

UNIT-ISEMICONDUCTOR PHYSICS

Band theory of crystals

atoms in a crystal

- \* 3D arrangement of atoms in a crystal
- \* due to less "interatomic spacing" and covalent bonds, a large number of closely spaced discrete energy levels called Valency band are occupied by valence electrons.

occupied by valence electrons

• Valence band  
Conduction band  
Forbidden energy gap. — free from any discrete energy levels

Insulator



CB

$E_g^{\text{ins}}$

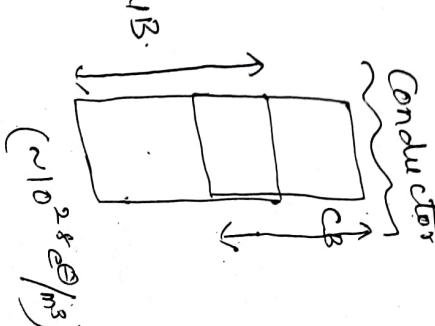
Semiconductor



CB

$E_g^{\text{sem}}$

Conductor



CB

$\sqrt{B}$

$(\sim 10^{28} e^-/\text{m}^3)$

At  $0^\circ\text{K}$

$E_g \approx 0.785 \text{ ev (Ge)}$

$E_g \approx 1.121 \text{ ev (Si)}$

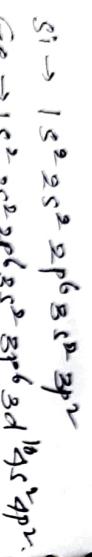
Intrinsic (on pure semi conductor)

Extrinsic (on impure  $\rightarrow E_g$  has new levels because of impurity)

At room

$$(Si) \quad E_g = 1.1 \text{ eV}$$

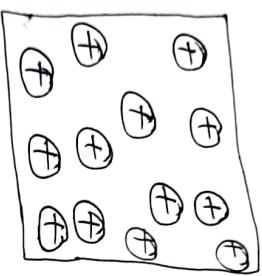
$$(Ge) \quad E_g = 0.72 \text{ eV}$$



Mobility and conductivity in metals

metals  $\rightarrow$  electron gas

- Random movement gives zero current - collisions
- avg. distance b/w two



- at any point in electric field intensity
- ext. field  $E$  (force on unit positive charge at any point in electric field intensity)
- Steady state speed  $v$

$$v = \mu E$$

$\mu \rightarrow$  mobility (cm/volt-sec)

$$\mathcal{E} \rightarrow v/m$$

current density  $\rightarrow$  current per unit area

$$J = nev$$

$$J \rightarrow \text{amp}/\text{m}^2$$

$$J = nev$$

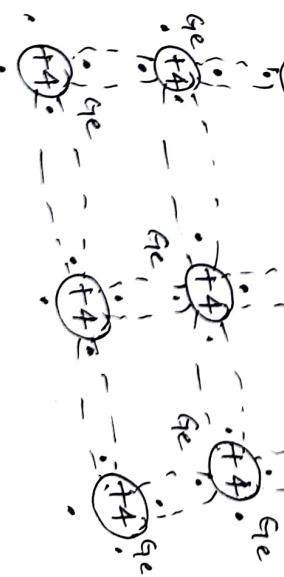
$$[J = \sigma E] \rightarrow \text{Ohm's law}$$

$$\sigma = \text{new}$$

$$\sigma \rightarrow \text{conductivity} \rightarrow (\text{ohm-m})^{-1}$$

$$\text{power dissipated} \rightarrow \text{ion-e}^- \text{ collision power} \quad J\mathcal{E} = \sigma E^2 \quad (\text{watt}/\text{m}^3)$$

holes in an intrinsic semiconductor (pure)



- At 0K, insulator  $\rightarrow$  conduction
- At room temp, free  $e^- \rightarrow$  (semi conductor)
- as move from VB to CB due to temp. rise.

