UNIT – I – PN JUNCTION DIODES

SEMICONDUCTOR MATERIALS AND JUNCTION DIODES.

CLASSIFICATION OF SOLIDS :-

Properties of solid are determined by the type of binding that exists between the atoms. The binding is determined by the, distribution of electrons in the outermost or valence shell of the atom.

For example, if the valance shell of an atom contains eight electrons, the material is inert. Eight electrons in the valence shell give stability to the atom. It is called the octet structure. If an atom has only seven electrons in the valence shell, it tries to acquire an election from its neighbour and becomes stable. Similarly if it has nine electons, it readily gives away an electron to its neighbour.

The binding forces in solids are electrostatic in nature. The binding in solids are divided into four types : ionic
covalent
metallic &
vander waal bonds.

Covalent Bonds : Covalent bonding occurs by sharing of electrons between neighbouring atoms. Group IV atoms like diamond, silicon, and germanium have covalent bonds.

For example, silicon (or germanium) has four valence electrons.

In the crystal lattice, each electron is shared with a nearby atom to form covalent bonds.

Every atom has a half share in eight valence electrons and this number leads to a stable structure. As a result we have a crystal structure from which it is difficult for electrons to escape from their parent atoms.

This is the reason why pure germanium and silicon are perfect insulators at 0k.

Based upon the property of electrical conductivity all materials can be classified into 3 categories :-

1) Conductors
2) Semiconductors
3) Insulators

Conductivity is a measure of a current carrying capacity of the material.

The difference between the conductors, Insulators and Semiconductors can be discussed on the basis of Energy band diagram:

→ Energy band - The Range of energies possessed by the electron in a solid is known as Energy Band.

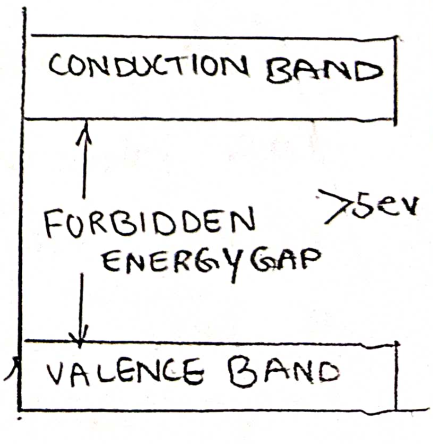
→ VALENCE BAND - The Range of energies possessed by the valence electrons is known as valence band.

→ CONDUCTION BAND - The range of energies possessed by the conduction electrons is known as Cond Band.

→ The Separation between the conduction band and valence band on the energy level diagram is known as Forbidden Energy Gap.

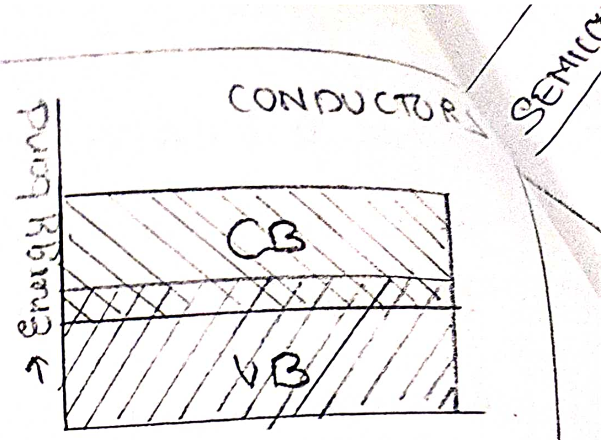
1). In an INSULATOR, the conduction band is practically empty and valence band is FULL.

Large amount of Energy would be required to push electron from VB to CB, across the forbidden gap.

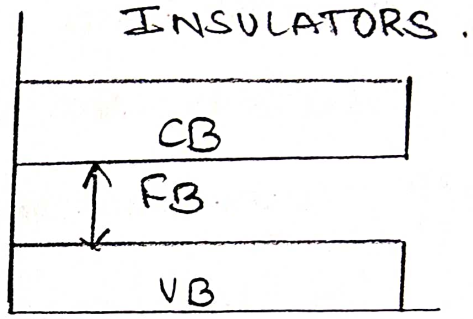


Hence an insulator cannot conduct, even if a strong electric field is applied.

2) CONDUCTORS :- The Vanlence band and conduction band overlap (i.e forbidden gap energy is 0ev) The conductor has free electrons in the conduction band even at 0°K.



3) SEMICONDUCTORS :- At 0°K, all valence electrons of semiconductor material locked in their outer-most shell of the atom with Energy levels associated with VB.



At room temperature (27°C or 300°K) a large number of valence electron have acquired sufficient energy to leave the VB and cross the forbidden energy gap and enter the CB.

Forbidden Energy Gap (Eg) (at 0°K) = 1.21 eV (silicon)
= 0.785 eV (Ge)
= 1.41 eV (GaAs)

∴ "A Semiconductor is a substance which has almost filled Valence band and nearly empty conduction band with a a very small energy gap separating the two bands".

1

SEMICONDUCTOR :-

Semiconductors are a class of materials of conductivity lies between the conductors and insulators. The range of conductivity is 10^5 to 10^{-4} Siemens/meter or the range of resistivity of a semiconductor lies in between conductors and insulators. i.e. ρ is in range of 10^{-4} to 0.5 Ωm.

Eg:- Ge $\rightarrow \sigma = 2.2 \times 10^{-2}$ S/m $\rightarrow \rho = 45.45\ \Omega$-m.

Si $\rightarrow \sigma = 4.35 \times 10^{-6}$ S/m $\rightarrow \rho = 0.229 \times 10^{6}\ \Omega$-m.

PROPERTIES OF SEMICONDUCTORS

1) The resistivity of a semiconductor is less than an insulator but more than a conductor.

2) Semiconductor have "NEGATIVE TEMPERATURE COEFFICIENT" of Resistance i.e the resistance of the semiconductor decreases with increase in Temperature.

3) When a suitable metallic impurity is added to a semiconductor, its current conducting properties change appreciably.

4) Depending on the intensity of light falling on the semiconductor the resistance changes

5) The junction between a p-type and n-type semiconductor posseses rectification property.

Conductivity is reciprocal of Resistivity.

$$\boxed{\sigma = \frac{1}{\rho}}.$$

where σ is conductivity and ρ is the resistivity.

Resistivity is a measure of a materials ability to oppose the flow of an electric current.

$$\boxed{\rho = \frac{RA}{l}} \ (\Omega\text{-}m)$$

R - Resistance of uniform specimen of material.

A - Cross sectional area

l - length.

CONDUCTOR :- conductor offers very little resistance to the flow of current through it.

A conductor is a substance which has very less resistivity or very high conductivity.

metals like copper, Aluminium, gold etc are very good conductors.

Copper is a GOOD CONDUCTOR.

$\sigma = 5.88 \times 10^7$ Siemens/meter.

INSULATOR :-

An Insulator offers very high Resistance to the flow of current through it.

An Insulator is a substance which has high Resistivity

Ex, Glass, $\sigma = \frac{1}{\rho} = 1.11 \times 10^{-12}$ S/m.

EFFECT OF TEMPERATURE ON SEMICONDUCTOR:-

At absolute $0^{\circ}K$, all the electrons are tightly held by the semiconductor atom. The innermost electrons are bounded whereas the valence e's are engaged in covalent bonding. At this temp, covalent bonds are very strong and there are no free electrons. Therefore the semiconductor crystal behaves as a insulator.

→ ~~At~~ Above absolute zero - When the temperature is raised, Some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons free which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a small current.

This shows that the resistance of a semiconductors decreases with increase in Temperature i.e, "Negative Temperature Coefficient of Resistance."

→ As temperature is rised, some of the valence electrons acquire sufficient energy to enter into the CB and thus become free electrons.

under the influence of electric field, these free electrons will constitute electric field, current.

→ Each time a valence electron enter into the CB, a HOLE is created in the VB.

HOLE is having POSITIVE CHARGE ie opposite to an $\bar{e}$.

→ CONDUCTOR :-

- As Temperature ↑, conductivity ↓
- This is +ve Temperature coef. of Resistance

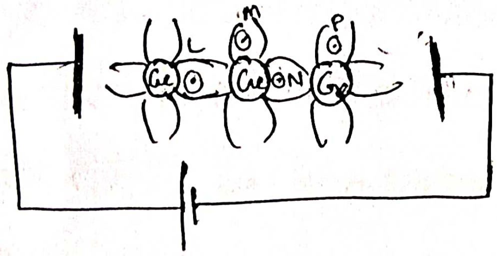
→ SEMICONDUCTOR :-

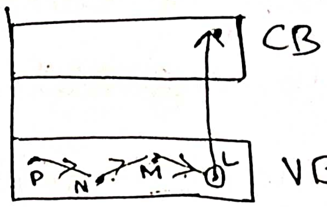
As T ↑, σ ↑

−ve temperature coef of resistance.

→ INSULATOR :-

As T ↑, σ ↑.





Suppose the valence electron at L becomes free $\bar{e}$ due to thermal energy. This creates a HOLE in the covalent bond at L. A hole is a strong centre of attraction for the electron. A valence electron from near by covalent bond carriers to fill in the hole at 'L'. This results creation of Hole at M. Another valence electron at N in turn may leave its bond to fill the hole at M. Thus creating a hole at N.

Another valence electron at P inturn may leave its band to fill the hole at N. Thus creating a hole at P. Thus hole is a positive charge has moved from L to P i,e towards the '-ve' terminal of supply. This constitutes 'HOLE CURRENT'.

"It is clear that valence electrons moves along the path PNML where as holes move in the opposite direction LMNP.

