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Solid-State Physics Notes for NET/GATE Physical Sciences
Semi-Conductors

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SEMICONDUCTORS :-

Semiconductors are those materials whose conductivity lies b/w conductors and insulators.

In S/C conductivity can be controlled with the help of Doping (the addition of impurity in a controlled manner is called Doping.)

Ge was the first S/C brought in industry. Mostely Si & Ge S/C are used

Si is better than Ge :-

→ Si has better thermal stability

→ " " less reverse saturation current

→ Mobality of e^-s in Si is greater than mobality of e^-s in Ge.

Mobality → Drift velocity of e^- / unit electric field is called Mobality.

band gap of Si & Ge → Si → 1.1 eV
Ge → 0.7 eV

Silicon is the abundent material on the earth. Curst of the earth is made by SiO_2.

Si & Ge are indirect band gap S/Cs, they can not be used in light emitting diode.

Types of Semiconductors :-

(1) S/C can be devided acc. to their application,

(i) Elemental → Si, Ge, Sn etc.

(ii) Compound → GaAs, GaP, AlGaAs etc.

- If there is same type of S/C on both side of jun^n Homojunction
" " different " " " " " Hetrojunction

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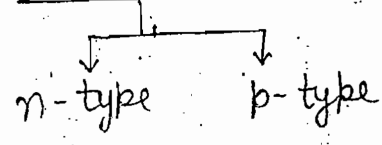
2) Semiconductors can be devided as

(i) Intrinsic – Pure

(ii) Extrinsic – Dopped

Extrinsic s/c can be of 2 types

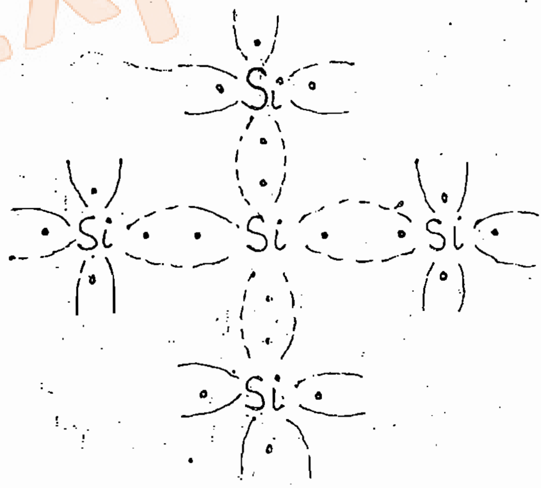


(3) (i) Direct Band Gap s/c

(ii) Indirect " "

Intrinsic Semiconductor :-

- Si, Ge are the Intrinsic s/c.
- There are 4 e^- in outermost orbit of Si & Ge.
- band gap of Si → 1.1 eV
- " " Ge → 0.7 eV
- Si has dimond cubic (dc) structure i.e. each Si atom is coordinated by 4 nearby Si atoms with sharing of 1 e^- each.



- No e^- per Si atom is free so it must fall in the category of insulator. But bcoz of small band gap, Si is a semiconductor.

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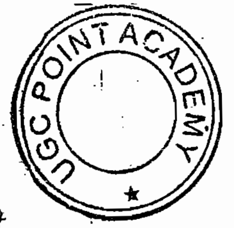
At $T = 0K$, No e^- is free. As T ↑, some e^- may be free but their conductivity will be very low so they are of No use.

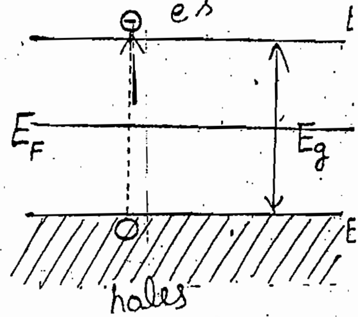
→ Minima of Conduction band → E_c



→ Maxima of Valance band → E_v

→ Gap b/w E_c & E_v is Energy band gap E_g

At $T = 0K$, Valance band is completely filled & conduction band is completely empty. & <u>No e^- is free at $T = 0K$</u> so fermi level will be the level of 50% occupacy i.e. <u>fermi-level will lie exactly in mid way</u> of the completely filled & empty band.



If Temp ↑ above $T = 0K$ i.e. T tends to room temp. then some e^- may be free bcoz bond breaks. When e^- become free then it leave a vacancy. This vacancy is called Hole. An <u>e^--hole pair</u> is called Excitons. & Excitons will follow B-E statistics.

In s/c, e^- will do motion in the conduction band & holes " " " Valance ".

- Charge of hole, +ve $= +1.6 \times 10^{-19}$ C

  Effective mass of hole :- $\boxed{m_h^* > m_e^*}$

  i.e. hole is heavier than e^- bcoz e^- move freely but hole can not move freely, it'll move one by one

- Curvature of C.B > Curvature of V.B

- hole is a fermi particle.

In Intrinsic S/c,
e^- & hole concentration will be same

$$\boxed{n_i = p_i}$$

$n_i \rightarrow$ no. of free e^- per unit volume
$p_i \rightarrow$ " " holes " " "

Extrinsic Semiconductor :-

1) n type S/c :-

generally, $m_h^* > m_e^*$

& Mobality $\mu = \frac{e\tau}{m}$

$$\mu_h = \frac{e\,\tau_h}{m_h^*} \quad \& \quad \mu_e = \frac{e\,\tau_e}{m_e^*}$$

Because $m_h^* > m_e$ so $\boxed{\mu_e > \mu_h}$

So In n type s/c, -ve charge particles i.e. electrons are majority carriers.
In p-type s/c, holes are majority carriers so n-type s/c is better than p-type s/c.

When a pentavalent impurity added to a pure Si semiconductor then it becomes n-type

Ex of pentavalent impurity → P, As, Sb, Bi etc.

Concentration of doping varies from 1 dopent atom per 10^6 to 10^8 atoms of Si

When 1 atom of phosphorus is at 10^6 Si atom then it is heavy doping as compare to 1 atom of P at 10^8 Si atom.

