CHENNAI INSTITUTE OF TECHNOLOGY
Transforming Lives

CHENNAI INSTITUTE OF TECHNOLOGY
(Autonomous)

SUSTAINABLE DEVELOPMENT GOALS

NBA

nirf 101 - 151 Band Engineering 2024

A+ NAAC

HAND WRITTEN MATERIAL
ELECTRONIC DEVICES

EC4101

COURSE OBJECTIVES:

1. To acquaint the semiconductor properties, examine the formation of PN Junction diode and its characteristics
2. To study the operation of Bipolar Junction Transistors (BJT)
3. To study the operation of Junction Field Effect Transistors (FET)
4. To study the operation of Metal Oxide Junction Field Effect Transistors (MOSFET)
5. To learn the construction and operation of Power Electronic Devices

COURSE OUTCOMES:

CO1:Describe the fundamental semiconductor theory, working principle of PN Junction Diode

CO2: Explain the working principle, construction and operation of BJT

CO3: Describe the construction, operation and applications of JFET

CO4: Examine the operation and characteristics of MOSFET

CO5: Describe the construction, operation and applications of Power Electronic Devices

UNIT I SEMICONDUCTOR THEORY

Classification of semiconductors - Energy Band Diagram -Conductivity of a semiconductor- Carrier concentration–Mass action law – Properties of intrinsic semiconductors – diffusion and drift currents – Carrier lifetime – Continuity equation. Generation & Recombination, Einstein' Relation, Direct & Indirect Band gap Semiconductors. PN junction diode, Current equations, Forward and reverse bias characteristics, Transition and Diffusion Capacitances

COURSE OBJECTIVES OF UNIT I:

1. To acquaint the semiconductor properties, examine the formation of PN Junction diode and its characteristics

CO-PO Mapping

COs	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
C103.1	1	1										
C103.2	2	2										
C103.3			3	3								
C103.4		4		4								
C103.5			5	5								
Avg	3	7	8	12								

PRACTICAL EXERCISE:

1. Characteristics of PN Junction Diode and Zener diode.

Prepared By Verified By Approved By

Introduction

Conductor - is a material, which easily allows the flow of electric current.
ex: Copper, Silver, Gold & aluminium.

Insulator - is a material that does not conduct electric current.
ex: Glass, air, wood, plastic & rubber.

Semiconductor

A semiconductor is a material that has an electrical conductivity that lies between conductor & Insulator.

A Semiconductor in its pure state is neither a good conductor nor a good insulator.
ex: Silicon, Germanium and carbon.

⇒ In terms of energy band, it is "partially filled conduction band and valence band".

Energy Band Diagram.

In a Single Isolated atom, the electron in any orbit possesses definite energy. But when the atoms combine into a crystal, there is an interaction b/w atoms.

As a result the electrons in the particular orbit of one atom have slightly different energy levels from electrons in the same orbit of an adjoining atom.

This is due to the fact that no two electrons see exactly the same pattern of surrounding changes.

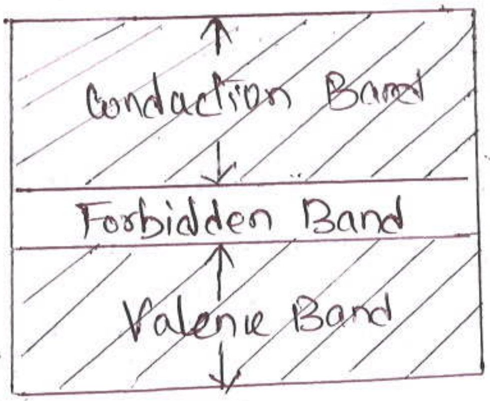
Since there are billions of electrons in any orbit, slightly different energy levels from a cluster or band.

Conduction Band.

⇒ It is defined as the range of energies possessed by conduction electrons.

Valence Band.

It is defined as the range of energies possessed by Valence electrons.



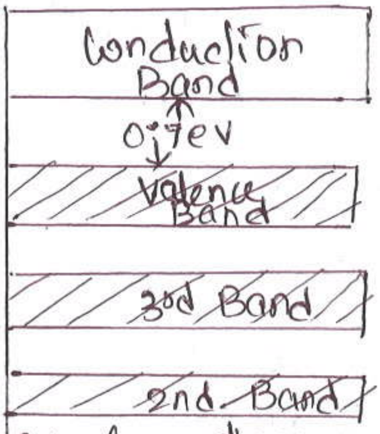
Energy band diagram of Semiconductor

At absolute zero (0°K) the Valence band is usually full and there may be no electrons in conduction band.

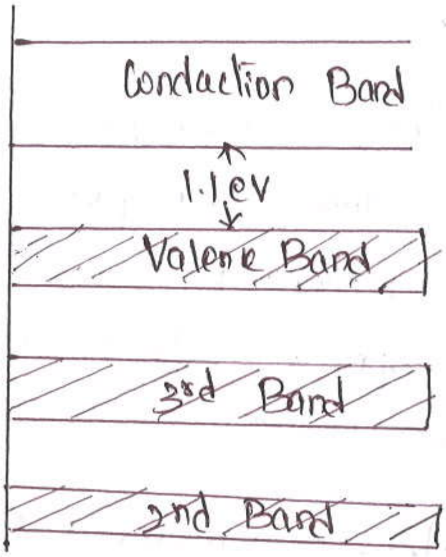
=> Forbidden energy gap for

Si - 1.2 eV

Ge - 0.785 eV.



Energy Gap diagram of (Ge)



Energy band Diagram of Silicon.

Classifications of Semiconductor.

Two Types

i) Intrinsic (pure)

ii) Extrinsic (impure)

↓

P Type extrinsic Semiconductor

N-Type extrinsic Semiconductor.

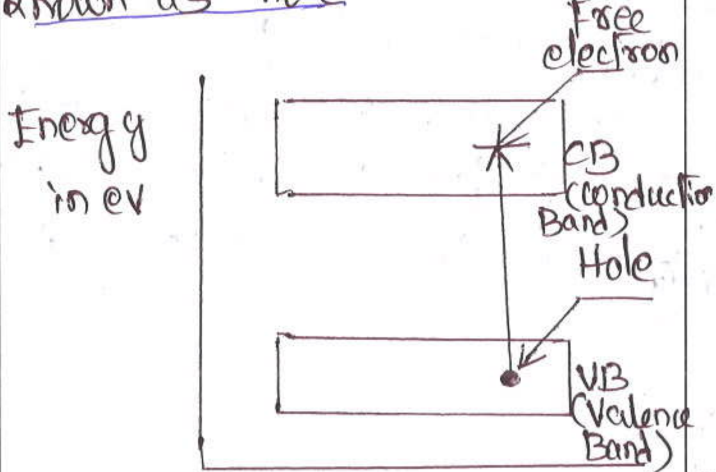
Intrinsic Semiconductor.

A pure Semiconductor is called intrinsic semiconductor.

=> Even at room temperature, some of the Valence electrons may acquire sufficient energy to enter the conduction band to form free electrons.

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

A missing electron in the valence band levels leaves a vacant space there, which known as hole.



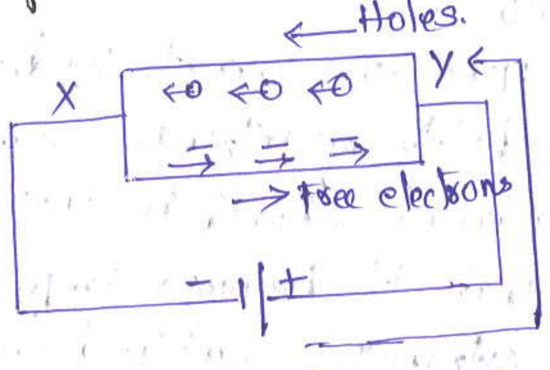
creation of electron-hole pair in a semiconductor.