INTRINSIC SEMICONDUCTORS :-

A Semiconductor in an extremely pure form is known as an Intrinsic SEMICONDUCTOR.

IV group elements are called Semiconductors, because they act as INSULATORS at $T=0°K$ and acts as Conductors at room temp. This group of elements possess both the properties of Insulator and conductor. So that we can't call as an Insulator or conductor. As the conductivity lies between these two materials, they are called Semiconductors.

IV group elements are:- C, Si, Ge, Sn, Pb and Fm.

Among the above elements, Si and Ge are only used.

because of the following reasons:-

1) We want always moderate no of carriers, which are existing in the Si and Ge atoms.

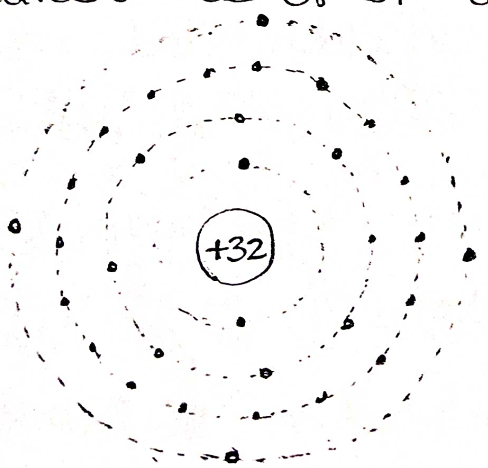
2) Compared to Ge, Si is mostly used material to manufacture the electronic devices.

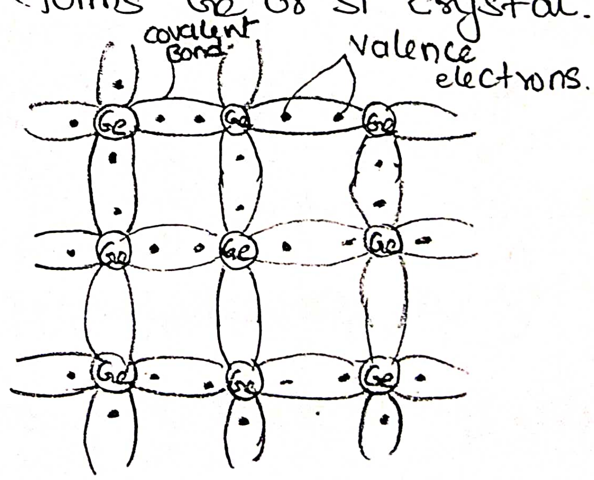
GERMANIUM CRYSTAL STRUCTURE :-

The atomic number of germanium is 32. Therefore, it has 32 protons and 32 electrons. Two electrons are in the first orbit, eight electrons in the second, eighteen electrons in the third and four electrons in the outermost or valence orbit.

i.e, germanium atom has four valence electrons i.e, it is a tetravalent element.

The Ge having four valence electrons in the outer most orbit. These four valence electrons of the Ge, share with the other four ~~valence~~ electrons nearest Ge or Si atoms forms Ge or Si crystal.





Here the valence electrons are bind with the atom to another. So there is no electric conduction with out any thermal excitation.

→ At $0^\circ K$ the crystal acts as an insulator because the valence band is completely filled and CB is empty so no Electric Conduction.

→ At room temperature ($300^\circ K$) some of the valence electrons have enough thermal energy to break their valence bonds. These electrons becomes free to move randomly through out the crystal.

→ When the covalent bond breaks, the electron becomes free and move away, a vacany is created in the broken covalent Bond. This vacancy is called a HOLE.

→ Whenever a free electron is generated, a Hole is also created simultaneously.

∴, the concentration of free electrons and holes are always equal in an INTRINSIC SEMICONDUCTOR.

∴ In intrinsic semiconductor, the no of free electrons is equal to the no of holes ie, the free electron concentration is equal to the equal hole concentration.

$$\boxed{n = p = n_i}$$

EXTRINSIC SEMICONDUCTOR :-

The need for the Extrinsic Semiconductor is

1) To increase the conduction without increasing the external energy.

2) To have less power consumption, less dissipation

→ In Intrinsic Semiconductor, the conductivity controlled by the excess free electrons or holes produced by the impurity atom.

→ If we add impurities to a intrinsic semiconductor the conductivity increases and is called, EXTRINSIC SEMICONDUCTOR.

→ "The process of adding impurities to a pure Semi-conductor is known as <u>Doping</u>.

The purpose of adding impurities is to increase either the <u>no</u> of electrons or holes in the Semi-conductor crystal.

If the impurities like ARSENIC, ANTIMONY, PHOSPHOROUS, and BISMUTH, are added to the Intrinsic Semi-conductor, a large number of free electrons are produced in the semiconductor. This is called <u>n-type semiconductor</u> and the impurities are <u>PENTAVALENT</u> impurities.

→ If the impurities, BORON, INDIUM and GALLIUM are added to intrinsic semiconductor creates a large no of holes in the semiconductor crystal. The resulting semiconductor is called P-TYPE Semiconductor, and the impurities are TRIVALENT impurities.

Therefore, Depending on the type of impurity, Extrinsic semiconductor are classified into -

1) n-type semiconductor
2) P-type semiconductor.

N-TYPE SEMICONDUCTOR :- When a small amount of pentavalent impurity is added to a pure semiconductor it is known as N-type semiconductor

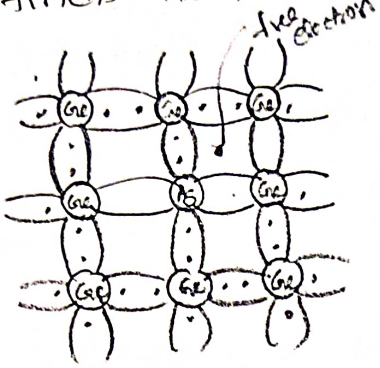
The addition of pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Typ. examples of pentavalent impurities are arsenic (At.no -33) and antimony (At.no. 51).

Such impurities which produce n-type semiconductor are known as Donor impurities because they donate or provide free electrons to the semiconductor crystal.

Germanium has four valence electrons.

-An Arsenic atoms fits in the Ge crystal in such a way that its four valence electrons form four covalent bonds with four 'Ge' atoms.

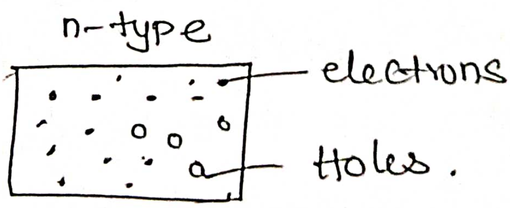
The fifth valence electron of 'As' atom finds no place in covalent bonds and then it is free.

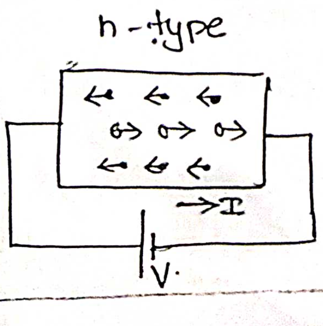


Therefore for each 'As' atom added, one free electron will be available in the 'Ge' crystal. So a small amount of impurity provides enough atoms to supply millions of free electrons.

→ At room temperature, still a few electron-hole pairs are generated, the no of free electrons provided by the pentavalent impurity far exceeds the no of holes. It is due to this predominance of electrons over holes, it is called as <u>n-type Semiconductor</u>.

→ In n-type semiconductor, the no of electrons are more than the no of holes. The free electrons are called as MAJORITY CARRIERS - Since the majority portion of the current in this by the flow of electrons. Holes are MINORITY CARRIERS.





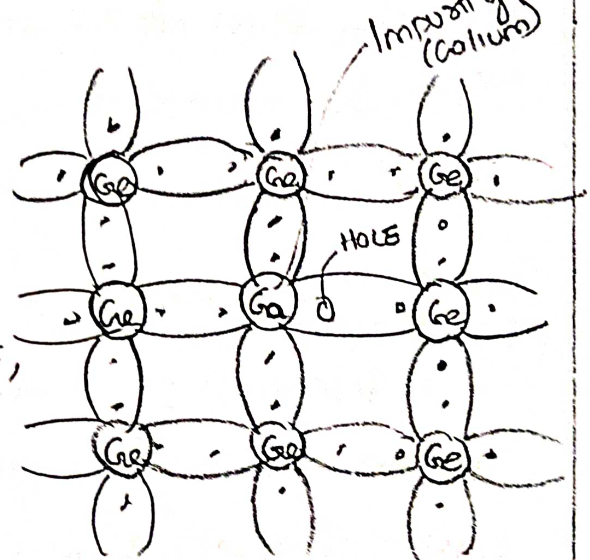
When voltage is applied across the n-type semiconductor, the free electrons ~~electrons~~

directed towards the +ve terminal constituting electric current.

As the current flows through the crystal is by free electrons which are carriers of negative charge. Therefore it is Negative type conductivity

P-TYPE SEMICONDUCTOR :-

When a small ~~type~~ amount of TRIVALENT Impurity is added to a pure semiconductor, ~~it~~ produces, P-type semiconductor.



The three valence electrons of Gallium atom can form only three covalent bonds with 3 Ge atom. In the fourth covalent bond, only Ge contributes one electron while 'Ga' atom has no valence electron to contribute, so that the fourth band is incomplete, being short of one electron. This missing electron is called a HOLE. Therefore for each 'Ga' atom added one hole is created. A small amount of 'Ga' provides millions of holes.

*. For stable crystal, each hole should accept one electron. So that this type material is called 'ACCEPTOR' material or Acceptor impurity.

→ Hole acts as a positive charge, so that material is called POSITIVE - CARRIER or P-TYPE SEMICONDUCTOR MATERIAL.

In - P-type Semiconductor

Majority carriers are HOLES.