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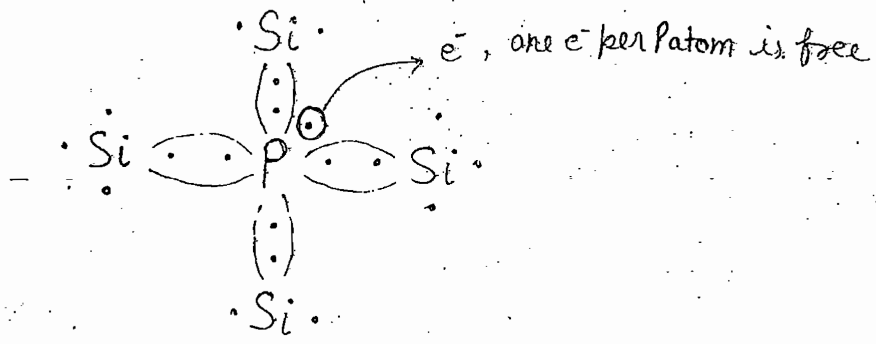
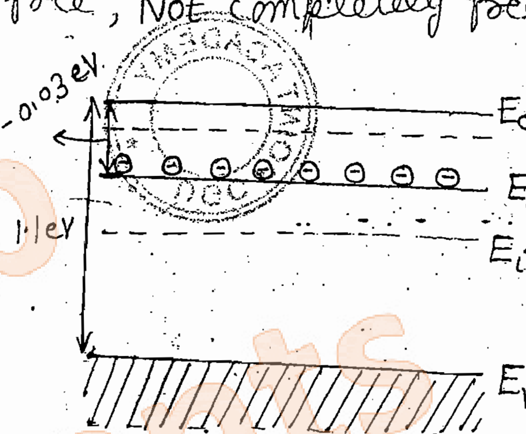


1 e⁻ per P atom remains almost free, Not completely free.

The level E_d is the level of 5th Phosphorus e⁻.

Now fermi level is still b/w highest filled level & highest empty level.

fermi level lies b/w near to the conduction band.



Order of energy b/w E_d & E_c = 0.01 - 0.03 eV

At room temp., all the e⁻s of E_d will go in C.B. & e⁻s become free.

For any s/c, $\boxed{np = n_i^2}$ ⇒ law of Mass action.

n → e⁻ concentration in doped s/c

p → hole " " "

n_i → intrinsic carriers concentration.

n-type s/c is Nutral i.e. charge on n-type s/c = 0

{ In s/c, $np = n_i p_i$ but In intrinsic s/c $n_i = p_i$ so
$np = n_i^2$ }

E_i → Intrinsic level in mid way of E_c & E_v.

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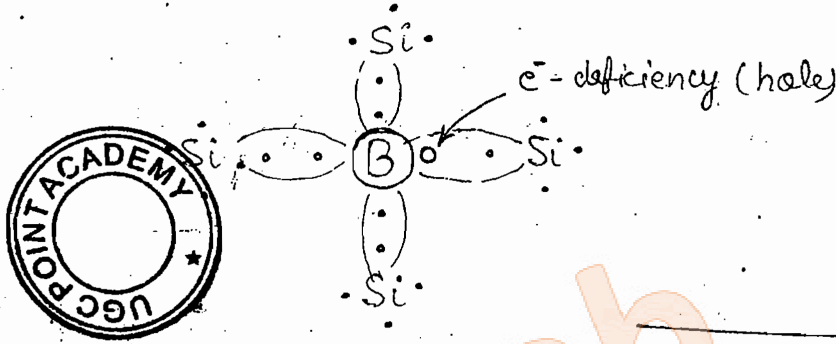
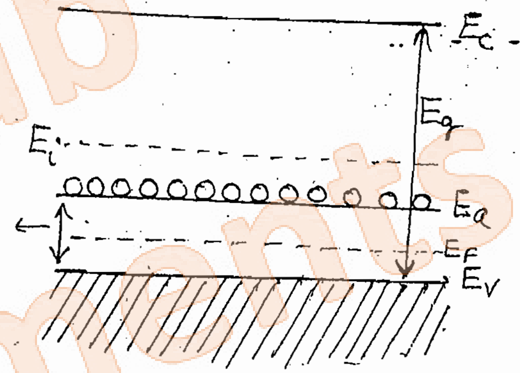
(2) P-type Semiconductor :-

p-means positive ⇒ holes are the majority charge carrier. When a trivalent impurity like; B, Al, Ga, In etc. added in the Si S/c it behaves as a p-type s/c.





At room temp, all the impurities are ionised.

Q. An intrinsic s/c is doped with 10^{16} Boron atom/cm³. Calculate the e⁻ & hole concentration at 300 K

A. Intrinsic carrier concentration $n_i = 1.5 \times 10^{10}/cm^3$

hole concn. $p = N = 10^{16}$ B atom/cm³

e⁻ concentration, $np = n_i^2$

$$\Rightarrow n = \frac{n_i^2}{p} = \frac{(1.5 \times 10^{10})^2}{10^{16}}$$

$$n = \frac{2.25 \times 10^{20}}{10^{16}} = 2.25 \times 10^4 /cm^3 \text{ Ans.}$$

In p-type s/c, fermi level lies near the V.B.
E_i is a fixed level, it lies b/w E_v & E_c.

* If we dope → Si on Ga site → n type
(GaAs) Si " As " → p type
} This type of impurity is Amphoteric impurity.

generally Si is dopped on Ga site.

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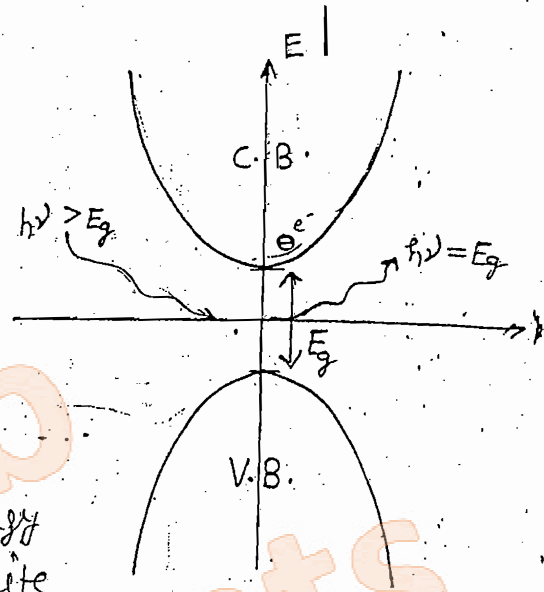
Direct & Indirect band gap S/C :-

Direct Band Gap S/c :- In direct band gap S/c, bottom of the conduction band & top of the valance band lies at same valu of K. In this, e^- can directly excite or deexite by the absorption or emission of photon & there is no phonon involvement in the process of excitation or deexitation.