⇒ In an intrinsic semiconductor even at room temperature, electron-hole pairs are created.

when electric field is applied across an intrinsic semiconductor, the current conduction takes places due to free electrons and holes.

⇒ Total current inside the semiconductor is due to free electrons and holes, the current in the external wire is fully by electrons.

In fig. holes being positively charged move towards the negative terminal of battery.



Current conduction in semi-conductor.

⇒ As the holes reach the negative terminal of the battery, electrons enter the semiconductor near the terminal (X) and combine with the holes.

⇒ At the same time, the loosely held electrons near the positive terminal (Y) are attracted towards the positive terminal. this creates new holes near the positive terminal which again drift towards the negative terminal.

Extrinsic Semiconductor.

→ Due to the poor conduction at room temperature, the intrinsic semiconductor as such is not useful in electronic devices.

→ Hence the current conduction capability of intrinsic semiconductor should be increased so, that it becomes impure or extrinsic semiconductor. This process of adding impurity is known as doping.

The amount of impurity added is extremely small, say 1 to 2 atoms of impurity of 10^6 intrinsic atoms.

N-type Semiconductor.

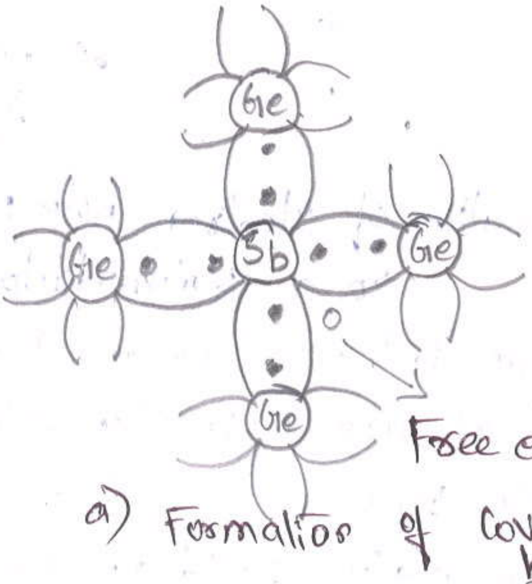
A small amount of pentavalent impurities such as arsenic, antimony (or) phosphorus is added to the pure semiconductor (Ge (or) Si) to get N-type semiconductor.

Germanium – 4 valence electrons

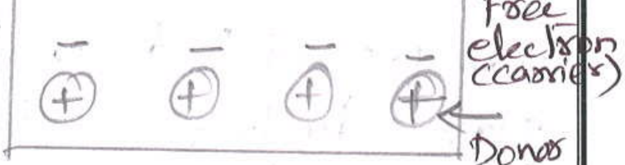
Antimony – 5 valence electrons

In fig, each antimony atom forms a covalent bond with surrounding four germanium atoms.

Thus 4 valence electrons of antimony atom form covalent bond with 4 valence electrons of individual germanium atom and 5th valence electron is left free which is loosely bound to the antimony atom.



a) Formation of covalent bonds



N-type

b)

N-type Semiconductor.

⇒ this loosely bound electron can be easily excited from the Valence band to the conduction band by the application of electric field (or) increasing the thermal energy.

⇒ Thus every antimony atom contributes ~~band by the application of electric field (or) increasing the thermal energy.~~ - one conduction electron without creating a hole. Such pentavalent impurities are called donor impurities because it donates one electrons for conduction. On giving an electron for conduction, the donor atom becomes positively charged ion because it loses one electron. But it cannot take part in conduction because it is firmly fixed in the crystal lattice.

⇒ Thus the addition of pentavalent impurity (antimony) increases the number of electrons in the conduction band thereby increasing the conductivity of N-type semiconductor.

As a result of doping, the number of free electrons far exceeds the number of holes in an N-type semiconductor. So electrons are called majority carriers and holes are called minority carriers.

Course Code/Title: Unit:

P type semiconductor:

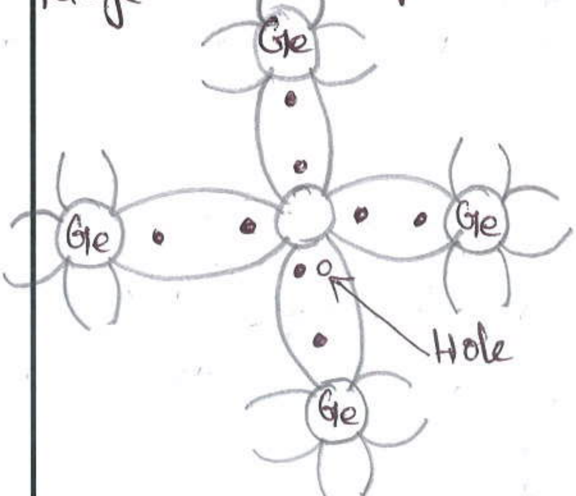
A small amount of trivalent impurity such as aluminium or boron is added to the pure semiconductor to get the P-types semiconductor.

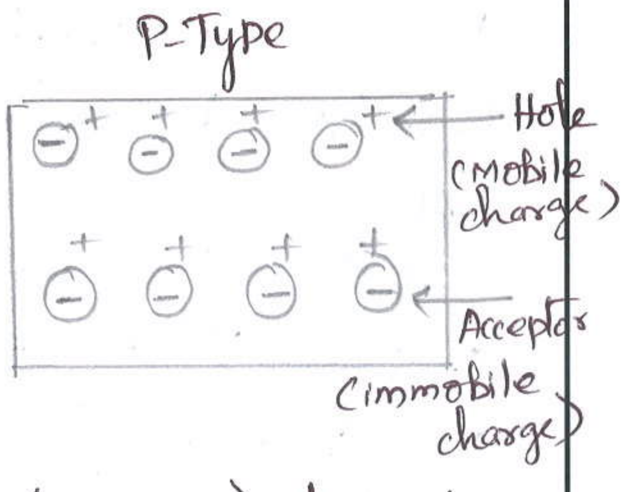
Ge → atom has 4 valence electrons

boron → atom has 3 valence electron.

In fig- 3 valence electrons in boron form covalent bond with 4 surrounding atoms of Ge leaving 1 bond incomplete which gives rise to a hole.

⇒ Thus trivalent impurity (boron) when added to the intrinsic semiconductor (Ge) introduces a large number of holes in the valence band.





a) Formation of covalent bonds b) charged carriers.

P_Type semiconductor

These positively charged holes increase the conductivity of P-types semiconductor.

Trivalent impurities such as boron is called acceptor impurity because it accepts free electrons in the place of holes. As each boron atom donates a hole for conduction, it becomes a negatively charged ion. As the number of holes is very much greater than the number of free electrons in a P-type material, holes are termed as majority carriers and electrons as minority carriers.

Conductivity of Semiconductor

⇒ In a pure semiconductor, the number of holes is equal to the number of electrons. Thermal agitation continues to produce new electron-hole pairs and the electron-hole pair disappears because of recombination.

⇒ With each electron-hole pair created, two charge-carrying particles are formed. One is negative which is the free electron with mobility μ_n.

⇒ The other is positive, i.e the hole with mobility μ_p. The electrons and holes move in opposite directions in an electric field E, but since they are of opposite sign, the current due to each is in same direction. Hence the Total current density J with in the intrinsic semiconductor is given by,

$$J = J_n + J_p$$
$$= q \cdot n \cdot \mu_n E + q \cdot P \cdot \mu_p \cdot E$$
$$= (n\mu_n + P\mu_p) qE$$
$$= \sigma E$$

J_n - electron drift current density

J_p - hole drift current density

n - number of electrons per unit volume, ie, magnitude of free-electron (negative) concentration

P - number of holes per unit volume, i.e, magnitude of hole (positive) concentration

E - applied electric field strength, V/m

q - charge of electron or hole, Colomb.