Minority carriers are ELECTRONS.

DRIFT CURRENT :- It is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

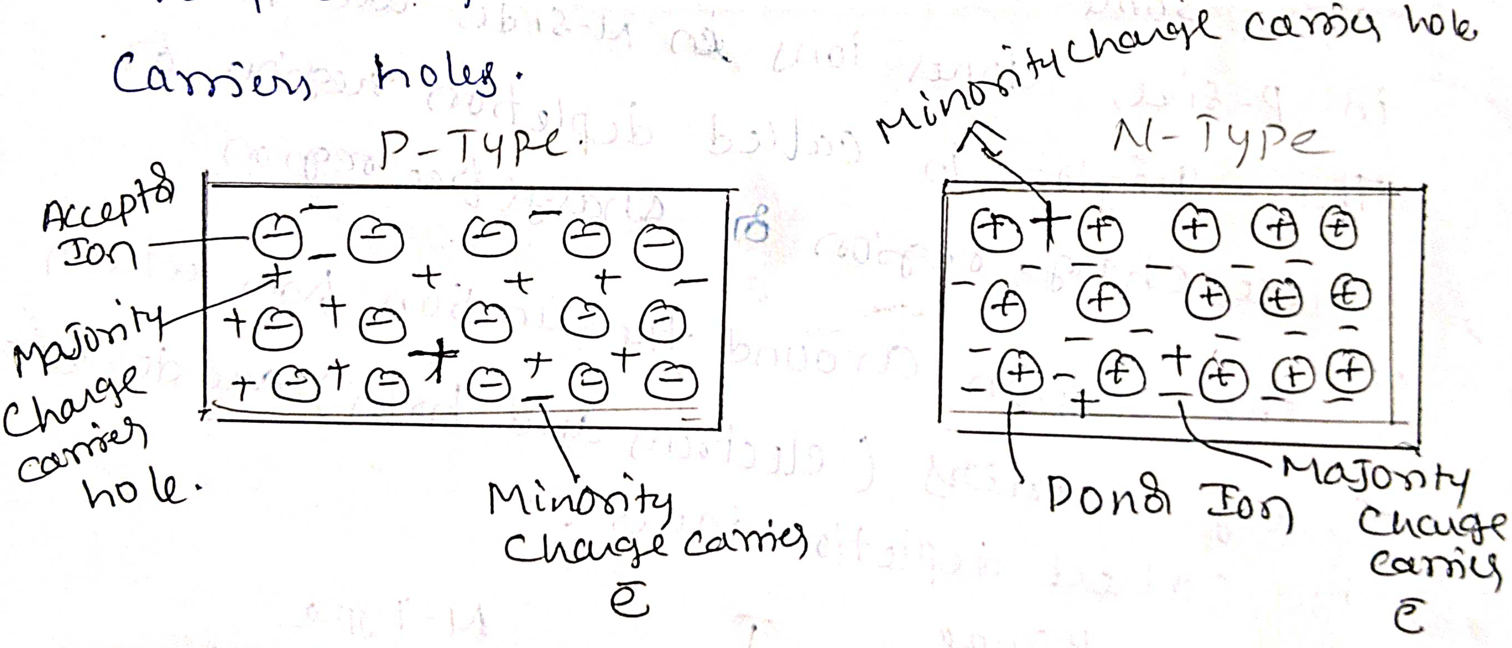
DIFFUSION CURRENT :- An electric current flows in a semiconductor even in the absence of the applied voltage provided a concentration gradient exist in the material. A concentration gradient exists ~~in the material~~ if the no of either electrons or holes is greater in one region as compared to rest of the region. This charge carriers moves from higher to lower concentration of the same type of charge carriers. This movement of charge carriers resulting in a ~~carrier~~ current called, 'DIFFUSION CURRENT'.

P-N JUNCTION DIODE

⇒ If Donor impurities are diffused in one side of pure semiconductor (say Ge & Si) and acceptor impurities are diffused to another side ~~of~~ a P-N Junction is formed.

⇒ P-Type semiconductor has -ve acceptor ions, +vely charged particle & minority charge carrier electrons.

⇒ N-Type semiconductor has +ve donor ions, -vely charged free $\bar{e}$ and minority charge carriers holes.



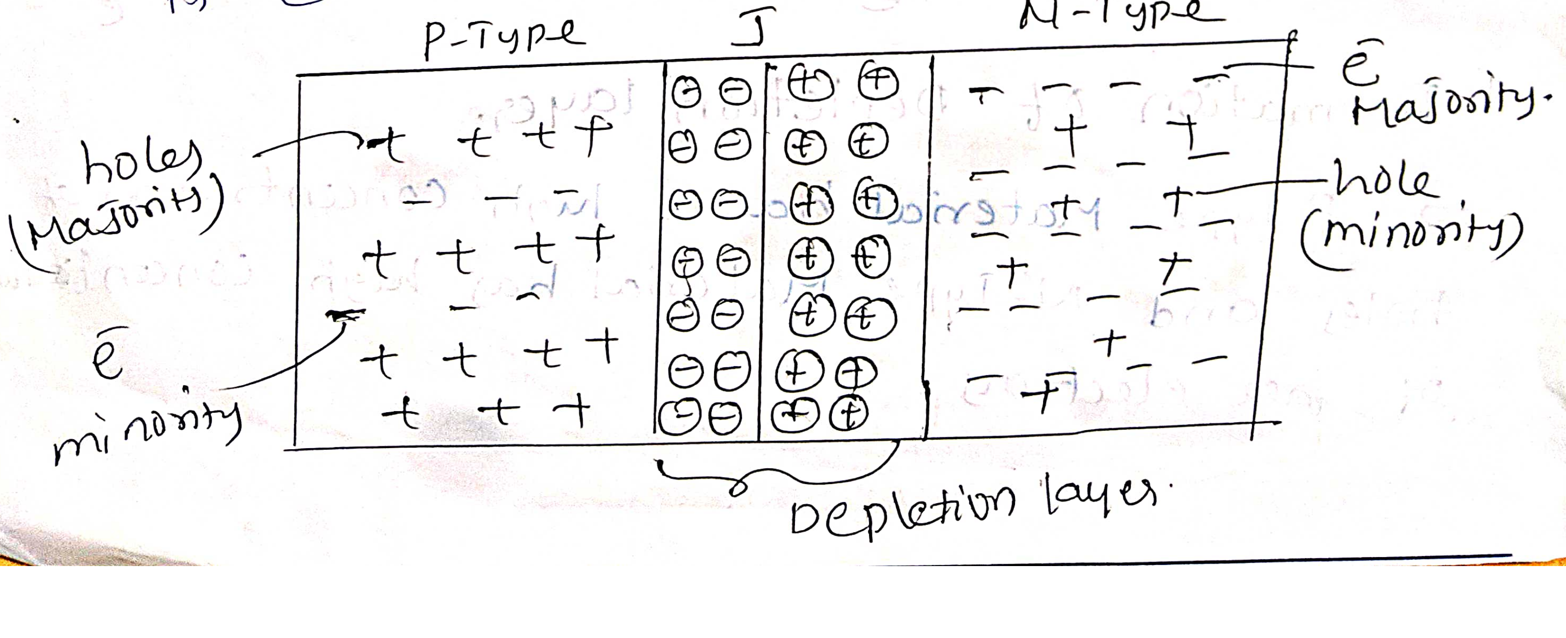
Formation of Depletion layer.

⇒ P-Type Material has a high concentration of holes and N-Type Material has high concentration of free electrons.

⇒ Due to high charge concentration, holes are ~~[illegible]~~ differing from P-Type to N-Type. and electrons diffusing from N-Type to P-Type. This process is known as diffusion.

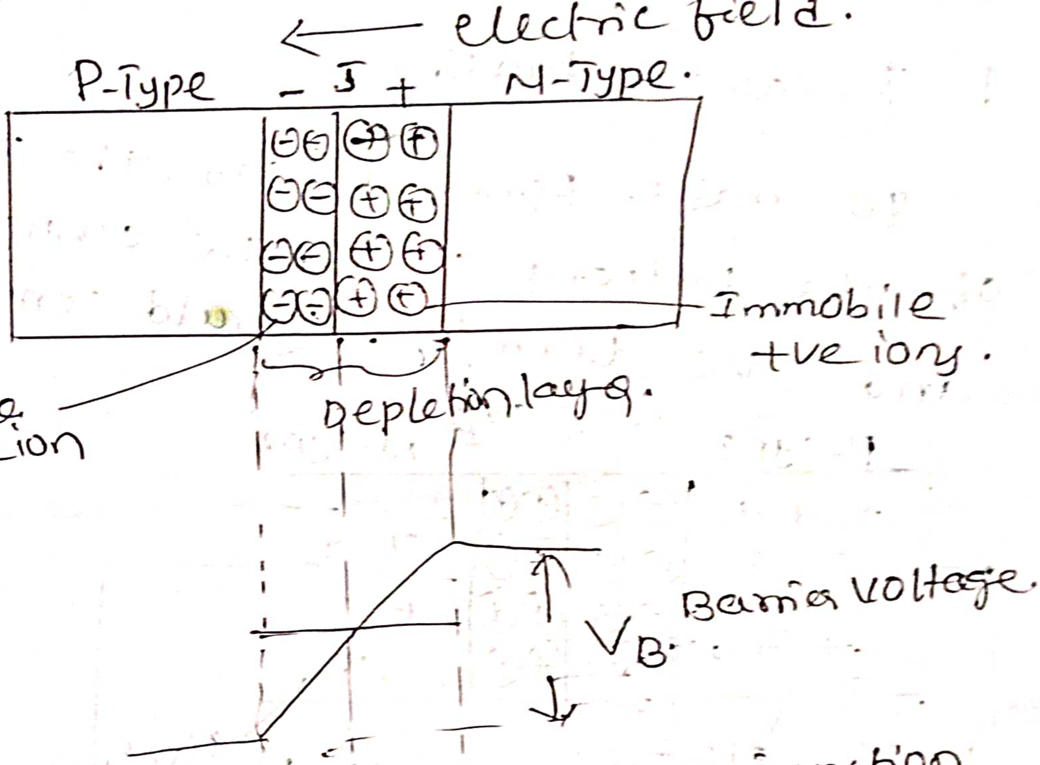
⇒ Due to diffusion some of holes from P-side cross ones to N-side, where they combine with electrons and become neutral. Similarly some of electrons from N-side crossoves to P-side where they combine with holes and become neutral. After some time nearer the Junction aceptor ions in P-side, doner ions ~~in~~ N-side are formed. This region is called depletion region or space charge region or charge free region.