If A photon incident of energy $h\nu$.
$h\nu > E_g$, there is absorption
($h\nu < E_g \rightarrow$ No absorption)
then e^- of V.B. will absorb this energy & excite to the C.B. & when it deexcite to V.B. then it will emit some energy i.e. $h\nu = E_g$.

There is no requirement of phonon or lattice in the conservai of energy & momentum.

Direct band gap S/c's are used in light emitting applica -ons like LED & LASERS.

ex - GaAs, CdS, ZnS, CdSe etc.

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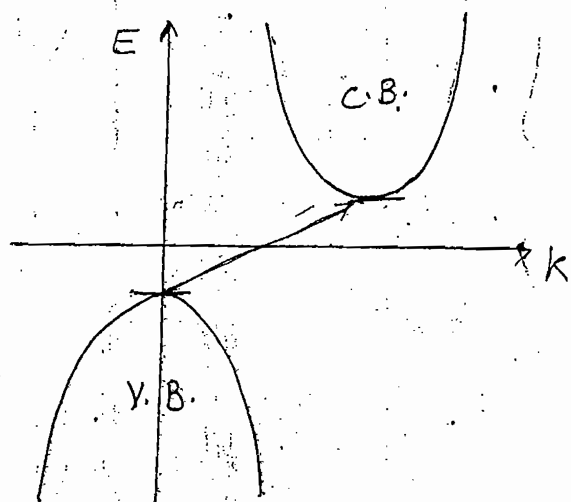
Indirect Band Gap S/c :- In Indirect band gap S/c, top of the V.B. & bottom of the C.B. lies at different values of K.

If e^- goes from top of the V.B. to bottom of the C.B., it has to change its energy as well as wave-vector K.

For mom. ($\hbar K$) & energy conservation, there is involvement of phonon in the conservation process.



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If there is dexitation of e^-, then not all the energy will be emitted in form of photon but some energy is emitted in form of photons & some part in form of phonons. i.e. some part is transfered to the lattice & lattice will vibrate & heat generate.

So Indirect band gap s/c is not suitable for light emission.

Ex - Si, Ge, GaP, SiC etc.

Equilibrium e^- & hole concentration in a s/c :-

e^- concentration, $$n = N_c e^{-\frac{(E_c - E_F)}{KT}} \quad \text{--- (1)}$$

$N_c \rightarrow$ Effective density of states at the C.B. edge

$$N_c = 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}$$

$m_e^* \rightarrow$ effective mass of e^-

$E_c \rightarrow$ energy of C.B.

$E_F \rightarrow$ fermi energy

As. Temp ↑, exponential term is dominating so n ↑ exponentially

hole concentration; $$p = N_V e^{-\frac{(E_F - E_V)}{KT}} \quad \text{--- (2)}$$

$$N_V = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2}$$

Multiply (1) X (2) ⇒

$$n_i^2 = np = N_c N_V e^{-\frac{(E_c - E_F)}{KT}} e^{-\frac{(E_F - E_V)}{KT}}$$

$$n_i = \sqrt{N_c N_V}\left[e^{-\frac{E_c + E_F - E_F + E_V}{KT}}\right] = \sqrt{N_c N_V}\, e^{-(E_c - E_V)/KT}$$

$(E_c - E_V = E_g)$

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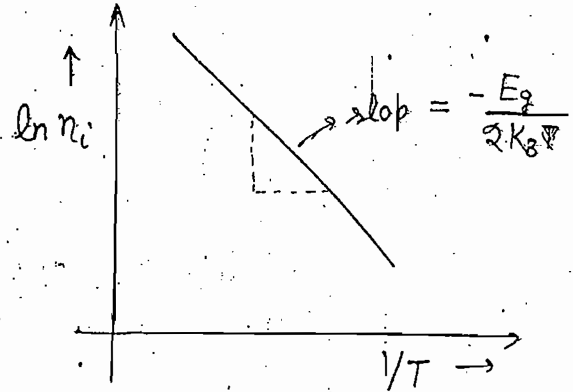
$$n_i = 2\left(\frac{2\pi K_B T}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2K_BT}$$

$$\Rightarrow \ln n_i = \ln\left[2\left(\frac{2\pi K_B T}{h^2}\right)^{3/2}\right] + \frac{3}{4}\ln(m_e^* m_h^*) - \frac{E_g}{2K_BT}$$



$$n = n_i e^{\left(\frac{E_F - E_i}{K_BT}\right)}$$

$$p = n_i e^{\left(\frac{E_i - E_F}{K_BT}\right)}$$

This n & p follow the law of mass action

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Exact Position of fermi level in a Semiconductor :-

In Intrinsic S/C :- $n_i = p_i$

$$\Rightarrow N_c e^{-\frac{(E_c - E_F)}{K_BT}} = N_v e^{-\frac{(E_F - E_V)}{K_BT}}$$

$\because m_h^* > m_e^*$ Hence $\frac{N_v}{N_c} > 1$

$$\therefore e^{\left(\frac{-E_c + E_F + E_F - E_V}{K_BT}\right)} = \frac{N_V}{N_c} = \frac{2\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/2}}{2\left(\frac{2\pi m_e^* K_BT}{h^2}\right)^{3/2}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$\Rightarrow e^{\frac{-E_V - E_c + 2E_F}{K_BT}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

Taking log, $\frac{-E_V - E_c + 2E_F}{K_BT} = \ln\left(\frac{m_h^*}{m_e^*}\right)^{3/2}$

$$\frac{2E_F}{K_BT} = \frac{E_c + E_V}{K_BT} + \frac{3}{2}\ln\left(\frac{m_h^*}{m_e^*}\right)$$

$$2E_F = E_c + E_V + \frac{3}{2}K_BT\ln\left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \left(\frac{E_c+E_V}{2}\right) + \frac{3K_BT}{4}\left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

At $T = 0K$, $\quad E_F = \frac{E_c+E_V}{2}$

Fermi level does not depand upon m_e^* & m_h^* But at fermi temp. it depand on m_e^* & m_h^*.