σ - conductivity of a semiconductor which is equal to $(n\mu_n + p\mu_p)q$.

The resistivity of (ρ) a semiconductor is the resiprocal of conductivity, ie $\rho = \frac{1}{\sigma}$.

From the above, the current density with in a semiconductor is directly proportional to applied elec. field.

For pure (intrinsic) semiconductor, $n = p = n_i$

n_i - intrinsic carrier concentration.

Therefore, $J = n_i(\mu_n + \mu_p)qE$ and

conductivity of an intrinsic semiconductor is

$$\sigma_i = q.n_i(\mu_n + \mu_p)$$
$$= q(n\mu_n + p\mu_p)$$

For N-type semiconductor,

as $n >> p$, then the conductivity, $\sigma = q.n.\mu_n$

For P-type semiconductor,

as $p >> n$, then conductivity $\sigma = q.p.\mu_p$.

Carrier Concentration in Intrinsic Semiconductor

To calculate the conductivity of semiconductor, the concentration of free electrons n & concentration of free p must be known,

$$dn = N(E)f(E)dE$$

dn - number of conduction electrons per cubic meter whose energies lie b/w E & E+dE

N(E) - density of states.

In a semiconductor, the lowest energy in conduction band is E_c & hence

$$N(E) = \gamma(E - E_c)^{1/2}$$

The Fermi Dirac probability fn $f(E)$ is given by

$$f(E) = \frac{1}{1+e^{(E-E_F)/KT}}$$

E_f - Fermi level (or) characteristic energy for the crystal in eV.

The concentration of electrons in the conduction band is,

$$n = \int_{E_C}^{\alpha} N(E) f(E) dE$$

for $E \geq E_C$, $E - E_F \gg KT$.

$$f(E) = e^{-(E-E_F)/KT}$$

and

$$n = \int_{E_C}^{\alpha} \gamma (E-E_C)^{1/2} e^{-(E-E_F)/KT} dE$$

Substitute $(E-E_C) = x^2$

ie. $E = x^2 + E_C$

and $dE = 2x dx$

at $x = 0$, $E = E_C$,

At $x = \alpha$, $E = \alpha$

Therefore,

$$n = \int_0^{\alpha} \gamma x e\left(-\frac{x^2+E_C-E_F}{KT}\right)[2x dx]$$

$$= 2\gamma e^{-\left(\frac{E_C-E_F}{KT}\right)} \int_0^{\alpha} x^2 e^{-\frac{x^2}{KT}} \cdot dx$$

W.K.T

$$\int_0^{\alpha} x^{2n} e^{-x^2/a^2} dx = \sqrt{\pi}\,\frac{2n!}{n!}\left(\frac{a}{2}\right)^{2n+1}$$

Here, $n=1$ & $a = \sqrt{KT}$

Therefore,

$$n = 2\gamma e^{-\left(\frac{E_C-E_F}{KT}\right)} \times 2\sqrt{\pi}\left(\frac{\sqrt{KT}}{2}\right)^3$$

Substituting $\gamma = \frac{4\pi}{h^3}(2m_n)^{3/2}(1.602\times10^{-19})^{3/2}$, we have

$$n = 2\times\frac{4\pi}{h^3}(2m_n)^{3/2}(1.602\times10^{-19})^{3/2}\times\frac{\sqrt{\pi}(kT)^{3/2}}{4}\times e^{-\left(\frac{E_c-E_F}{kT}\right)}$$

$$= 2\left(\frac{2m_n\pi kT}{h^2}\right)^{3/2}\times(1.602\times10^{-19})^{3/2}\, e^{-\frac{(E_c-E_F)}{kT}}$$

$$= N_c\, e^{-\left(\frac{E_c-E_F}{kT}\right)}$$

where $N_c = 2\left(\frac{2\pi m_n kT}{h^2}\right)^{3/2}(1.602\times10^{-19})^{3/2}$

m_n - effective mass of an electron

When the maximum energy in valence band is E_V, the density of states is given by,

$$N(E) = \gamma(E_V - E)^{1/2}$$

The Fermi fn of a hole is $[1-f(E)]$ and is given by

$$1-f(E) = \frac{e^{(E-E_F)/kT}}{1+e^{(E-E_F)/kT}}$$

$$= e^{-(E_F-E)/kT}$$

where $E_F - E \gg kT$ for $E \le E_V$,

The concentration of holes in valence band is,

$$p = \int_{-\infty}^{E_V}\gamma(E_V-E)^{1/2} e^{-(E_F-E)/kT}\, dE$$

This integral evaluates to

$$p = N_V e^{-(E_F - E_V)/KT}$$

where

$$N_V = 2\left(\frac{2\pi m_p KT}{h^2}\right)^{3/2} (1.602\times10^{-19})^{3/2},$$

m_p - effective mass of a hole,

Fermi level in an intrinsic Semiconductor

In case of intrinsic material, the crystal must be electrically neutral.

$$n_i = p_i$$

$$\therefore N_C e^{-(E_C - E_F)/KT} = N_V e^{-(E_F - E_V)/KT}$$

Taking the log on both sides,

$$\ln \frac{N_C}{N_V} = \frac{E_C - E_V - 2E_F}{KT}$$

$$E_F = \frac{E_C + E_V}{2} - \frac{KT}{2} \ln \frac{N_C}{N_V}$$

If the effective masses of a free electron and hole are the same,

$$N_C = N_V$$

$$E_F = \frac{E_C + E_V}{2}$$

From the above eqn, at the centre of the forbidden energy band, Fermi level is present.

Donor and acceptor impurities.

If a pentavalent substance (antimony, phosphorous or arsenic) is added as an impurity to pure germanium. four of the five valence electrons of the impurity atoms will occupy covalent bonds and the fifth electron will be available as a carrier of current. These impurities donate excess electron carriers and are called donor (or) N-type impurities.

If a trivalent impurity (boron, gallium (or) indium) is added to an intrinsic semiconductor, only three covalent bonds are filled, and the vacancy in the fourth bond constitutes a hole. These impurities are known as acceptor or P-type impurities.

Fermi level in a semiconductor having impurities

The Fermi level in an N-type material is given by $E_F = E_C - kT \ln \frac{N_C}{N_D}$