"The region around the Junction from which charge carriers (electrons and holes) are depleted is called depletion layer".



Junction Voltage:

when depletion layer is formed, there are Negative immobile ions in P-side, and Positive immobile ions in N-Type Semiconductor.



As -ve ions are created on P-side of junction, so P-side acquires a -ve potential. Similarly the +ve ions are created on N-side, so N side acquires +ve potential. Thus, the initial diffusion of charge carriers creates a potential barrier at the Junction, Therefore due to charge separation, a voltage V_B is developed across the junction under equilibrium condition. This voltage is known as Junction Voltage or internal voltage or Barrier Voltage. The potential barrier is about 0.3 V for Ge, 0.7 V for Si at room temperature (300 K).

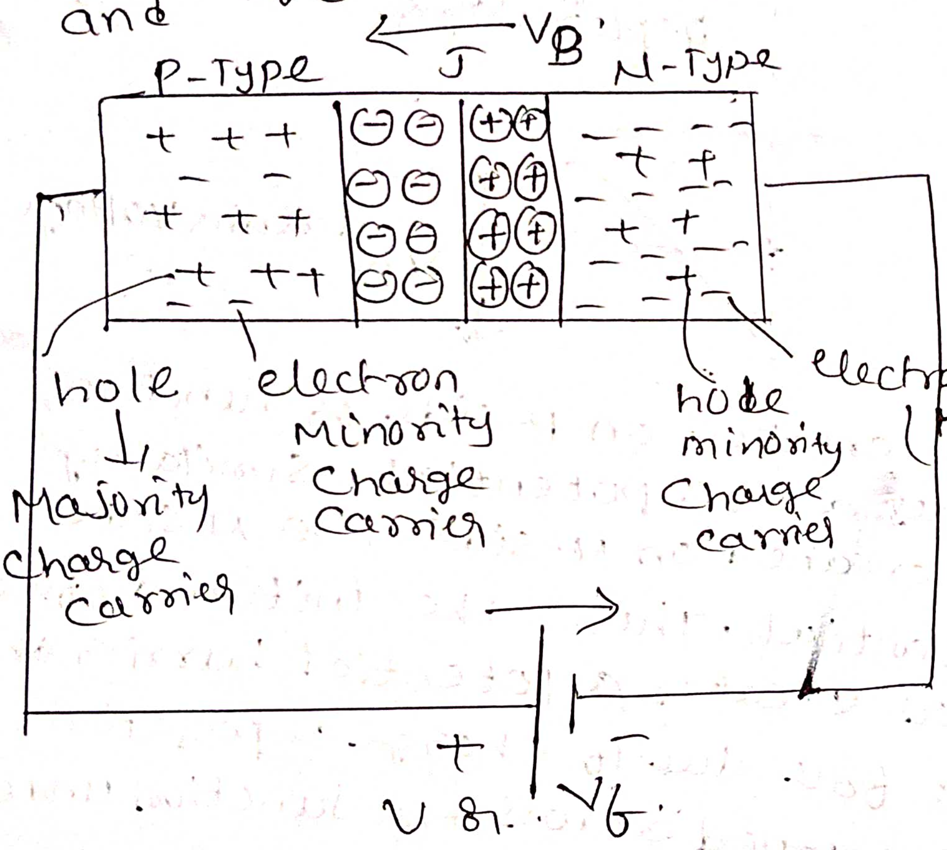
WORKING OF DIODE:

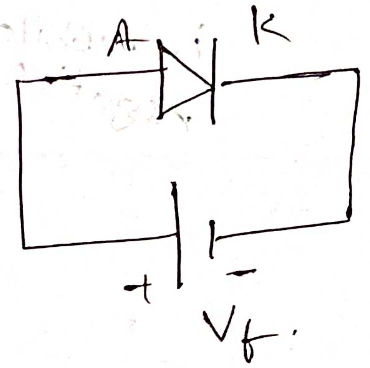
External voltage is applied to a P-N Junction is called biasing.

1. Forward biasing
2. Reverse biasing.

1. Forward biasing :-

To make Forward Bias, the positive terminal of the battery should be connected to P-type. and -ve terminal should connected to N-Type.





⇒ The applied forward voltage establishes an electric field opposite to the potential barrier. Therefore the potential barrier is reduced. As potential barrier is very small (0.3V for Ge, 0.7V for Si) ~~Therefore~~ Therefore, a small forward voltage is sufficient to completely eleminate the barrier. Now current will flow.

⇒ In Forward bias. the holes from P-type are repelled by +ve terminal of battery so holes are moving towards to the Junction and simultaneously, the electrons in N-type are repelled by -ve terminal of battery so electron are moving towards to Junction, resulting barrier width is reduced.

⇒ Now the combination of these two repelling forces Makes the Junction width very small and also reduces the barrier potential to $(V_B - V)$. Where V_B is barrier potential, & V is applied voltage.

⇒ The current passing through the diode depends upon the applied voltage.

<u>case(i)</u> when $V < V_B$

→ As applied potential is less than barrier potential, which is not sufficient to overcome the barrier, no current flows.

<u>case (ii):-</u> when $V = V_B$.

when $V = V_B$ the barrier potential reduces and starts the flow of majority charge carriers across the Junction hence resulting is called as forward current.

when $V = V_B = V_r$ (V_r is cut-in voltage or threshold voltage)

$V_r = 0.3V$ for Ge

$V_r = 0.7V$ for Si.

~~When~~

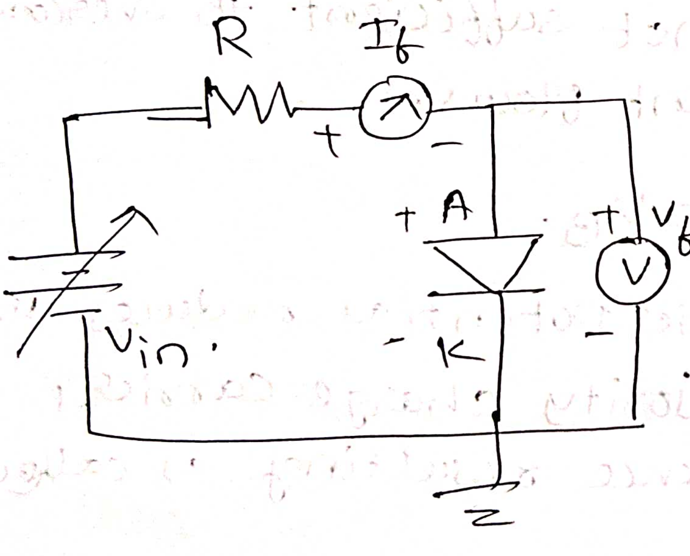
At V_r, the barrier is overcome and current I_f (mA) through the Junction starts to increase exponentially.

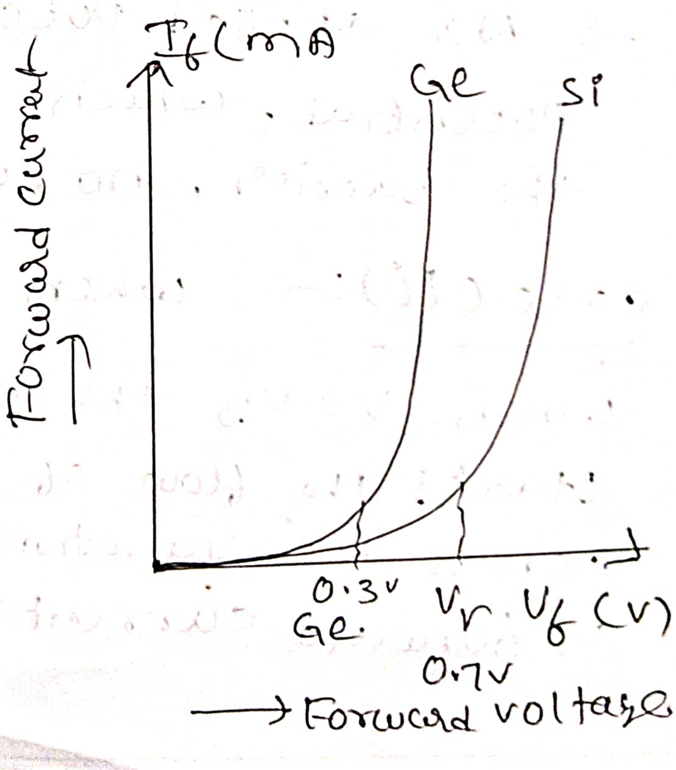
case (iii) $V > V_B$ or $V > V_r$.

For small change in applied voltage, the Large current produced.

NOTE:- when Jn is Forward biased, the Majority charge carriers move towards the Junction, Minority carriers are move away from the Junction.

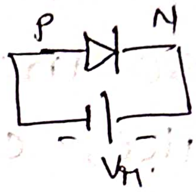
$\Rightarrow$ The Forward biase Jn offers very low resistance.