- \* Absence of  $e^-$  in a covalent bond ion empty valency energy level is called "Hole"

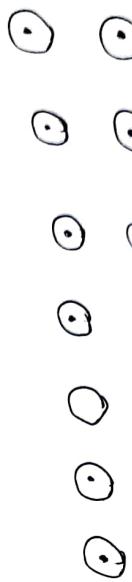
\*  $e^-$  movement is opposite to hole movement

$e^-$  from one bond fills hole and repeats

- \* holes in VB (no free  $e^-$ ) constitutes current
- $e^-$  in CB

\* Recombination and generation happens

hole conduction in VB



$e^-$  - hole movement

hole  $\rightarrow$  positive charge carrier

Conductivity of a semi conductor ( $\sigma$ ):  
conductivity is due to  $e^-$  and hole pair, conductivity is due to both of them.

Current density :-

$$J = (n \mu n + p \mu p) e E = \sigma E$$

$\mu_p, \mu_n \rightarrow$  mobility of hole and  $e^-$

$$\text{For intrinsic semiconductor:}$$

$$n_p = n_e = N_i$$

$$\text{For Ge, conductivity raises approx. } 6(8)\% \text{ per degree rise in temperature.}$$

$$\mu_p = \mu_n = 1800 \quad | \quad \mu_n > \mu_p$$

$$\mu_p = \mu_n = 1300, \mu_p = 500$$

$$P = n = n_i$$

for Ge, conductivity raises approx.  $6(8)\%$  per degree rise in temperature.

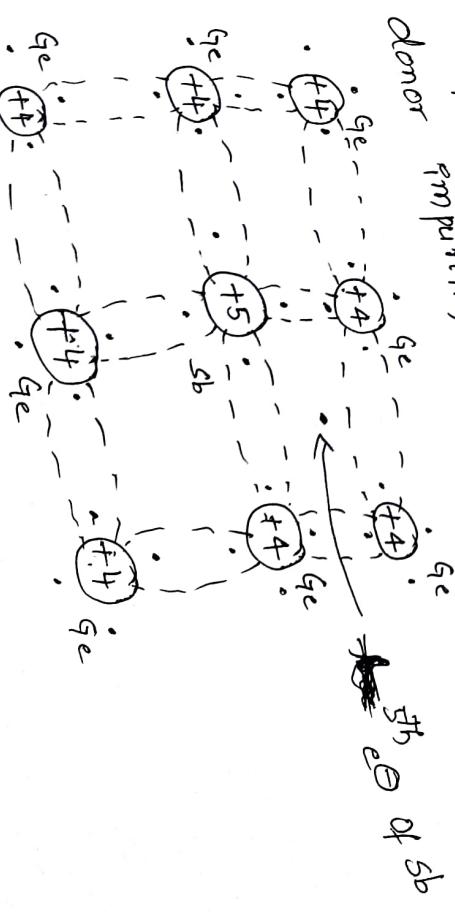
for metals, resistance raises  $0.4\% / {}^\circ C$  - collisions with "semi conductors", resistivity decreases with "semi conductors", resistivity decreases with increase of temperature.

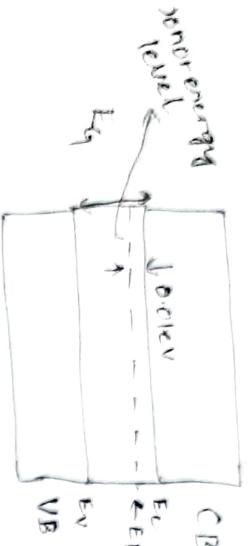
Extrinsic semi conductor: when added a trivalent ion or a pentavalent impurity becomes an extrinsic semi conductor.

Donor (no pentavalent bismuth, phosphorous, arsenic, antimony (Sb)) are generally

Bismuth, phosphorous, arsenic, antimony (Sb)

donor impurities





Donor level

$\text{C} \rightarrow \text{Ge}$

$\text{O} \rightarrow \text{Ge}$

$\text{n-type}$

\* The pentavalent impurity causes a free 5<sup>th</sup> e<sup>-</sup>

which is not in any covalent bond and needs just one to enter conduction band.

\* It forms a new energy level called donor level near to CB.

\* The no. of e<sup>-</sup>s raises in an n-type semiconductor because of (and opposition force in CB.)