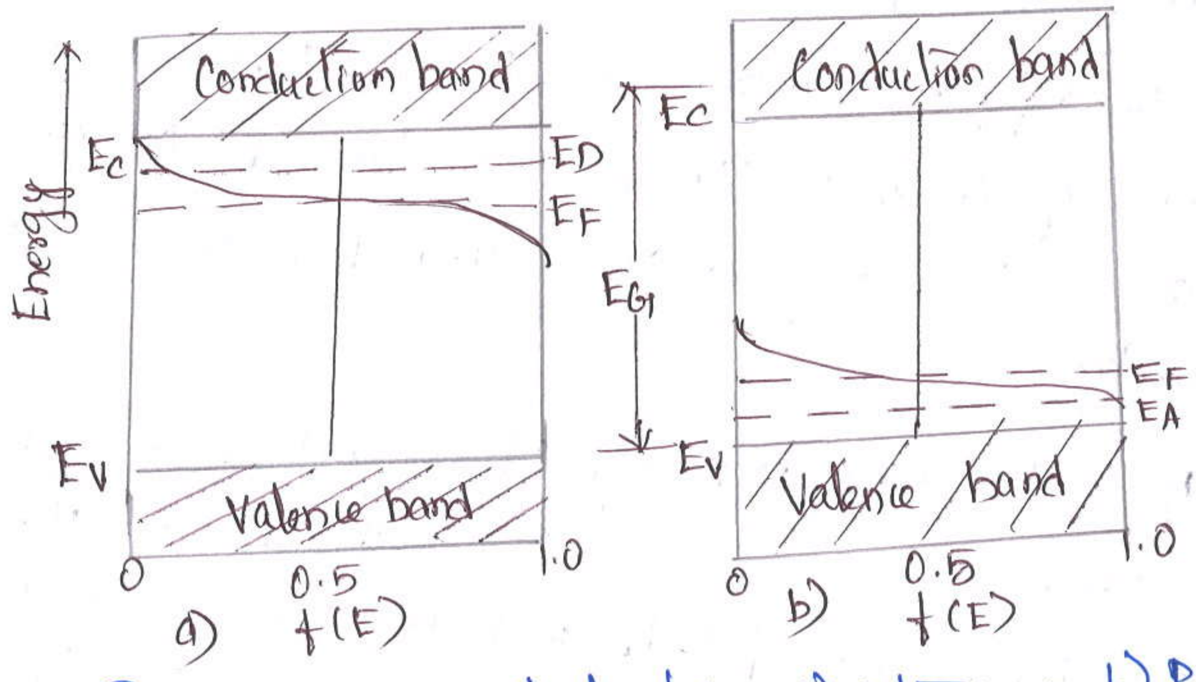
$\therefore N_D = N_C e^{-(E_C - E_F)/kT}$, the concentration of donor atoms.

The Fermi level in a P-type materil is given by

$$E_F = E_V + kT \ln \frac{N_V}{N_A}$$

where $N_A = N_V e^{-(E_F - E_V)/kT}$, the concentration of acceptor atoms.

The change in position of Fermi level in N & P type semiconductors is given by in fig -



Positions of Fermi level in a) N type & b) P-Type Semiconductors

Movement of E_f with temperature.

⇒ In N-type semiconductor, temperature T increases, more number of electron - hole pairs are formed.

⇒ At very high temp T, the concentration of thermally generated electrons in the conduction band will be far greater than concentration of donor electrons

⇒ In such case, a concentration of electrons and holes become equal, the semiconductor becomes essentially intrinsic and E_F returns to the middle of the forbidden energy gap.

Hence, it is concluded that as the temperature of the P type & N type semiconductor increases E_F progressively moves towards the middle of the forbidden energy gap.

Mass Action law.

Under thermal equilibrium, the product of number of holes and number of electrons are constant and independent of the amount of donor and acceptor atoms. This relation is known as mass-action law. It is given by.

$$\boxed{np = n_i^2}$$

n - number of free electrons per unit Volume ele/m^3

P - number of holes per unit Volume.

n_i - Intrinsic concentration

While considering the conductivity of the doped semi-conductors, only the dominant majority charge carriers have to be ~~d~~ considered.

Charge densities in N-type and P-type Semiconductors.

The law of mass action has given the relation-ship b/w free electron concentration & hole concentration. It is related by law of Electrical Neutrality as below,

N_D - concentration of donor atoms in N-type semiconductor.

To maintain the electric neutrality of the crystal, we have

$$n_N = N_D + p_N$$
$$\simeq N_D$$

n_N, p_N - electron and hole concentration in N-type semiconductor.

The value of p_N is obtained from the relations of mass action laws as,

$$p_N = \frac{n_i^2}{n_N}$$
$$\simeq \frac{n_i^2}{N_D}, \text{ where is } << n_N \text{ (or) } N_D.$$

Similarly, in P-type semiconductor we have,

$$p_P = N_A + n_P$$
$$\simeq N_A$$

N_A, p_P & n_P → concentrations of acceptor impurities, holes and electrons respectively in a P-type semiconductor.

From mass-action law, $n_p = \frac{n_i^2}{P_p}$

$n_p = \frac{n_i^2}{N_A}$, which is $\ll P_p$ (or) N_A

Extrinsic Conductivity

Conductivity of an N-type semiconductor is given by

$$\boxed{\begin{aligned} \sigma_N &= q n_N \mu_n \\ &\simeq q N_D \mu_n \end{aligned}}$$ since $n_N \simeq N_D$.

The conductivity of P-type semiconductor is given by

$$\boxed{\begin{aligned} \sigma_P &= q P_p \mu_p \\ &\simeq q N_A \mu_p \end{aligned}}$$ since $P_p \simeq N_A$

The doping of intrinsic semiconductor considerably increases its conductivity.

⇒ If concentration of donor atoms added to a P-type semiconductor exceeds the concentration of acceptor atoms, ie $N_D \gg N_A$, then the semiconductor is converted from P-type to N-type. ~~of acceptor atoms. ie $N_D \gg N_A$, then the semiconductor is conver~~

Similarly, a large number of acceptor atoms added to an N-type semiconductor can convert it to a P-type semiconductor (or) if $N_A \gg N_D$. This concept is precisely used in fabrication of PN Jn, which is an essential part of semiconductor devices.

Properties of Intrinsic semiconductors.

Important properties of intrinsic Silicon and Germanium at room temperature (300 K).

	Si	Ge	$GaAs$
Atomic number	14	32	-
Atomic weight	28.09	72.59	-
Atomic density (m^{-3})	5.02×10^{28}	4.42×10^{28}	-
Lattice constant, a (nm)	0.543	0.565	0.563
Relative permittivity, ε_r	11.8	16.0	13.5
Density, g/cm^3	2.33	5.32	-
Energy gap, E_G (eV)	1.08	0.666	1.58
Electron mobility, μ_n $(m^2/V\text{-}s)$	0.13	0.38	0.85
Hole mobility, μ_p $(m^2/V\text{-}s)$	0.05	0.18	0.04
Intrinsic concentration, n_i (m^{-3})	1.38×10^{16}	2.5×10^{19}	9×10^{12}
Electron diffusion constant, $D_n\,(m^2/s) = \mu_n V_T$	0.0034	0.0099	0.020
Hole diffusion constant, $D_p\,(m^2/s) = \mu_p V_T$	0.0013	0.0047	-
Density of states at conduction band edge, N_c (m^{-3})	2.8×10^{25}	1.0×10^{25}	4.7×10^{23}
Density of states at Valance band edge, N_v (m^{-3})	1.0×10^{25}	6.0×10^{24}	7.0×10^{24}
Intrinsic resistivity, Ω-cm	23×10^{4}	45	-
Melting point	1420	936	1250

Drift and Diffusion Currents.

The flow of charge i.e. current, through a semiconductor material of two types, namely drift and diffusion.

The net current that flows through a P.N Jn diodes has two components.

i.e. Drift Current

Diffusion Current.

Drift Current.

When a small electric field is applied across a semiconductor bar, the holes move in the direction of applied field whereas the electrons move in a electron opposite to that of applied field.

=> This combined effect of movement of holes and electrons constitute an electric current, is known as drift current.

