
- For t_3 to t_4; A = 0, B = 1; Hence Y = 1
- For t_4 to t_5; A = 0, B = 0; Hence Y = 0
- For t_5 to t_6; A = 1, B = 0; Hence Y = 1
- For $t > t_6$; A = 0, B = 1; Hence Y = 1

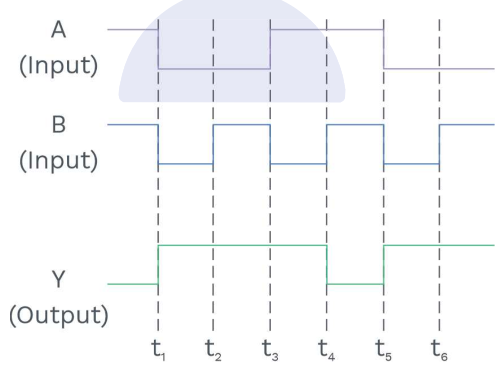
Hence, the waveform Y will be as shown in the Figure.



Q.11 **Sketch the output Y from a NAND gate having inputs A and B given in figure.**

Sol. For $t < t_1$; A = 1, B = 1; Hence Y = 0

- For t_1 to t_2; A = 0, B = 0; Hence Y = 1
- For t_2 to t_3; A = 0, B = 1; Hence Y = 1
- For t_3 to t_4; A = 1, B = 0; Hence Y = 1
- For t_4 to t_5; A = 1, B = 1; Hence Y = 0
- For t_5 to t_6; A = 0, B = 0; Hence Y = 1
- For $t > t_6$; A = 0, B = 1; Hence Y = 1



Q.12 **Calculate the conductivity and the resistivity of intrincis silicon crystal at 300 K. It is given that μ_e = 1350 cm^2 / volt, sec, μ_h = 480 cm^2 / volt, sec and at 300 K, the electron-hole pair concentration is 1.072 x 10^{10} per cm^3.**

Sol The conductivity for intrinsic semiconductor is

$$\sigma = e\,(n_e\mu_e + n_h\,\mu_h)$$

Given, $n_e = 1.072 \times 10^{10}\ m^3$

1.072×10^{16} per m^3

Also, $n_e = n_h$ for intrinsic

Semiconductor, Further

$\mu_e = 1350\ cm^2$ / volt. sec

$= 0.1350\ m^2$ / volt-sec $\mu h = 0.048\ m^2$ / volt-sec

Therefore,

$\sigma = 1.6 \times 10{-}^{19} \times 1.072$

$\times 10^{16} \times (0.135 + 0.048)$

$= 3.14 \times 10^{-4}$ ohm / meter

$= 3.14 \times 10^{-4}$ siemen per meter

The resistivity, $r = \frac{1}{\sigma} = 10^4 / 3.14$

= 3185 ohm-meter.

Q.13 **The concentration of acceptor atoms in a p-type germanium crystal is 4×10^{15} per cm^3. Find the conductivity of the crystal at 300 K. The μ_h for germanium at 300 K is 1900 cm^2 / volt sec. It is considered that all the acceptor atoms are ionized at this temperature.**

Sol. For extrinsic semiconductor (p-type)

$\sigma = n_h e\mu_h$

Given $n_h = 4 \times 10^{15}$ per cm^3

$= 4 \times 10^{21}$ per m^3

$\mu_h = 1900\ cm^2$ / volt-sec

Thus $\sigma = 4 \times 10^{21} \times 1.6 \times 10^{-19} \times 0.190$

$= 1.216 \times 10^2$ ohm/m

$= 121.6$ siemen/m.

Q.14 **When the emitter current of a transistor is changed by 1 mA, its collector current changes by 0.995 mA. Calculate:**

(i) Its common base current gain and

(ii) Its common emitter current gain

Sol. (i) $\alpha = \frac{\Delta I_C}{1-\alpha} = \frac{0.995(mA)}{1(mA)} = 0.995$

(ii) $\beta = \frac{\alpha}{1-\alpha} = \frac{0.995}{1-0.995} = \frac{0.995}{0.005} = 199$

Q.15 In certain transistor α_{dc} is 0.98 and I_E is 1 mA. Determine the corresponding values of base current and collector current.

Sol. (i) $\alpha_{dc} = \frac{I_C}{I_E}$ or $0.98 = \frac{I_C}{I(mA)}$

thus $I_C = 0.98$ mA

(ii) Using, $I_B = I_E - I_C$

We get,

$I_B = (1 - 0.98)$ mA = 0.02 mA.

Mind Map

Junction Transistor

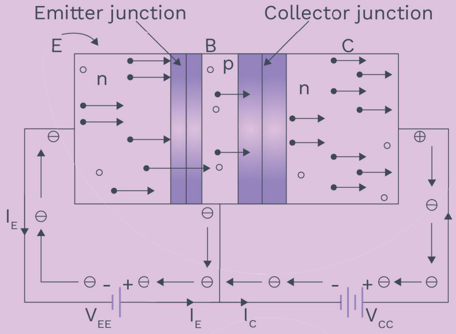
An important combination of p type and n type semiconductors is a transistor. It consists of a thin base placed between two different type of semiconductors called emitter and collector.

Parts of Transistor

(a) **Base** lightly doped and thin.
(b) **Emitter** Heavily doped and moderately sized.
(c) **Collector** Moderately doped and largest in size.

Working Principle

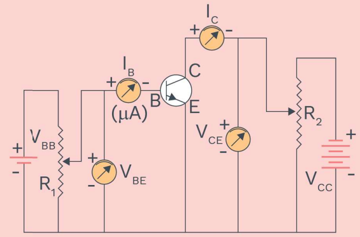
Emitter base junction of transistor is kept in forward bias and collector-base junction is kept in reverse bias. This facilitates flow of charge carriers (electrons in n-p-n) to the base where they tend to recombine with holes in the base.



As the base is thin and lightly doped, many of charge carriers pass into collector region. By regulating base supply, we can regulate number of charge carriers going into collector. So, we can control flow of charge carriers across a high resistance reverse bias layer.

Transistor Characterstics

To study voltage and current variations of a transistor (its characterstic curves), we use following circuit:



Characteristic curves for an npn CE transistor configuration are as shown;