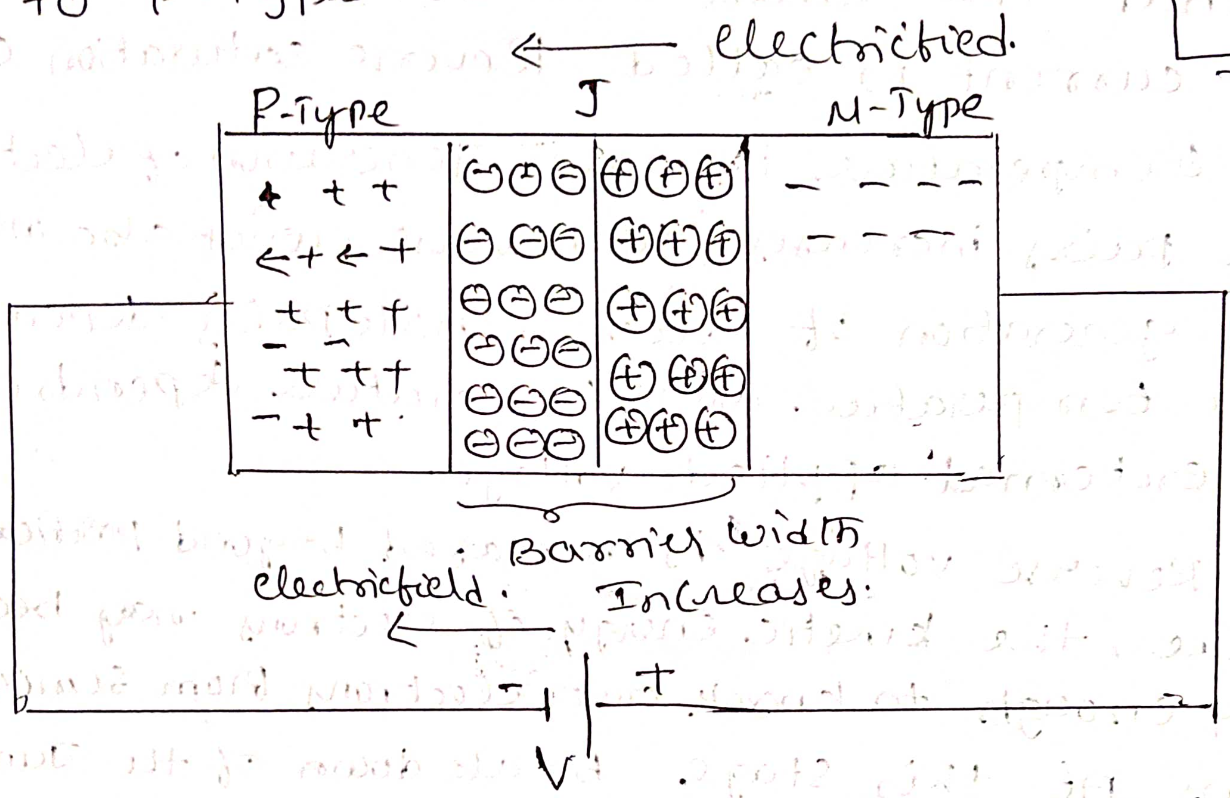




REVERSE BIAS:

To make Reverse bias, the +ve terminal of the battery should be connected to N-Type, and -ve terminal of the battery should be connected to P-Type Material.





⇒ when -ve terminal is connected to P-type Material and +ve terminal is connected to N-Type Material, The positively charged carriers i.e holes move away from the Junction because they are attracted by the negative (-ve) terminal, and the electrons move away from the Junction because they are attracted by the positive terminal.

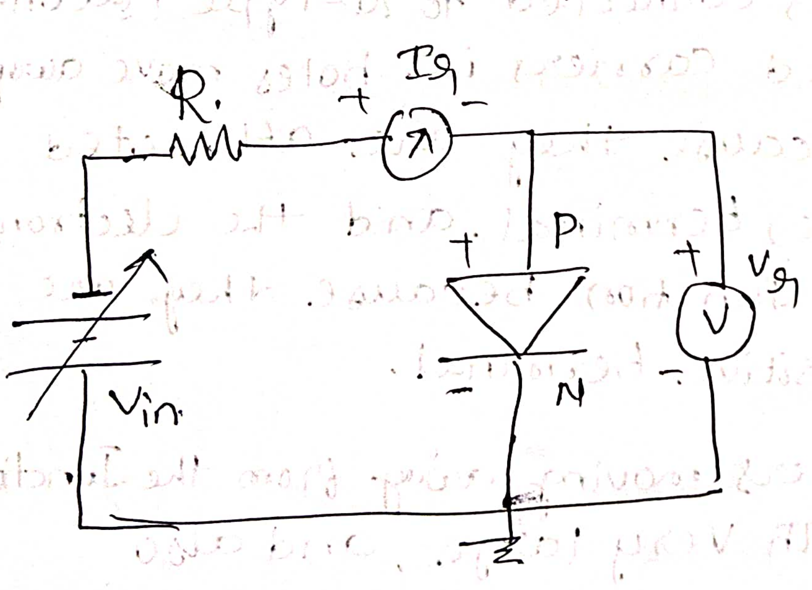
⇒ As the charge carriers moving away from the Junction Makes the barrier width very large, and also increases the barrier potential to $(V_B + V)$

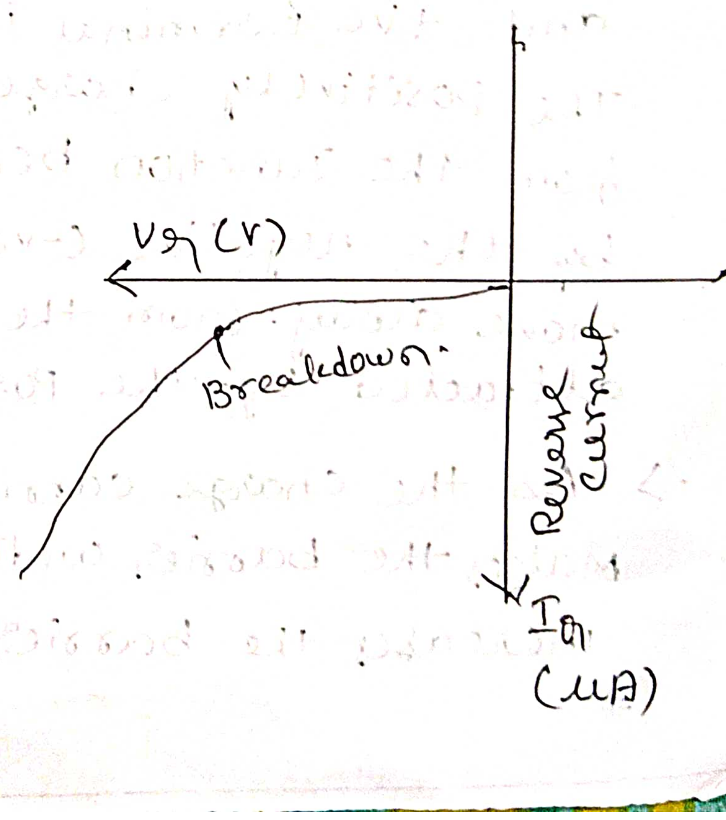
⇒ when the Junction is reverse biased, The Majority charge carriers moving away from the Junction and the minority charge carriers [$\bar{e}$ in P-side holes in N-side] only crosses the Junction. so that the small amount of current flows This current is called Reverse saturation Current

⇒ As temperature increases, generation of electron-hole pairs increases, so Reverse current also increases

⇒ The generation of electron-hole pairs depends upon temperature and temperature depends on the external applied voltage.