The drift current density J_n due to free electrons is given by $J_n = qn\mu_n E$ A/cm^2

the drift current density J_p due to hole is given by

$$J_p = qp\mu_p E \; A/cm^2$$

n - number of free electrons per cubic centimetre

p - number of holes per cubic centimetre

μ_n - mobility of electrons in $cm^2/V\text{-}s$

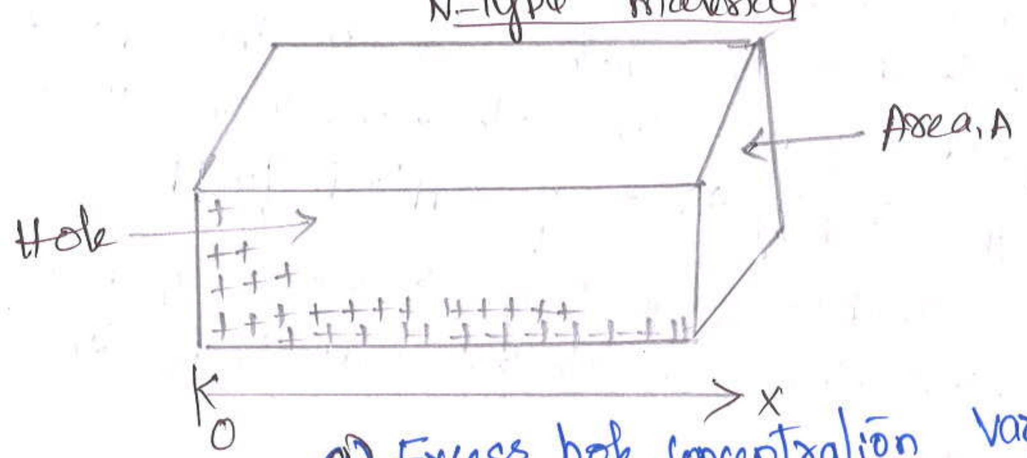
μ_p - mobility of holes in $cm^2/V\text{-}s$

E = applied elec. field intensity in V/cm

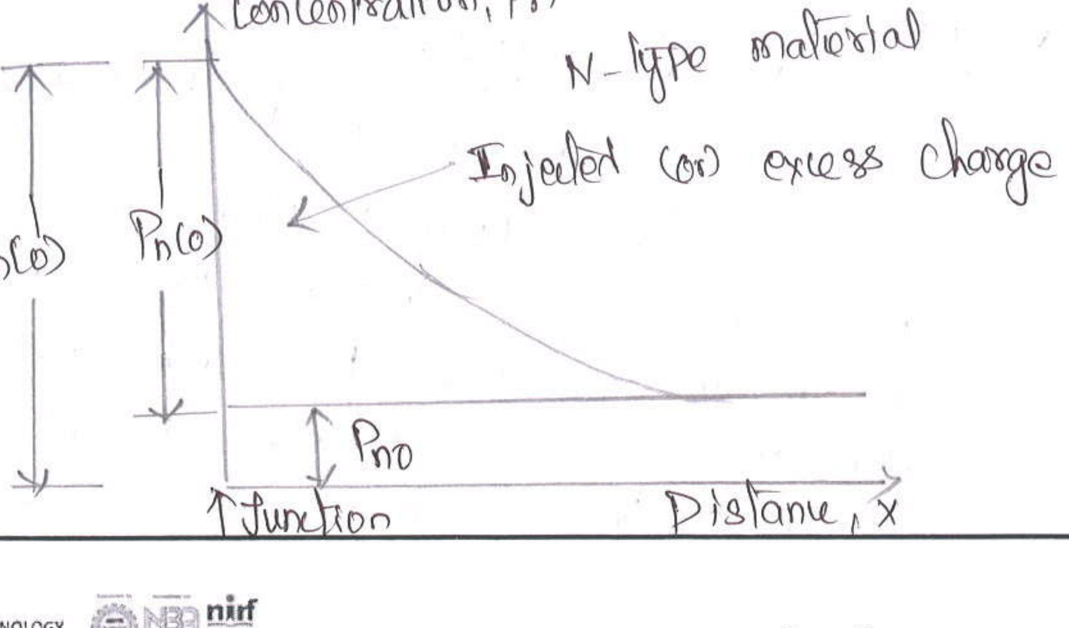
q - charge of an electron = 1.602×10^{-19} coulomb.

Diffusion Current.

Diffusion is a process of movement of carriers from a region of high concentration to a region of ~~high~~ low concentration of the same type of charge carriers. Thus the movement of charge carriers takes place resulting in a current called diffusion current.



a) Excess hole concentration varying along the axis in an N-type semiconductor bar.



b) The resulting diffusion current

fig a) the hole concentration $p(x)$ in a semi conductor bar varies from a high value to a low value along the x axis and is constant in y and z directions.

Diffusion current density due to holes, J_p is given by $J_p = -q D_p \frac{dp}{dx}$ A/cm²

Since the hole density $p(x)$ decreases with increasing x in fig (b)

dp/dx - is (-) negative & minus sign in above eqn is needed in order that J_p has (+) sign in the (+ve) x direction.

D_p & D_n - diffusion co-efficient expressed in cm²/s for electrons and holes, respectively.

Total current.

The total current in a semiconductor is the sum of drift current and diffusion current. Therefore, for a p-type semiconductor, the total current per unit area, the total current density is given by

$$J_p = q p \mu_p E - q D_p \frac{dp}{dx}$$

Similarly, the total current density for an N-type semiconductor is given by

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

Einstein Relation.

The drift current density is proportional to mobility (μ), while diffusion current density is proportional to the diffusion constant (D).

There exist a fixed relation between mobility and diffusion constant known as Einstein's relation.

At a fixed temperature, the ratio of diffusion constant to the mobility is constant.

$$\boxed{\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = kT}$$

For intrinsic Silicon, $D_p = 13\,cm^2/s$
$D_n = 34\,cm^2/s$.

For an intrinsic germanium $D_p = 47\,cm^2/s$
$D_n = 99\,cm^2/s$.

Carrier Life Time

In an intrinsic semiconductor the number of holes is equal to number of free electrons. However, thermal agitation generates new electron-hole pairs.

⇒ The electrons have limited life time (τ_n) in conduction band and periodically fall back to the valence band, so that the electron-hole pair disappears in the recombination process with the

energy of excitation appearing as heat energy.
On an average, an electron will exist for τ_n seconds and a hole for τ_p seconds before recombination.
The mean life times τ_n & τ_p of electrons and holes are very important parameters as they indicate the time required for the excessive electron and hole concentrations to return to their equilibrium values.

⇒ Thus the carrier life time is defined as the time for which, on an average, a charge carrier will exist before recombination with a carrier of opposite charge.

For N-type semiconductor, the thermal equilibrium concentration P_0 & n_0 of holes and electrons respectively. When the specimen is illuminated by light or injection of carriers, additional electron-hole pairs are generated uniformly throughout the medium.

⇒ This causes the concentration of holes and electrons to increase from P_0 and n_0 to new values.

⇒ The rate of change of hole density is equal to their rate of generation minus the rate at which they recombine with electrons, thus

$$dP/dt = G - R.$$

P - minority hole concentration at any time t,

G & R - Generation and recombination rates for the minority carriers.

The Generation rate G, is a function of temperature only since charge carriers are produced only by thermal excitation in the absence of current flow. Hence, at a constant temperature, G(t) is constant.

The mean life time of hole τ_p is independent of the magnitude of the hole concentration, we get

$R = \frac{P}{\tau_p}$ - decrease in hole concentration per second due to recombination.

Also, from the definition of the generation rate, we get

G = increase in hole concentration per second due to thermal generation.