If temp. ↑, then fermi level is slightely moves in upward dirⁿ but this movement is neglesible. It can be neglected at room temp.

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N-Type S/C :-

$$E_F = \frac{E_d+E_c}{2} + \frac{K_BT}{2}\ln\left(\frac{N_d}{N_c}\right)$$

where, E_d → donar level energy
n_d → " " concentration

As temp ↑, then intrinsic carrier conc n_i ↑ exponontially
As n_i ↑, fermi level moues in downward dirⁿ $\left[\ln\left(\frac{N_d}{N_c}\right) < n_i\right]$
& when $n_i = N_d$ then S/C will behave like Intrinsic S/C. then fermi level move to mid way.

P-Type S/C

$$E_F = \frac{E_a+E_V}{2} \mp \frac{K_BT}{2}\ln\left(\frac{N_a}{N_V}\right)$$

Variation of drift velocity with applied electric field in a S/C :-

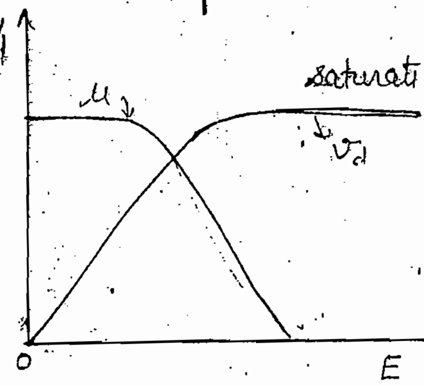
drift velocity $V_d = \mu E \Rightarrow \boxed{V_d \propto E}$

μ → mobility

Hence drift vel. v_d ↑ with applied field linearly.

For large value of E, v_d become constant.

∴ On applying more ele. field, energy will transfer to the lattice instead of v_d.



Mobality is just the slop of this graph.

graph of mobility is Ist constant & then ↓ to 0.

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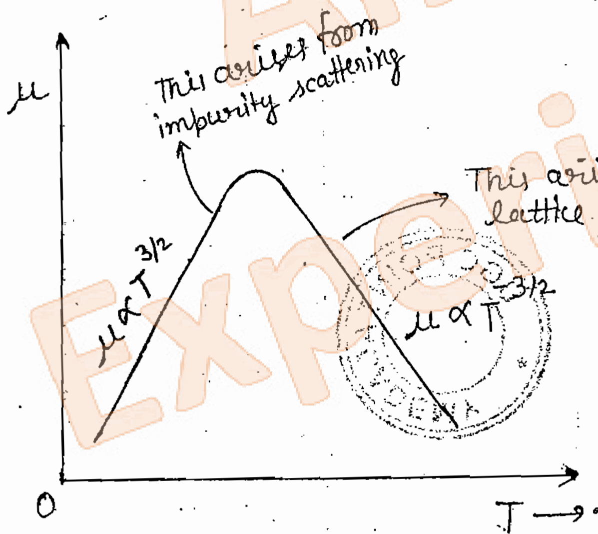
__Temprature Variation of Mobality:__ Initially, when impurit are not ionised, we does'n get mobality.



If e^- scatter from phosphoarus atom then it is impurity sca.

& If e^- scatter from Si atom then it is lattice sca.

e^- will help to ionise th impurity.

[P → impurit
Si → lattice

At Room temp., Mobility will be $\mu \propto T^{-3/2}$

bcoz at room temp., all the impurities will be ionised

$\mu = \frac{e\tau}{m}$, at high temp., lattice will vibrate more frequently so τ ↓ So μ ↓.

Temperature Variation of Conductivity in a Semiconductor :-

Dopped S/C , $\sigma = ne\mu_e + pe\mu_h$

If it is n-type , $n > p$

$$\sigma = ne\mu_e + \frac{n_i^2}{n} e\mu_h$$

$\sigma \simeq ne\mu_e$

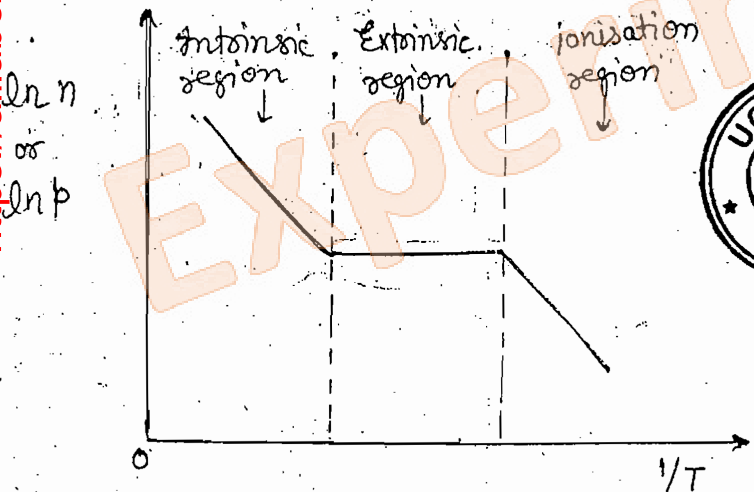
If p-type : $\sigma \simeq pe\mu_h$

Temp. dependance of conductivity σ is decided by e^- conc. & mobality.

no. of free e^-/unit vol. , $n = N_d e^{-\frac{(E_c - E_d)}{kT}}$

donars exponentially ionise with temp.

$(E_c - E_d) \rightarrow$ donar ionisation energy



When temp. is so high that $n_i \rightarrow n$

$n_i \propto e^{-E_g/2kT}$

All the S/C devices works in extrinsic region bcoz on ↑ing temp. there should be no variation with e^- conc.