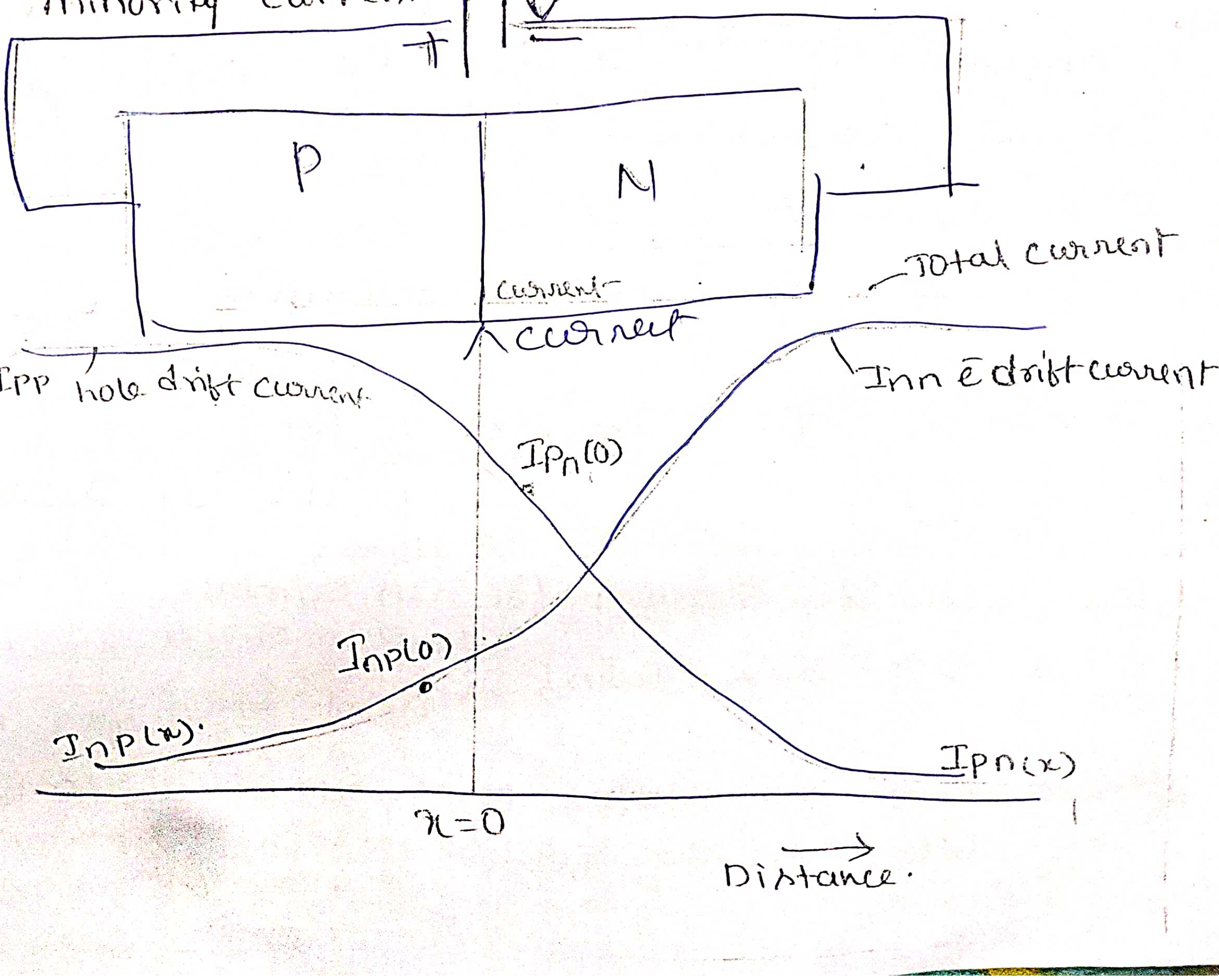
⇒ If Reverse voltage is increased beyond particular value, the kinetic energy of electrons may become high enough to knock out electrons from semiconductor atoms. At this stage break down of the Junction occurs, resulting sudden rise in Reverse current.





CURRENT COMPONENTS IN P-N DIODE

consider a Forward bias P-N Junction. Now, the holes from P-region and electrons from N-region drift towards to the Junction. The holes drifted from P-region towards the Junction enter the N-region where they represent minority carriers. Similarly, the electrons drifted from N-region towards the Junction enter the P-region where they represent minority carriers. The minority carriers diffuse away from the Junction exponentially with distance. Their concentration reduces steadily with distance because of recombination with electrons and holes respectively. we know that diffusion current of minority carriers is proportional to the concentration gradient and hence this must also vary exponentially with distance. The two minority current components are Ipn and Inp



where

$I_{pn}(x)$ = Hole current in n-material as a function of

$I_{np}(x)$ = $\bar{e}$ current in P- material as a fn of x.

$I_{pn}(0)$ = hole current in N-Material at junction ($x=0$)

$I_{np}(0)$ = $\bar{e}$ current in P- Material at Junction ($x=0$).

⇒ The $\bar{e}$ Crossing the Jn at $x=0$ from right to left constitute a current in same direction as holes Crossing the Jn from left to right. Hence the total current at the Junction ($x=0$) is

$$I = I_{pn}(0) + I_{np}(0).$$

Since the Current is the same through out in a series circuit, Hence I is Independent of x. and it is indicated as a horizontal line.

Consequently in p-side there must be a majority current I_{pp} which when added to I_{np} gives Total current I

$$I = I_{pp}(x) + I_{np}(x).$$

Similarly

$$I = I_{nn}(x) + I_{pn}(x).$$

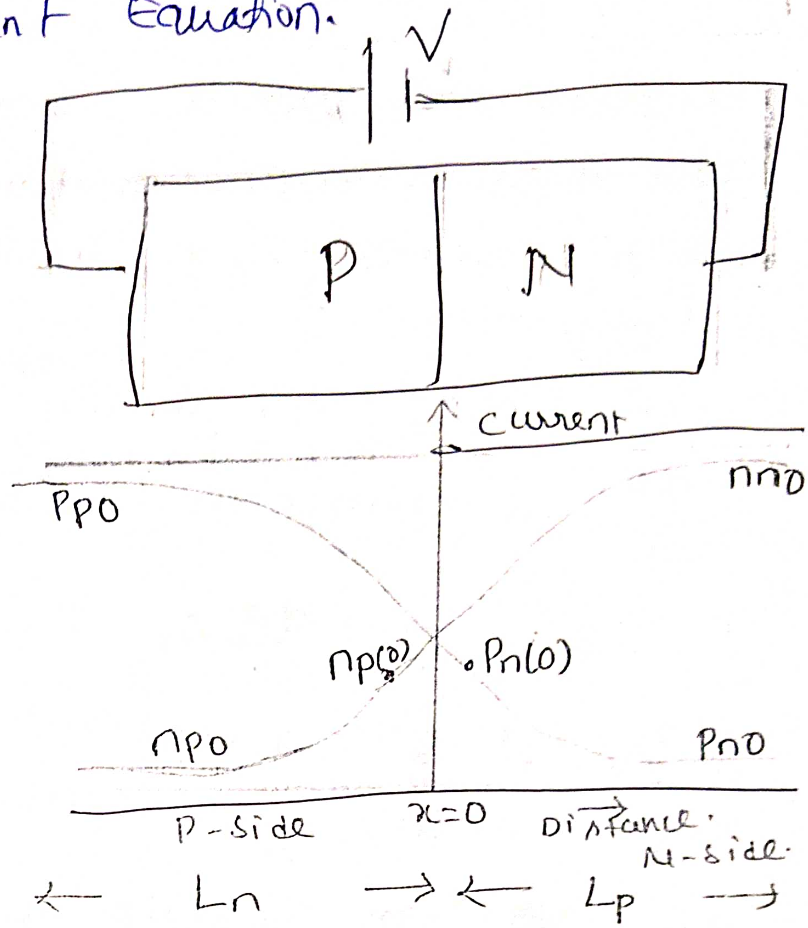
This current is plotted as a function of distance (x).

For above fig drawn for un symmetrical doped diode.

So $I_{pn} \neq I_{np}$.

NOTE: First letter refers to the type of carrier and second to the type of Material.

Diode current Equation.



$P_n(0)$: Hole concentration in n-Type at $x=0$

P_{no} = Hole concentration in n-Type at $x = L_p$
(minimun concentration of holes in n-Type i.e open ckt)

$n_P(0)$ = $\bar{e}$ Concentration in P-Type at $x=0$
n_{po} = $\bar{e}$ concentration in P-Type at $x = L_n$
(min concentration of electrons in P-Type i.e open ckt & under equilibrium condition).

L_p = Diffusion length of holes
L_n = Diffusion length of electons.

Diffusion is a process of movement of carriers from a region of high concentration to a region of low concentration.
The movement of charge carriers takes place resulting in a current known as diffusion current.

⇒ Holes are move from p. side to n-side due to
The hole concentration in decreases exponentially
with distance (x) in increase from the junction in
+ve side.

so the current density is $J_p \propto \frac{dp}{dx}$.

$\frac{dp}{dx}$ is change in hole concentration w.r.t distance x.

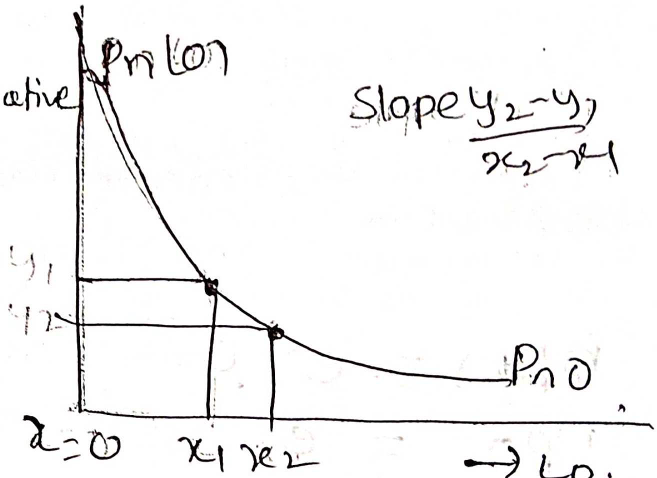
$$J_p = -q \frac{dp}{dx} D_p \quad \text{(Due to -ve slope)}$$

D_p is diffusion constant for holes (m²/sec)

J_p = Diffusion current density due to holes A/m²

The -ve sign Indicates the
concentration gradient is negative
with increasing value of x.

Similarly in n-Type



$$J_n = -(-q) D_n \frac{dn}{dx}.$$

$$J_n = q D_n \frac{dn}{dx}.$$

D_n = Diffusion constant for $\bar{e}$ m²/sec

J_n = Diffusion current density due to $\bar{e}$ A/m²

	Si	Ge
D_n	34 cm²/sec	99 cm²/sec
D_p	13 cm²/sec	47 cm²/sec

Total current density in a semiconductor is sum of drift current density and diffusion current density.

P = no of holes
E = electric field
n = no of $\bar{e}$

J_p = Drift + Diffusion

$$J_p = \underbrace{-q D_p \frac{dp}{dx}}_{\text{Diffusion}} + \underbrace{q \mu_p P E}_{\text{Drift}}$$

$$J_n = q D_n \frac{dn}{dx} + q \mu_n n E$$

We know that drift current density is proportional to the mobility (μ) while diffusion current density is proportional to Diffusion constant (D). there is exist a fixed relation between mobility and diffusion constant known as Einstein's relation.

$$\boxed{\frac{D}{\mu} = KT}$$

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = KT$$

$K = 8.62 \times 10^{-5}$ eV/K

As hole diffuse and move deeper, They recombine with $\bar{e}$ resulting in a decreasing in concentration. the average distance travelled by a hole before recombination is known as Diffusion Length L_p.

$$L_p = \sqrt{D_p \tau_p}$$

Where τ_p is known as carrier life time.