Since charge can neither be created nor destroyed, the rate dP/dt, at every instant of time, equals the algebraic sum of rates given in above eqns R & G,

Thus,

$$\frac{dP}{dt} = G - \frac{P}{\tau_p}$$

under steady state conditions, $\frac{dP}{dt} = 0$, with no radiation falling on the semiconductor, the hole concentration P reaches its equilibrium value P_0. Therefore

$$G = P_0/\tau_p$$

Hence $\frac{dP}{dt} = \frac{P_0 - P}{\tau_p}$

Similarly, the change in excess electron density with time in P-type semiconductor is given by

$$\frac{dn}{dt} = \frac{n_0 - n}{\tau_n}.$$

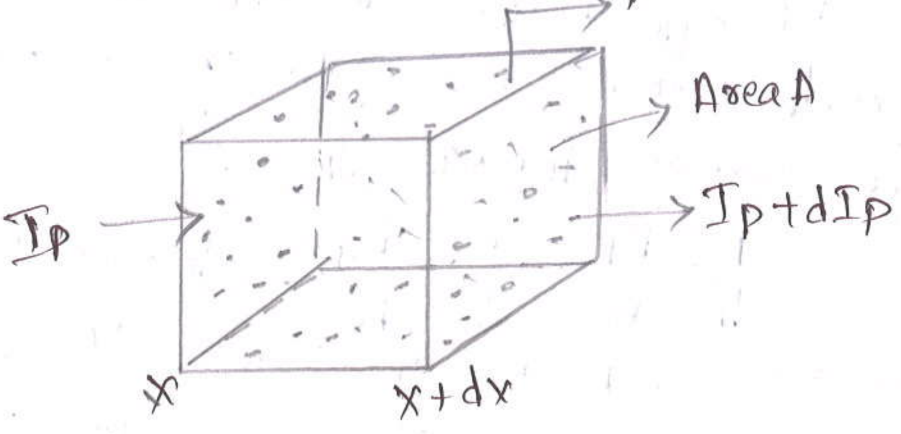
Continuity Equation

The continuity equation is based on the fact that a charge can neither be created nor destroyed. The fundamental law governing the flow of charge is called Continuity equation. The variation in density is attributable to two basic causes

i) the rate of generation and loss by recombination of carriers with in element.

ii) drift of carrier into or out of the element.

The continuity equations enable us to calculate the excess density of electrons or holes in time and space.



Relating to continuity eqn.

Consider an infinitesimal N-type semiconductor bar of volume of area - A, length - dx, minority carrier (hole) concentration - P

which is very small compared with density of majority carriers.

At time t, if minority carriers (holes) are injected, the minority current entering the volume at x is I_p leaving at $x + dx$ is $I_p + dI_p$, which is predominantly due to diffusion.

⇒ The minority carrier concentration injected into one end of the semiconductor bar decreases exponentially, with distance into specimen, as a result of diffusion and recombination.

Here, dI_p is decreases in number of coulombs per second with the volume.

The magnitude of carrier charge is q, then dI_p equals the decrease in number of holes per second within the elemental volume $A\,dx$,

As the current density $J_P = \frac{I_P}{A}$, we have

$$\boxed{\frac{1}{qA} \cdot \frac{dI_P}{dx} = \frac{1}{q} \cdot \frac{dJ_P}{dx}} = \text{decrease in hole concentration per second, due to current } I_P.$$

This is the continuity equation (or) equation of conservation of charge for holes stating the condition of dynamic equilibrium for the density of mobile carrier holes.

Special Cases of Continuity equation.

Concentration Independent of distance with zero electric field.

The continuity eqn can be changed into

$$\frac{\partial p}{\partial t} = -\frac{P-P_0}{\tau_p}$$

Solving the eqn $P-P_0 = A_1 e^{-t/\tau_p}$ where A - constant.

Concentration Independent of time with zero electric field.

– The continuity equation can be changed into

$$0 = \frac{P-P_0}{\tau_p} + D_p \frac{d^2 p}{dx^2}$$

$$\frac{d^2 P}{dx^2} = \frac{P-P_0}{\tau_p D_p}$$ Solving the eqn,

we get $P-P_0 = A_1 e^{-x/L_P} + A_2 e^{x/L_P}$

A_1 & A_2 - constant.

$L_P = \sqrt{D_p \tau_p}$ = diffusion length for holes.

Concentration varies sinusoidally with time and with zero electric field.

Let $P(x,t) = P(x) e^{j\omega t}$

Continuity eqn changed into $j\omega P(x) = \frac{P_x}{\tau_p} + D_p \frac{d^2 P(x)}{dx^2}$

$$\frac{d^2p}{dx^2} = \frac{(1+j\omega\tau_p)}{L_p^2} \cdot p$$

At $\omega = 0$ $\boxed{\frac{d^2p}{dx^2} = \frac{p}{L_p^2}}$ the eqn is same as second special case.

Direct & Indirect Band Gap Semiconductor.

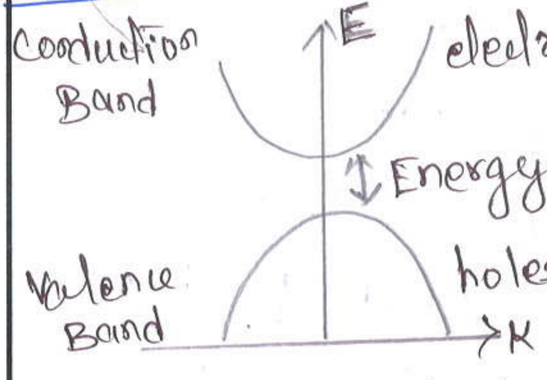
The energy of an electron is given by

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

p - momentum
m - mass of an electron
$\hbar$ - Planck's constant
k - propagation constant.

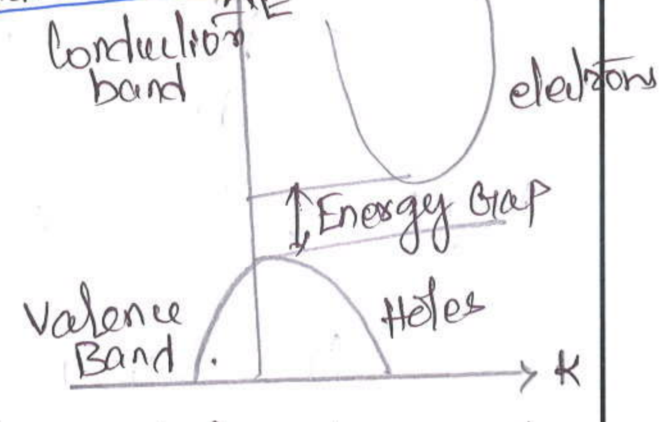
Thus $E \propto k^2$ which is an eqn of Parabola.

Direct - Band Gap:



=> Max of Valence band and min of conduction band occur at same momentum values.

Indirect band gap semiconductor -



=> Max Valence band and min of Conduction band occurs at two diff momentum Vales.

=> Electron making a transition from valence band to conduction band need not undergo any change in its momentum.

=> The compound semiconductor eg. GaAs are direct gap semiconductor.

=> Used in LED and semi-conductor lasers.

=> In order to make a transition from max point in valence band to min point in conduction band, the electron requires energy for the change in momentum in addition to the energy gap Eg.

=> All elemental semiconductors such as Si, Ge are indirect gap semiconductors.

=> Not useful for LEDs + semiconductor lasers.

Pn-Junction Diode.

Pn-junction diode formed by two blocks of semiconductor material

1. P-type material
2. n-type material.

=> In P-region the holes are majority carriers and electrons are minority carriers.

=> In n-region the electrons are majority carriers and holes are minority carriers.

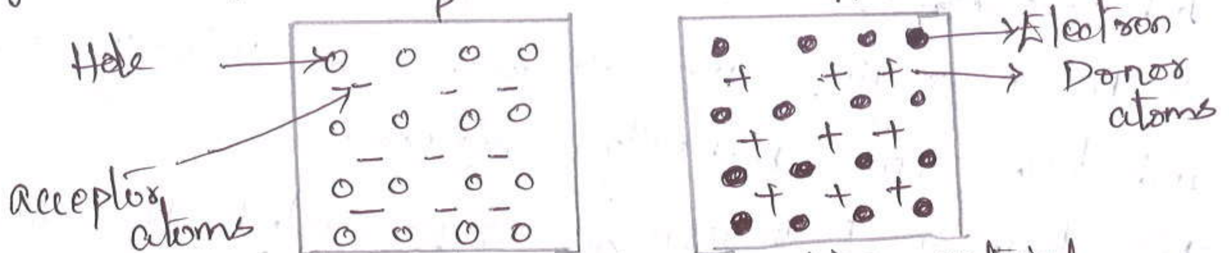
The holes in P-region are represented by small circles and the electrons in n-region are represented by dots in fig. Since the concentration of electrons of electrons in an n-region is more compared to P-side.

free electrons from the n-side diffuse across the junction and fill the holes on the p-side. Simillarly the holes from p-side diffuse across the junction and recombine with electrons in n-side.