For σ variation, combine the variation of n with μ.

$$\sigma = ne\mu_e$$

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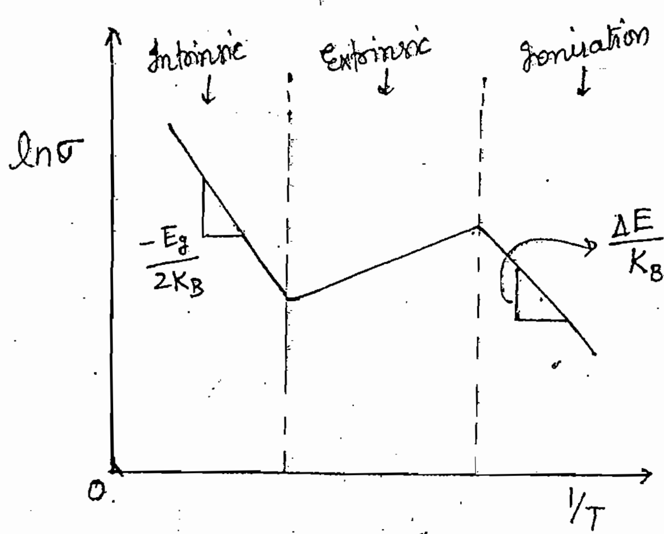
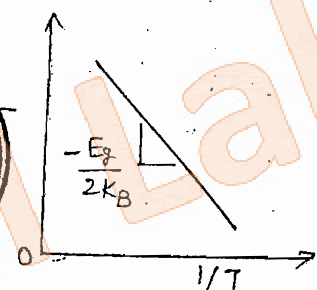
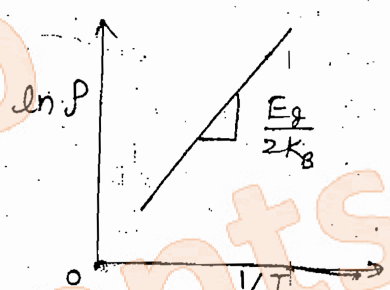


{ acceptor ionisation e
p-type $\Delta E = E_a - E$
Donor ionisation ener
n-type, $\Delta E = E_d -$

If graph b/w ($\ln\rho$ & $1/T$) then slop = $+E_g/2K_B$ in intrinsic region

for intrinsic S/c,



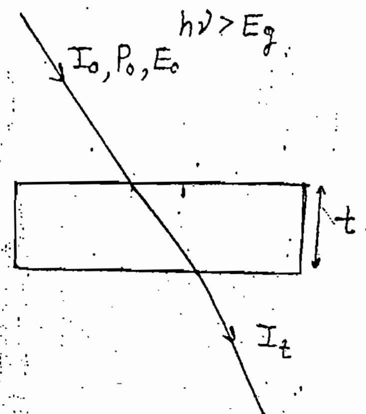


The information of band gap is obtained only in Intrinsic region.

Transmitted Power, Intensity, Energy through a semi-conducting crystal :-

Suppose we have a semi-conducting crystal of thickness t. A light wave of intensity I_0 & power P_0, incident on it. [Power → Intensity per unit area]

If $h\nu > E_g$ then some part of the power will be absorbed & some will be transmitted.



$$I_a + I_t = I_0$$

Here, In S/c, absorbance + Transmitance = 1.

$$A + T = 1$$

(generally $R + T = 1$)

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$$I_t = I_0 e^{-\alpha t}$$

$$P_t = P_0 e^{-\alpha t}$$

$\alpha \to$ absorbtion coefficient
$t \to$ thickness of the crystal
$I_0 \to$ Incident Intensity
$I_t \to$ Transmitted "

Absorbed Intensity $I_a = I_0 - I_0 e^{-\alpha t}$

If $h\nu < E_g$ then No absorption
$I_a = 0$
All the Intensity (light) will be transmitted

$$I_t = I_0$$

bcoz this photon is not capable to generate e⁻-hole pair.

- Quantum Efficiency :-

100% Quantum efficiency means, each photon absorbed create 1e⁻ & 1 hole.

60% Q. efficiency means, only 60% photon, from 100% are absorbed capable to generate e⁻ hole pair.

Quantum efficiency is the measurement of betterness of light emitting device.

p-n Junction :-

p-n jucⁿ is a combination of two types of semiconductors p & n type. This is formed within the single s/c, On one side we have acceptor impurity, on the other side we have donar impurity. #

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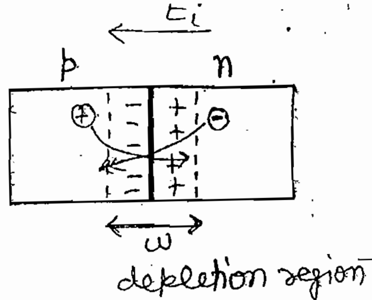


Due to concentration gradient, there will be diffusion.
Holes will diffuse from $p \rightarrow n$
e^-s " " $n \rightarrow p$.

Due to diffusion e^- from n side will leave behind the immobile +ve ion core & ||ly holes from p side will leave behind the -ve ion core.

n side is +vely charged & p side is -vely charge & But junction as a whole is neutral.

depletion region is depleted of free (mobile) charge carri & width of depletion region is w. Its typical order is 1 um.

Due to the flow of e^- & holes there will flow diffusio current.

I_n (diffusion) $\longrightarrow$ $p \rightarrow n$

I_p (diffusion) $\longrightarrow$ $p \rightarrow n$

Net diffusion current $\rightarrow$ $p \rightarrow n$

There is a internal electric field in depletion region, E_i
It will oppose the diffusion. It will try to stop the diffusion. It will help the minority charge carriers to cross the jun".