⇒ In a Jn Diode, the amount of the current in decided by diffusion so consider Diffusion current only.

$$J = \frac{I}{A}$$

$$I = J \times A.$$

$$I = I_{pn} + I_{np}$$

I_{pn} = Hole current in n-Material

I_{np} = $\bar{e}$ current in p-region.

I_{pn} = $J_p \times$ Area

I_{np} = $J_n \times$ Area

$$I_{pn} = -q D_p \frac{dp}{dx} \cdot A$$

$$I_{np} = D_n q \frac{dn}{dx} \cdot A$$

$$I_{pn} = -q D_p . A \left[\frac{P_n(0) - P_{n0}}{0 - L_p}\right]$$

$$= D_p q A . \left[\frac{P_n(0) - P_{n0}}{L_p}\right] \quad \text{—(1).}$$

Similarly

$$I_{np} = q D_n A \left[\frac{n_p(0) - n_{p0}}{0 - (-L_n)}\right]$$

$$= \frac{q D_n A}{L_n} \left[n_p(0) - n_{p0}\right] \quad \text{—(2)}$$

Let us consides an open circuit P-N Junction. Let hole and electron densities in P-region are P_p and n_p. similarly electron and hole densities in N-region are n_n and P_n respectively

The density of holes in P-region and density of holes in n-region are related by Boltzman relation

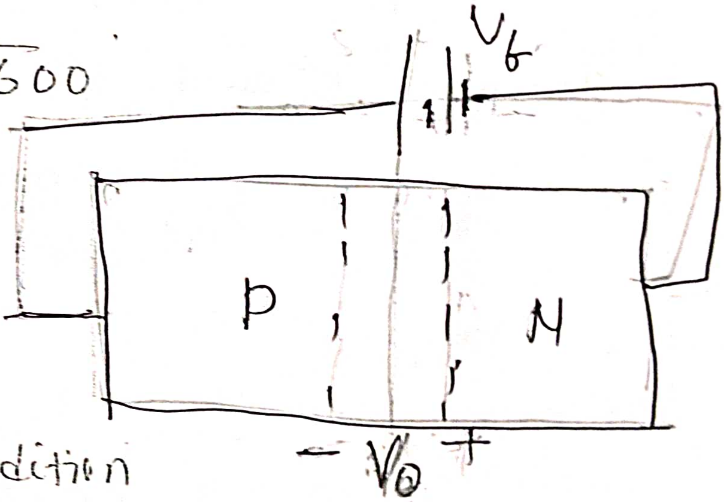
$$P_p = P_n e^{V_B/V_T} \quad — ③$$

where V_B is Barrier potential across Depletion layer

V_T is volt equivalent temperation

$$V_T = \frac{T}{11,600}$$

$V_T = 26mV$



under open circuited condition

$P_p = P_{po}$ $\quad P_n = P_{no}$ $\quad V_B = V_0$

$$P_{po} = P_{no} e^{V_0/V_T} \quad — ④$$

under Forward bias condition

when p-n Junction is Forward bias by applied voltage V. The barrier voltage V_B is decreases by amount of V i.e $V_B = V_0 - V$

p- region

The Hole concentration throught p-region constant (equal to equilibrium value)

$$P_p = P_{po} \quad \text{(max concentration of holes in p-region.)}$$

n-region :

The hole concentration in n-region, varies with distance. At the edge of depletion region at $x = 0$

$$P_n = P_{n(0)}.$$

equation (3) can be written as

$$P_{po} = P_{n(0)} \, e^{(V_0 - V)/V_T} \quad — 5$$

equate 5 and 4

$$\cancel{P_{po}} = P_{no} \, e^{V_0/V_T} = P_{n(0)} \, e^{(V_0 - V)/V_T}$$

$$P_{no} \, \cancel{e^{V_0/V_T}} = P_{n(0)} \, \cancel{e^{V_0/V_T}} \cdot e^{-V/V_T}$$

$$P_{no} = P_{n(0)} \, e^{-V/V_T}$$

$$P_{n(0)} = P_{no} \cdot e^{V/V_T} \quad — (6)$$

Similarly

$$n_{p(0)} = n_{po} \, e^{V/V_T} \quad — (7)$$

Substute eq 6 and 7 in eq (1) and (2)

$$I_{pn} = \frac{D_p q A}{L_p}\left[P_n(0) - P_{n0}\right] \quad -(1)$$

$$I_{np} = \frac{D_n q A}{L_n}\left[n_p(0) - n_{p0}\right] \quad -(2)$$

$$I_{pn} = \frac{D_p q A}{L_p}\left[P_{no}\, e^{V/V_T} - P_{no}\right] = \frac{D_p q A}{L_p} P_{no}\left[e^{V/V_T} - 1\right] \quad -8$$

$$I_{np} = \frac{D_n q A}{L_n}\left[n_{po}\, e^{V/V_T} - n_{po}\right] = \frac{D_n q A}{L_n} n_{po}\left[e^{V/V_T} - 1\right] \quad -9$$

Total current $I = I_{pn} + I_{np}$

$$I = \frac{D_p q A}{L_p} P_{no}\left[e^{V/V_T} - 1\right] + \frac{D_n q A}{L_n} n_{po}\left[e^{V/V_T} - 1\right]$$

$$= \left\{e^{V/V_T} - 1\right\}\underbrace{\left[\frac{D_p q A}{L_p} P_{no} - \frac{D_n q A}{L_n} n_{po}\right]}_{I_0 = \text{Reverse saturation current}}$$

$$I = I_0\left[e^{V/V_T} - 1\right]$$

This current in changes for different semiconductors materials so In General

$$\boxed{I = I_0\left[e^{V/\eta V_T} - 1\right]}$$

$\eta = 1$ for Ge
$\eta = 2$ for Si

where η is constant
$\eta \rightarrow$ can not calculate theoritically
it can find only with experimentally

Under Forward biased junction:

the value of V will be +ve. For Large forward biased voltage $e^{V/\eta V_T} >> 1$ in this case so neglect Io.

$$I_f = I_0 e^{V/\eta V_T}$$

The above equation shows that for a given temp the Forward current ↑ exponentially with voltage V except for a Small value of V.

For Reverse biased Junction:

In this we have

$$I_R = I_0 (e^{-V/\eta V_T} - 1).$$

For a Reverse bias whose magnitude is Large compared with V_T (~ 26mV at Room temp), we have

$$e^{-V/\eta V_T} << 1. \quad \text{so}$$

$$I_R \approx -I_0$$

Hence **Io** is called Reverse saturation current. This is constant independent of applied reverse bias.

Ex: The Reverse Saturation current at 300°K of a Ge diode is 5µA. Determine the voltage to be applied to obtain I_f of 50 mA.

Sol: Given Data: $I_0 = 5\mu A$ $I_f = 50mA$ $T = 300°K$

We know $I = I_0 (e^{V/\eta V_T} - 1)$.

for Ge $\eta = 1$ $V_T = 26mV$.

so I is Forward (& Reverse current).

$I = 50mA$.

TEMPERATURE DEPENDANCE OF V-I CHARAC

→ The Relation b/w Applied voltage V and current through the diode is

$$I = I_0 (e^{V/V_T} - 1) \Rightarrow I = I_0 (e^{V/\eta V_T} - 1).$$

The above eq. contains two temperature dependent terms.

① $V_T = \frac{T}{11,600}$ where T is in $0^\circ K$.

$V_T \propto$ Temp. (T↑ Minority carri. increases)

2. I_0 varries with temp.

From experimental data in can found that reverse saturation current I_0 ↑ approximately at the rate of 7% per 0^c (centigrade) rise in Temp.

For every $10^\circ c$ rise in temp, the I_0 doubles.

$$I_{02} = I_{01} \, 2^{(T_2 - T_1)/10} \qquad T_2 >> T_1$$

I_{01} – Reverse current at T_1 (Low temp).

I_{02} – Reverse saturation current at T_2. (high Temp)

If T ↑ current increases (with volt remain constant)

→ To keep current constant, The volt should be decreased by amount of $-2.5 \, mV/^\circ c$.

$$\frac{dV}{dT} = -2.5 \, mV/^\circ c \quad \text{for constant current}$$

The voltage across diode ↓ at rate of $2.5 \, mv/^\circ c$ rise in temp.

$$\frac{dv}{dT} = -2.5 \, mv/^\circ c$$

$\frac{dv}{dT}$ – $-2.1 \, mv/^\circ c$ Ge

$\frac{dv}{dT}$ – $-2.3 \, mv/^\circ c$ Si

Diode Resistances:

Static Resistance: R_f: It is defined as ratio of d.c voltage across diode to current flowing through diode.