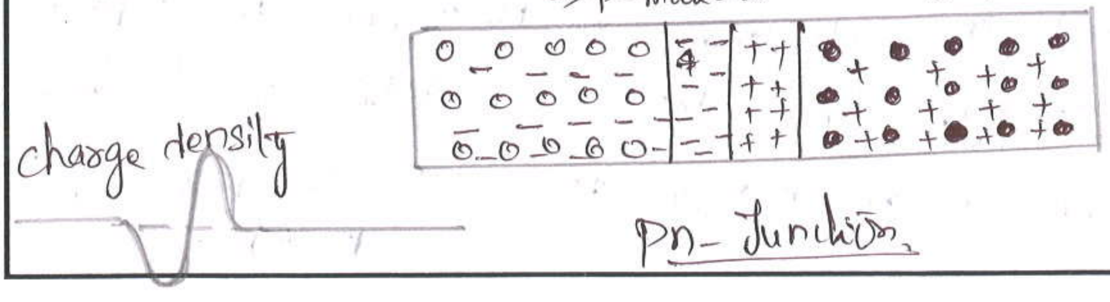
⇒ The free electrons that cross the junction create positive ions (sine an atom lost one electron) on the n-side.

⇒ Simillarly the diffusion of holes in the p-material creates negative ions. Since the negative ions are created on p-side of junction, the region close to the junction acquires a negative charge.

⇒ Simillarly the positive ions created on the n-side give a positive charge near junction. the charge density p on two sides of pn junction in fig. the shape of charge density ρ depends on the doping level of diode.



a) p-material b) n-material.



pn-Junction.

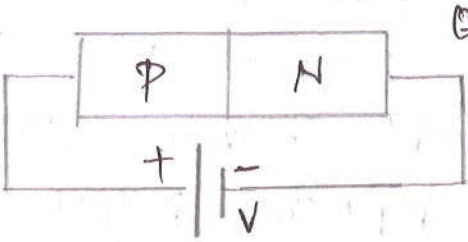
As these charges build up a point is reached where the total negative charge in p-region repels any further diffusion of electrons (-ve charge particles) into the p-region (+ve repel) and the diffusion stops.

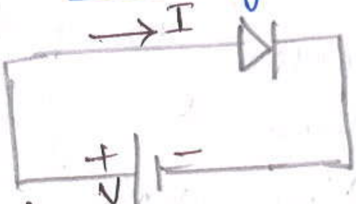
⇒ At this point the (+ve) ions on n-side and (-ve) ions on p-side are immobile (fixed). They cannot serve as current carriers. The carriers originally present (before diffusion) in this region, have transversed the junction to combine with the atoms on the other side. As a result the junction region is almost completely depleted of carriers. This region near the junction is called depletion region, space charge region (or) transition region.

Biasing

When an external source is connected to a device, then that device is said to be biased. When the positive terminal of a battery is connected to p side of the device and the negative terminal is connected to n-side of the device, then the device is said to be forward biased.

circuit symbol.

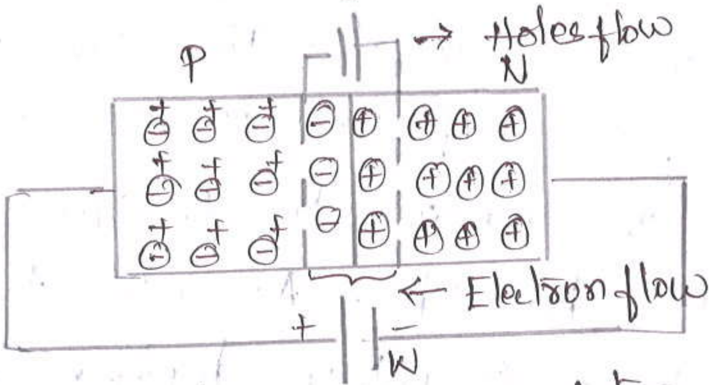




Forward Biasing of PN Junction Diode.

Under Forward Bias Condition - Operation.

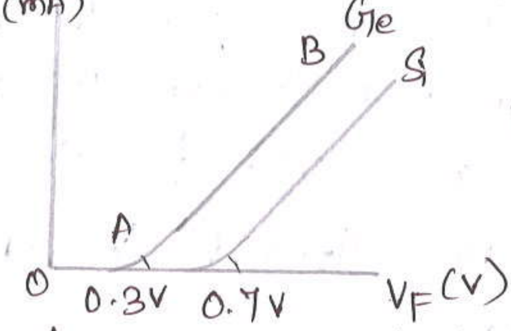
the applied potential with external battery acts in opposition to the internal potential barrier and disturb the equilibrium. As soon as equilibrium is disturbed by the application of an external voltage, the Fermi level is no longer continuous across the region.



⇒ Under the forward bias condition, the applied positive potential repels the holes in P-type region so that the holes move towards the junction and the applied negative potential repels the electrons in the N-type region and electrons move towards the junction.

V-I characteristics of a diode under forward Bias.

⇒ As forward voltage (V_F) is increased, for $V_F < V_0$, the forward current I_F is almost zero (region OA) because the potential barrier prevents the holes from P-region and electrons from N-region to flow across the depletion region in the opposite direction.



V-I characteristics of a diode under forward bias condition

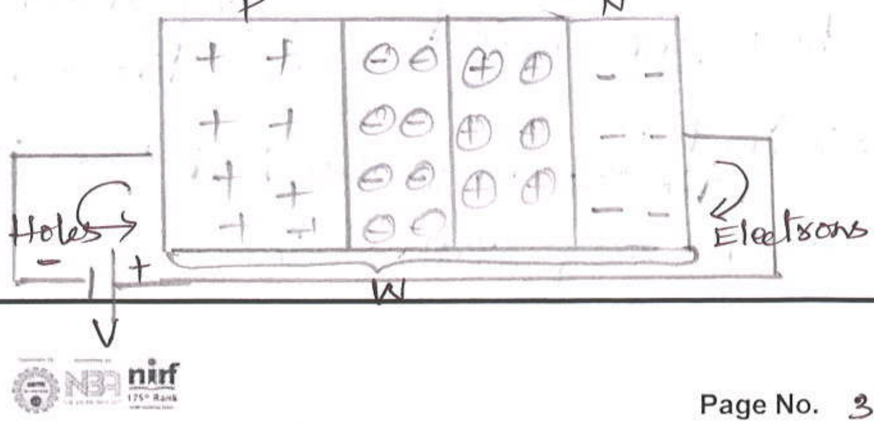
For $V_F > V_0$, potential barrier at the junction completely disappears and hence, the holes cross the junction from P type to N type and the electrons cross the junction in the opposite direction, resulting in relatively large current flow in the external circuit.

The cut in (or) threshold voltage (V_γ) below which the current is very small.

For Germanium 0.3V
Silicon 0.7V. At the cut in voltage, the potential barrier is overcome and the current through the junction starts to increase rapidly.