The motion under this electric field is drift motion & there will be drift current

~~I_n (diff)~~

I_n (drift) = $n \rightarrow p$

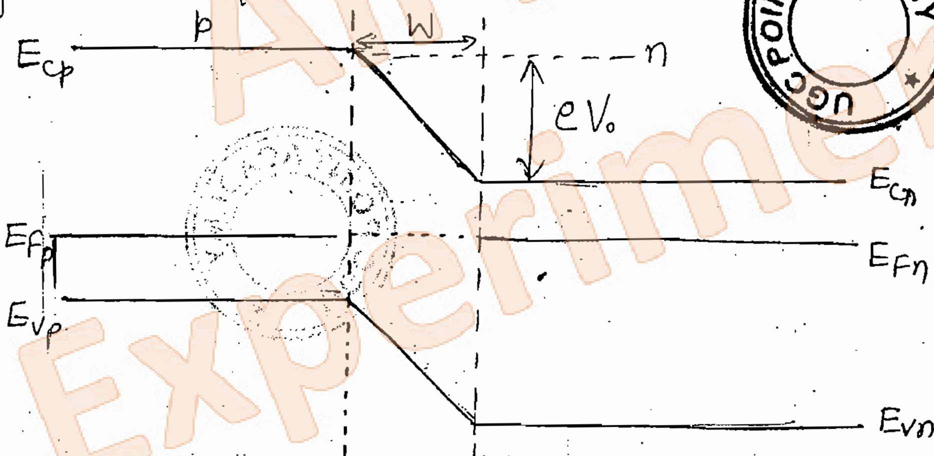
I_p (drift) = $n \rightarrow p$

Net current is zero as no external force is applied

$$I_n(\text{diff.}) + I_n(\text{drift}) = 0$$

$$I_p(\text{diff.}) + I_p(\text{drift}) = 0$$

Fermi-level 'll act as a reference level.
If we join two s/c then their fermi level will be alligned at equilibrium.



The pot^n of Elec. field E is called contact pot^n V_0.
(This E field is arised by coming in contact p & n type s/c.)
This Contact pot^n V_0 is the characteristic property of the junc^n.

Energy barrier → eV_0

V_0 depends ~~of~~ on temp & dopping concentration on both the sides.

$$V_0 = \frac{KT}{e} \ln\left(\frac{p_p}{p_n}\right)$$

$$V_0 = \frac{KT}{e} \ln\left(\frac{n_n}{n_p}\right)$$

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$p_p \to$ conc. of holes i.e. hole conc. on p side
$p \to$ type

$p_n \to$ hole conc. on n side
$n_n \to e^-$ " " n "
$n_p \to e^-$ " " p "

If p side & n side are dopped by N_a & N_d then
$$p_p \simeq N_a$$
$$n_n \simeq N_d$$

$$p_n = \frac{n_i^2}{N_d}$$

$$n_p = \frac{n_i^2}{N_a}$$

$p_n n_n = n_i^2$
$p_p n_p = n_i^2$
$p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_d}$
$n_p = \frac{n_i^2}{p_p} = \frac{n_i^2}{N_a}$

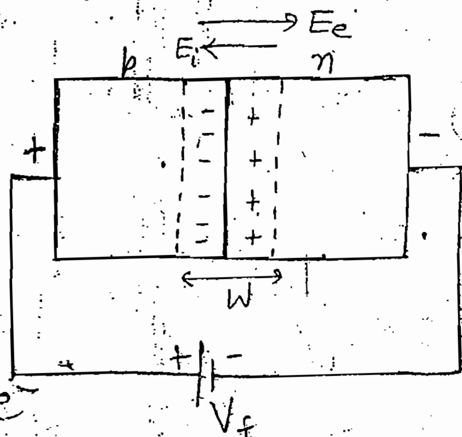
$$\therefore V_0 = \frac{kT}{e} \ln\left(\frac{N_a}{n_i^2/N_d}\right)$$

$$\boxed{V_0 = \frac{kT}{e} \ln \frac{N_a N_d}{n_i^2}}$$

Contact potⁿ depends upon doping concentration.
If doping conc. is heavy (i.e. jucⁿ is heavily dopped) then V_0 will be more.

p-n Jucⁿ under forward bias :-

Potⁿ at p side $\to$ +ve
" " n " $\to$ -ve



External e. field will be $p \to n$
by External E. field, strength of the internal E-field will ↓
So barrier height will ↓ then e^- will easily cross the barrier so e^- can move from C.B. of n side to C.B. of p side.

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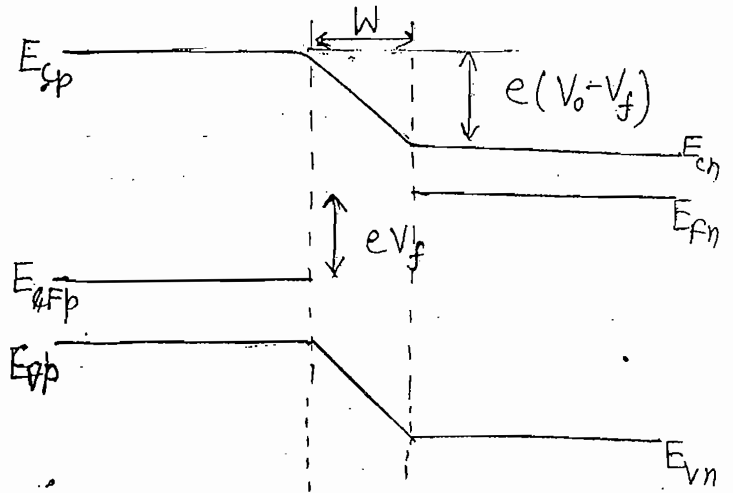
holes from V.B. of p side can move to V.B. of n side



I_n (diffusion) ↑

– I_p (diffusion) ↑

So Total diffusion current ↑

Depletion region width W ↓

Pot^n developed by E_i is sheilded by the pot^n developed by E_e.

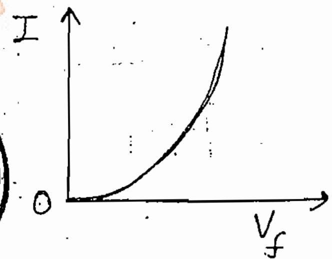
Current flowing from $p \rightarrow n$ ⇒ forward current

$n \rightarrow p$ ⇒ Reverse "

In F.B., Net current flow from $p \rightarrow n$. There is no effect on reverse current.

Reverse current is due to minority carriers. At low voltage minority carrier is Independent of applied voltage.