In Forward bias condition

Static Resistance or d.c Resistance $R_f = \frac{V_f}{I_f}$

In Reverse bias condition

$$R_r = \frac{V_r}{I_r}.$$

Dynamic Resistance or a.c Resistance r_f

It is defined as ratio of change in voltage to change in current.

or

It is defined as reciprocal of slope of forward characteristics.

$$r_f = \frac{V_{f2} - V_{f1}}{I_{f2} - I_{f1}} \qquad r_r = \frac{V_{r2} - V_{r1}}{I_{r2} - I_{r1}}$$

(in F.B) In R.B

$$\text{or} \quad r_{ac} = \frac{1}{\frac{dI}{dV}} = \frac{dV}{dI}$$

We know

$$I = I_0 \left(e^{V/\eta V_T} - 1 \right) \Rightarrow I + I_0 = I_0 \cdot e^{V/\eta V_T}$$

differentiate above eq w.r.t V

$$\frac{dI}{dV} = \frac{d}{dV} \left[I_0 \left(e^{V/\eta V_T} - 1 \right) \right]$$

$$= I_0 \frac{d}{dV} \left[e^{V/\eta V_T} - 1 \right]$$

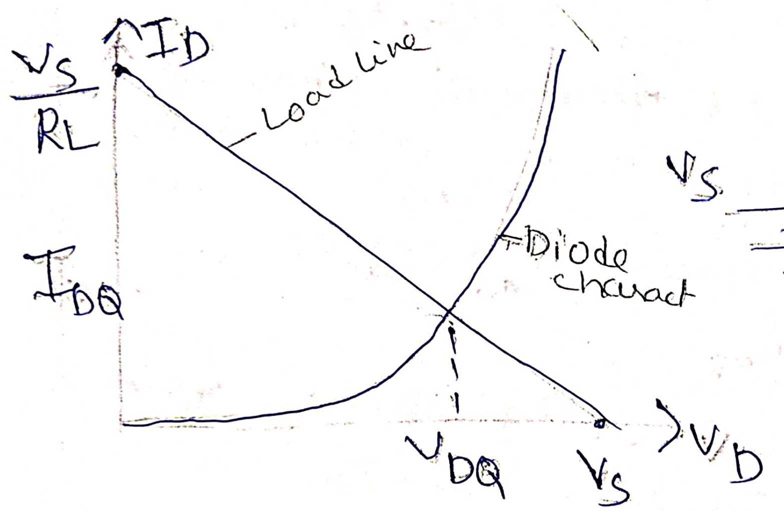
$$= I_0 \cdot \frac{e^{V/\eta V_T}}{\eta V_T} \Rightarrow \frac{I + I_0}{\eta V_T}$$

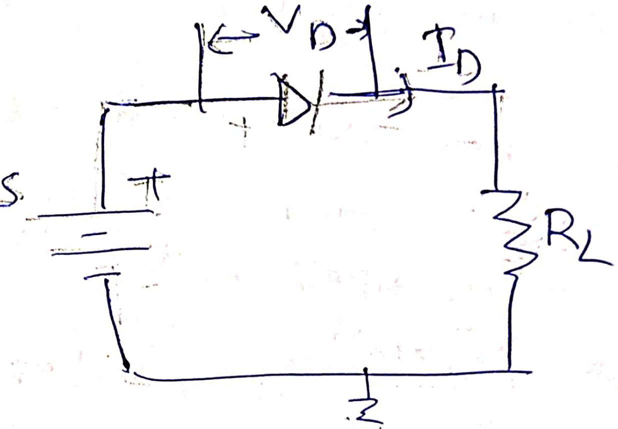
$$\boxed{\frac{dV}{dI} = \frac{\eta V_T}{I + I_0}}$$

D.C Load line.

consider the diode connected in series with a Load Resistor R_L across supply voltage V_s as shown in fig.

=) A Line drawn on the forward characteristics of diode that represents all d.c Conditions of the circuit for given V_s and R_L is called d.c Load line.





Apply the KVL to above circuit

$$V_s - V_D - V_0 = 0$$

$$V_s - V_D - I_D R_L = 0$$

when $V_D = 0$

$$I_D = \frac{V_s}{R_L}$$

when $I_D = 0$

$$V_D = V_s.$$

A line drawn on Forward characteristics, where it is intersect that point is called Q-point & operating point & quiescent point.

Q point is I_{DQ}, V_{DQ}.

Forward Bias cap (or) DIFFUSION CAPACITANCE (or) STORAGE CAPACITANCE :

→ When the Jn is F.W.B, The potential barrier at the Jn is decreases & holes move from the P-Side to the n-Side. Similarly $\bar{e}$ move from n-Side to P-Side. This process is called MINORITY CARRIERS INJECTION.

→ These carriers diffuse away from the junction and progressively recombine. The density of carriers is high near the junction and decays exponentially with distance. Thus a charge is stored on both sides of the junction when a forward-bias voltage applied.

→ It is observed that the amount of stored charge varies with applied potential. This effect is similar to a capacitor in which amount of charge stored varies with applied voltage

→ The rate of change of stored charge with applied voltage is defined as diffusion capacitance and it is denoted by C_D

$$C_D = \frac{dQ}{dV} = \frac{\text{Rate of change of charge at Jn}}{\text{rate of change of applied forward voltage}} \quad \text{—(1)}$$

The Flow of charge Q results in a diode current I and is given by

$$I = \frac{Q}{\tau} \qquad Q = I\tau \quad \text{—(2)}$$

where τ = carrier life time.

We know Diode current equation

$$I = I_0 (e^{V/\eta V_T} - 1) \quad \text{—(3)}$$

$$I = I_0 e^{V/\eta V_T} - I_0.$$

$$I + I_0 = I_0 e^{V/\eta V_T} \quad \text{—(4)}$$

substitute eq 2 in eq 3

$$\frac{Q}{\tau} = I_0 \left(e^{V/\eta V_T} - 1\right)$$

$$Q = \tau I_0 \left(e^{V/\eta V_T} - 1\right)$$

differentiate above eq. w.r.t V

$$\frac{dQ}{dV} = \frac{\tau I_0}{\eta V_T} \cdot e^{V/\eta V_T} = \frac{\tau (I + I_0)}{\eta V_T}$$

$$\boxed{C_D = \frac{I \tau}{\eta V_T}} \qquad I >> I_0$$

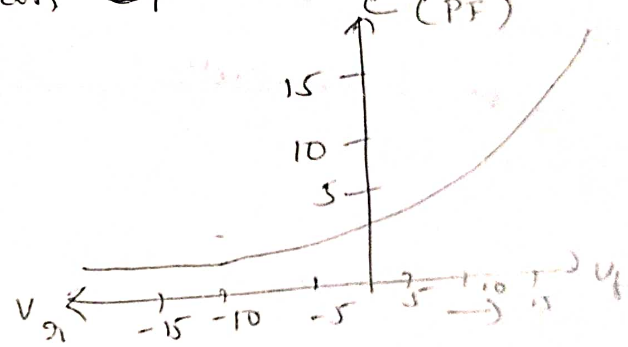
C_D is Directly proportional to current flowing through Diode

C_D is varies 800pF to 20μF

C_D much larger than C_T

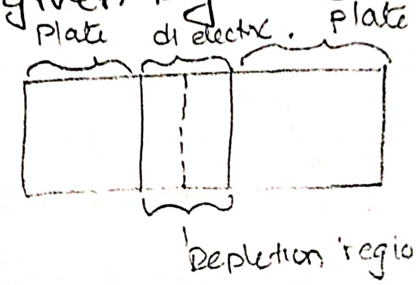
C_D is ↑ with V_f ↑

C_D is ↓ with V_R ↑



TRANSITION CAPACITANCE (C_T) (space charge capacitance)

When a P-N junction is reverse biased, the depletion region acts like an insulator or dielectric material while P and N type regions on either side have low resistance and act as the plate. In this way a P-N junction may be regarded as parallel plate capacitor. The junction capacitance is called the space charge capacitance or transition capacitance and is denoted by C_T. This capacitance is voltage dependent and is given by the relation,



$$C_T = \frac{K}{(V_K + V_R)^n}$$

where V_K = knee voltage

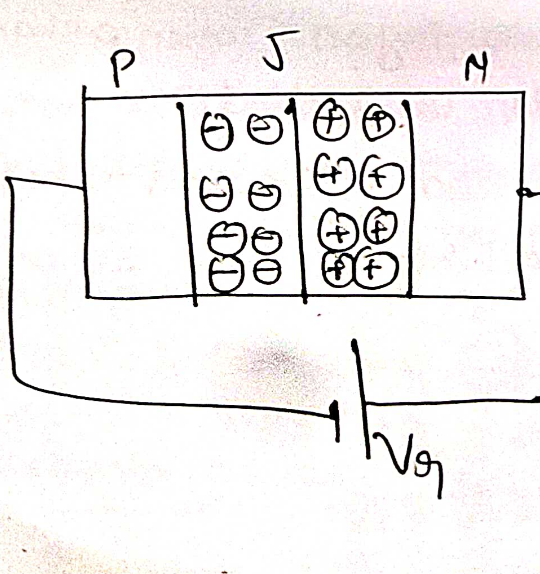
V_R = applied reverse voltage

K = constant depending on semiconductor material.

$n = (1/2)$ for alloy junction

$n = 1/3$ for diffused junction.

Fig below shows the variation of space charge capacitance with applied reverse voltage



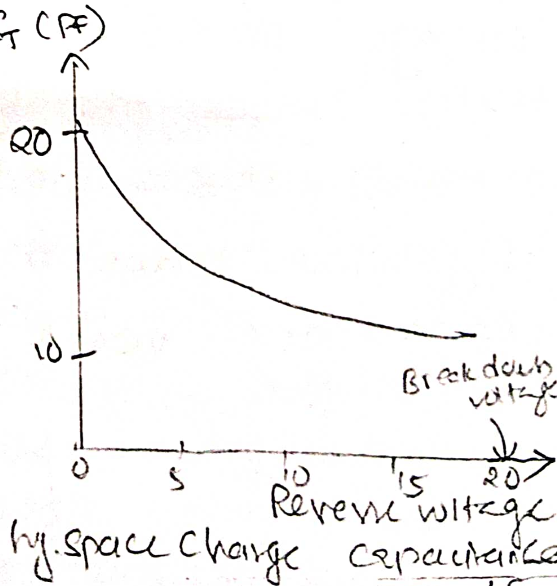


fig. space charge capacitance variation