Under Reverse Bias condition

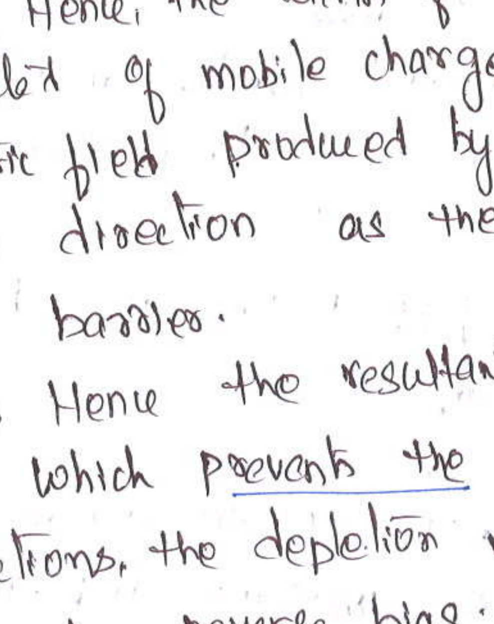
⇒ When the negative terminal of the battery is connected to the P-type and positive terminal of the battery is connected to the N type of the PN junction, the bias applied is known as reverse bias.



Operation ⇒ the Holes which form the majority carriers of the P side move towards the negative terminal of the battery and electrons which form the majority carrier of the N-side are attracted towards the positive terminal of the battery.

⇒ Hence, the width of the depletion region which is depleted of mobile charge carriers increases. Thus the electric field produced by applied reverse bias, in the same direction as the electric field of the potential barrier.

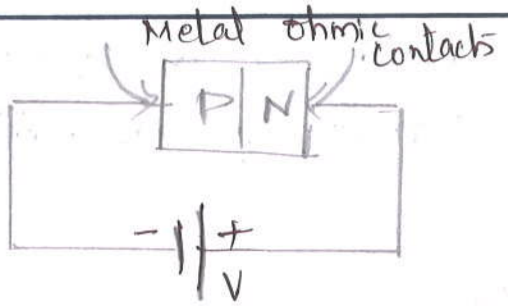
⇒ Hence the resultant potential barrier is increased which prevents the flow of majority carriers in both directions, the depletion width W is proportional to $\sqrt{V_0}$ under reverse bias.



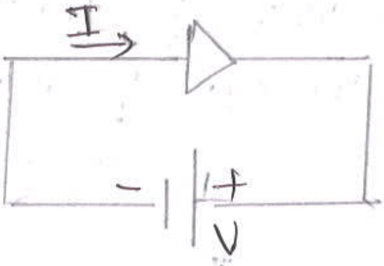
Therefore, theoretically no current should flow in the external circuit.

Electrons forming covalent bonds of semiconductor atoms in the P and N type region may absorb sufficient energy from heat and light to cause breaking of some covalent bonds.

The cut in or threshold volt (V_r) below which the current is very small. Ge = 0.3V Si = 0.7V.



Reverse Biased PN Junction Diode



symbol.

Diode Current Equation.

The diode current equation relating the Voltage V and current I is given by

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

I – Diode Current

I_0 – diode reverse saturation current at room temperature

V – external Voltage applied to the diode.

η – constant, 1 for Ge, 2 for silicon.

$V_T = kT/q = T/11600$, volt-equivalent of temp, i.e. thermal energy.

k – Boltzmann's constant (1.38×10^{-23} J/K)

q – charge of electron (1.602×10^{-19} C)

T – Temperature of diode junction (K) = ($^\circ C + 273^\circ$)

At room temperature (T = 300K), V_T = 26mV. substitute this value in current eqn,

we get ~~$I = I_0[e^{(40/V}$~~ $I = I_0\left[e^{(40V/\eta)} - 1\right]$

For Germanium diode $I = I_0\left[e^{40V} - 1\right]$, since $\eta = 1$ for Germanium.

For Silicon diode, $I = I_0\left[e^{20V} - 1\right]$, since $\eta = 2$ for silicon.

If the value of applied voltage is greater than unity, then the eqn of diode current for germanium,

$$I = I_0 (e^{40V})$$

for silicon $I = I_0 (e^{20V})$

when the diode is reverse biased, its current eqn may be obtained by changing the sign of the applied voltage.

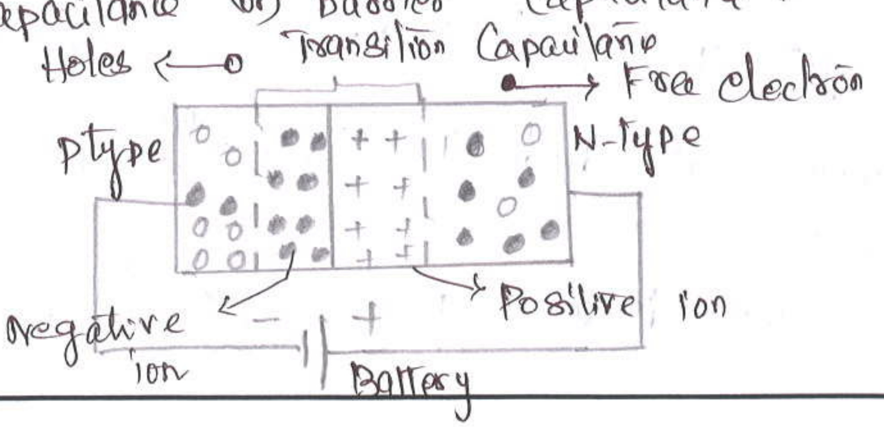
thus the diode current with reverse bias is

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

If $V >> V_T$, then the term $e^{(-V/\eta V_T)} << 1$, therefore $I \simeq I_0$, termed as reverse saturation current, which is valid as long as external voltage is below the breakdown value.

Transition Capacitance.

The amount of capacitance that changes with an increase in voltage is called as Transition Capacitance. It is also known as depletion region capacitance, junction capacitance (or) barrier capacitance.



=> When PN-Junction is reverse biased the depletion region act as an direct medium and the P type & N Type region have low resistance and act as the plates.

=> Thus this PN-Junction can be considered as a Parallel plate capacitor.

=> This junction capacitance is called as space charge (or) Transition Capacitance and is denoted as CT.

=> Since reverse bias causes the majority charge carriers to move away from the junction, so the thickness of the depletion region denoted as W increases in reverse bias voltage.

$$C_T = \frac{dQ}{dV}$$

~~dQ ↑, dV ↓~~

dV - change (or) increase in Voltage.

dQ - increase in charge

=> The depletion region increases with increases in reverse bias potential, the resulting Transition Capacitance decreases.

=> $C_T = A\varepsilon/W$

A - cross sectional area of region

W - width

Diffusion Capacitance.

=> When the junction is forward biased, a capacitance comes into play, is known as diffusion capacitance CD. It is greater than transition capacitance.

=> Due to diffusion of minority carriers on both sides of the junction.

These carriers get accumulated near the junction before they diffuse and recombine with the majority carriers. As a result the holes in n-region and electrons in the p-region are seperated by a very thin depletion layer which leads to the capacitance.

The diffusion capacitance is defined as ratio of change of injected charge with voltage.

$$C_D = \frac{dQ}{dV}$$

dQ - change in charge due to minority carriers out side the depletion region.

dV - change in volt across diode.

τ - mean life time of hole & electrons

$dQ = \tau dI$ Sub in above

$$C_D = \tau \frac{dI}{dV} = \tau g = \frac{\tau}{r}$$

where diode incremental conductance $g = \frac{dI}{dV}$

Since $r_f = \frac{\eta V_T}{I}$

$$C_D = \frac{\tau}{\frac{\eta V_T}{I}} = \frac{\tau I}{\eta V_T}$$

Diffusion capacitance is proportional to the current I.