In F.B., Current ↑ exponentially with forward voltage (applied)



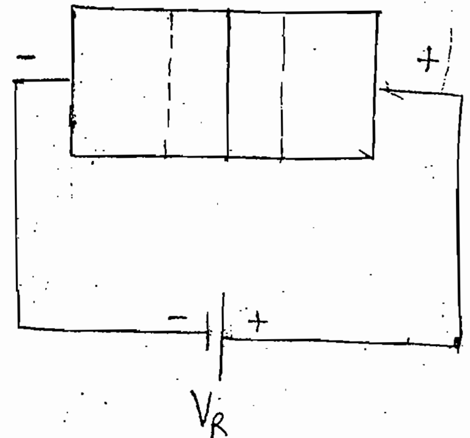
P-n junc^n under Reverse Bias :-

External E field will be in dir^n of internal E field. Diffusion will be completely stoped.

Barrier hight ↑

Hence diffusion of e^- & holes would become impossible.

Diffusion Current = 0



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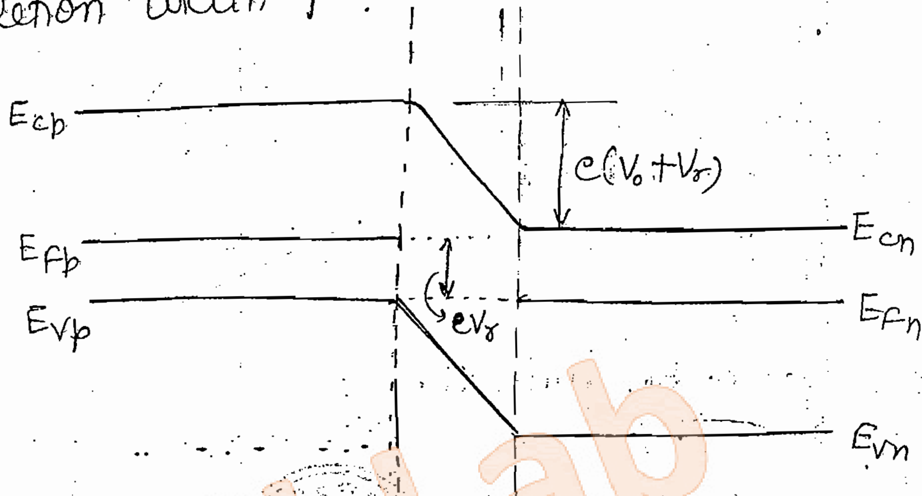
~~Drift current~~ Effect on reverse current ($n \to p$) $\Rightarrow$
No effect i.e. Reverse ~~current~~ will be same as it depend on minority carrier cacn. & independent of applied vol.
depletion width ↑.



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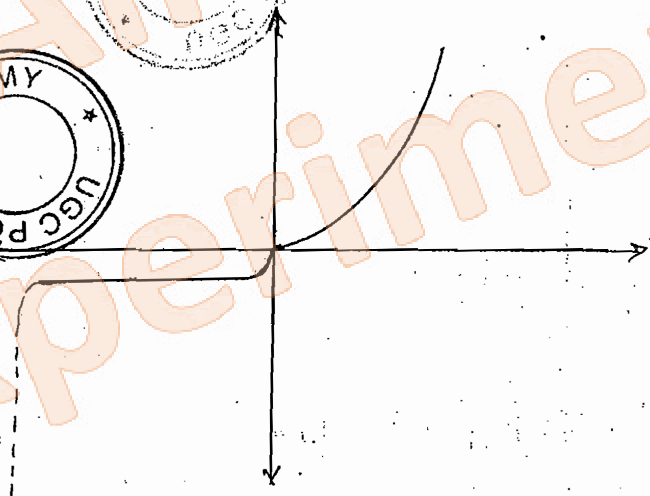
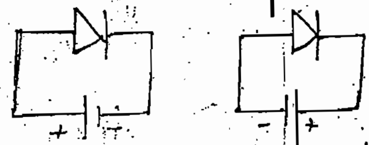
I-V characteristic,



Reverse current is constant with applied voltage untill very high voltage is applied. If vol. is high then junc' will breakdown (Zener diode)

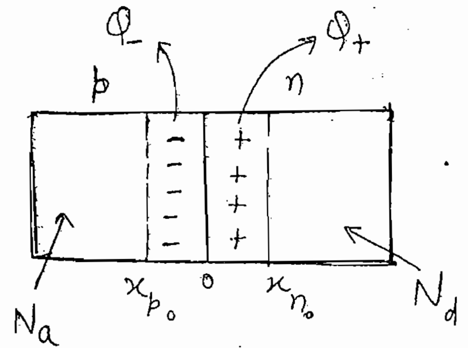
Diode is design s.t. If F.B. then there will be current flow with small resistance i.e. current is ~~small~~ large.
& In R.B., current flow, (minority current flow with high resistance. current is small



This is a ractifing property.
Diode will behave as a Ractifier.
(Minority current is large in Ge so Ge is less thermal stable)

space

Slop charge at the Junction :-



Extension of depletion layer on n side is x_{n_0} & on p side is x_{p_0}

So $\boxed{x_{n_0} + x_{p_0} = W}$ ——— (1)

As junc^n as a whole is neutral

so $|Q_-| = Q_+$

N_d → donar conc. per unit vol.
N_a → acceptor " " " "

$Q_+ = e N_d x_{n_0} A$
$Q_- = e N_a x_{p_0} A$

So $e N_d x_{n_0} A = e N_a x_{p_0} A$

$\Rightarrow \boxed{N_d x_{n_0} = N_a x_{p_0}}$ ——— (2)

So depletion layer width extension will be more on lightely dopped side

If $N_d = 10^{17}$ P atoms / cm^3 , $N_a = 10^{16}$ B atoms/cm^3

then $x_{p_0} > x_{n_0}$

so depletion layer width is more on lightely doped side.

from (1) & (2),

(1) $\Rightarrow$ $x_{n_0} = W - x_{p_0}$

(2) $\Rightarrow$ $N_d (W - x_{p_0}) = N_a x_{p_0}$

$-N_d x_{p_0} - N_a x_{p_0} = -N_d W$

$$\boxed{x_{p_0} = \frac{W N_d}{N_d + N_a}}$$

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$$x_{n_0} = W - \frac{W N_d}{N_a + N_d} = \frac{W N_a + W N_d - W N_d}{N_d + N_a}$$

$$\boxed{x_{n_0} = \frac{W N_a}{N_a + N_d}}$$

Maximum Electric field in the depletion Region :-

It is given by $\boxed{E_0 = -\frac{e}{\varepsilon} N_d x_{n_0} = -\frac{e}{\varepsilon} N_a x_{p_0}}$

$\varepsilon \rightarrow$ permitivity of the material

The value of Electric field at junc^n $\longrightarrow E_0$

E_0 depend on permitivity, doping conc., extension of depletion regio

Depletion Region Width W :-

$$W = \left[\frac{2\varepsilon (V_0 - V)}{e} \left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

If doping conc. N_a, N_d $\uparrow$ then $W \downarrow$.

In F.B., $V = V_f$, $W \downarrow$

In R.B., $V = -V_r$, $W \uparrow$

Effect of Temprature :-

If No Bias is applied, If $T \uparrow$, $W \uparrow$

$$W \propto (T)^{1/2}$$

$V = 0$

$$V_0 = \frac{KT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Capacitance of p-n junc^n :-

There are 2 types of capacitances associated with p-n junc^n

(1) <u>junction capacitance</u> :- This is due to inmobile (cant move) +ve & -ve charges in the junc^n. This is forming a parallel plate capacitor. This is also called Depletion region capacitance.

This is dominent under <u>reverse bias</u> and

$$\boxed{C_j = \frac{\varepsilon A}{W}}$$ Imp

In free space $\varepsilon \to \varepsilon_0$

A → Cross sectional area of the diode.

$$\boxed{C_j \propto \frac{1}{W}} \qquad \boxed{C_j \propto (V_0 - V)^{-1/2}}$$

(2) <u>Charge Storage Capacitance</u> :- This is arising from stored charges on p & n side. This is also called diffusion capacitance.

This is dominent under <u>forward bias</u>.

$$\boxed{C_d = \frac{1}{3}\frac{e^2}{K_B T} A\, l\, n_p\, e^{eV/K_BT}}$$

l → diffusion length

V → applied voltage

$$\boxed{C_d \propto e^{eV/K_BT}}$$ eponential depandancy on V

If V → -ve ; C_j is dominating (R.B.)

V → +ve ; C_d is dominating (F.B.)

Diffusion Length :-

It may be defined for hole as well as for e^-. (L_p, L_n) This is the average distance travelled by e^- or hole before the recombination. If any e^- diffuse from n to p side the e^- diffusion length is measured on p side.

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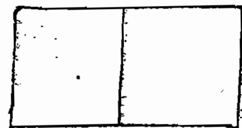
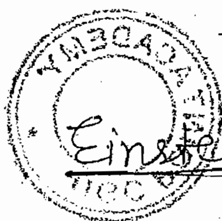
holes. diffusion length measured on n side.



Diffusion length is defined in the opposite region.

$$L_p = \sqrt{D_p \tau_p}$$
$$L_n = \sqrt{D_n \tau_n}$$

where, $D_p, D_n \rightarrow$ diffusion cofficient of hole & e^-



$\tau_p, \tau_n \rightarrow$ relaxation time of hole & e^-

Einstein Relation for a semiconductor :-

$$\frac{D}{\mu} = \frac{K_B T}{e}$$

Ratio of diffusion cofficient & mobility

Einstein relation is independent of perticular type of charge carrier. i.e.

Imp
$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{K_B T}{e}$$

Diode Equation :- Relation b/w diode voltage & diode current

$$I = eA\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right)\left(e^{\frac{eV}{K_B T}} - 1\right)$$

$e \rightarrow$ electronic charge
$A \rightarrow$ cross-sectional area
$D_p, D_n \rightarrow$ diffusion cofficient
$L_n, L_p \rightarrow$ " length
$p_n, n_p \rightarrow$ hole conc. of n side, e^- conc. of p side

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$$I = I_0\left(e^{\frac{eV}{K_BT}} - 1\right)$$

In F.B. $V = V_f$ $\Rightarrow$ $I_f = I_0 e^{\frac{eV}{K_BT}}$ (e^{eV/K_BT} term dominate)

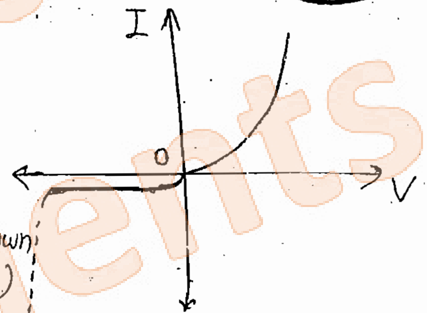
forward current ↑es exponentially with voltage.

If R.B. $V = -V_r$ $\Rightarrow$ $I_{pr} = I_0$

reverse current is independent on applied voltage.

Zener Breakdown & Avalanche Breakdown :

Zener Breakdown Current :- Reverse current is almost independent of applied reverse voltage but if reverse voltage is very high so that it can break the covalent bonds then due to generation of large no. of e^--hole pairs reverse current increases very sharply. This current is called Breakdown Current. Breakdown can occur by two mechanism



(i) Zener

(ii) Avalanche

Zener breakdown :-

(i) Zener breakdown occurs in heavily doped junction

(ii) " " voltage is low.

(iii) " " voltage decreases as temp. increases.

(iv) Zener Effect is field ionisation of host atoms at the junction,

W (width of d-region) is small so that e^- & holes directly tunnel from one side to another.

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Avalanche Breadown

(i) Avalanche breakdown occurs in lightely dopped junction

(ii) " " voltage is high.

(iii) " " voltage increases as temp. increases.

(iv) " " occurs due to impact ionisation of host atoms by highely accelerated e^-'s.

Here W is large so e^- can not tunnel but highly accelerated e^- scattered with atoms & bond break so impact ionisation.

Impact of scatt ionisation occur due to scattering.

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