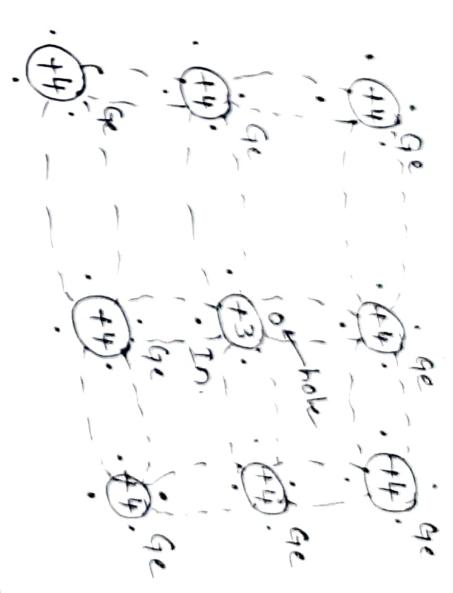
\* And holes decrease recombination. (and opposition force in CB.)

Acceptor (or) trivalent impurity :- (p-type)

When a trivalent impurity (boron, gallium or indium) is added to an intrinsic semiconductor 3 e<sup>-</sup>s will form 3 covalent bonds and leave one covalent bond short of an e<sup>-</sup>.

\* The vacancy in 4<sup>th</sup> bond constitutes a hole.

\* Such holes accept e<sup>-</sup>s and such impurities are acceptor impurities and it becomes a p-type semiconductor.



Acceptor energy level

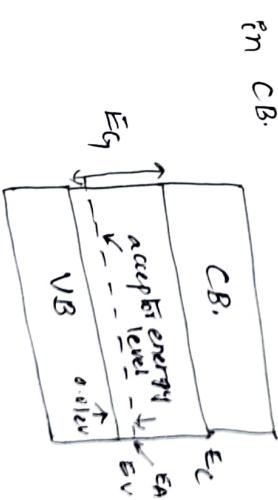
$\text{C} \rightarrow \text{Ge}$

$\text{Li} \rightarrow \text{Ge}$

$\text{In} \rightarrow \text{Ge}$

$\text{p-type}$

\* The acceptor impurity will form an acceptor energy level near to Valency band and e<sup>-</sup>s can move easily to acceptor level and form holes. Large number of holes in VB but no e<sup>-</sup>s in CB.



p-type extrinsic semiconductor

\* So acceptor makes p-type carrier holes " "

(Conductor " "

" "

\* " donor (majority majority - e<sup>-</sup>s)

" "

charge densities in a semi conductor :-

In an intrinsic semi conductor

$$n_p = n_i^2 \quad (\because n_p = n_i)$$

for extrinsic semiconductor.

Since the semi conductor is electrically neutral,

let  $N_D$  is concentration of donor atoms,  $N_D$  positive charges ( $/m^3$ )

then constitute  $N_A$  positive

$$\text{Total} = N_D + P. \quad (\text{positive charge density})$$

Similarly  $N_A$  acceptor ions make  $N_A$  negative

charges. ( $/m^3$ )

$$\text{Total} = N_A + n.$$

Since semi conductor is electrically neutral.

( $\because$  positive charge density = -ve charge density)

$$N_D + P = N_A + n$$

In n-type  $\rightarrow N_A = 0$ ,  $n >> P$ .

$$\Rightarrow \boxed{n \approx N_D}$$

$$\Rightarrow \boxed{N_A \approx N_D}$$

Concentration  $p_n$  of holes in n-type is varying from

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

$$\begin{aligned} \text{Similarly for p-type} \\ p_p = n_i^2 \end{aligned}$$

### Drift and Diffusion:-

#### Diffusion.

Due to non-uniform concentration of charged particles in a semiconductor, the charges move from a region of greater concentration to a region of smaller concentration.

for eg. the concentration of holes 'P' varies with distance 'x' and concentration with gradient  $\propto \frac{dp}{dx}$  (density of carriers)

gradient  $\propto \frac{dp}{dx}$

$\begin{array}{c} \text{high concentration} \\ \downarrow \\ \text{low concentration} \end{array}$   
holes move across surface

This constitutes a current and diffusion hole-current density  $J_P$  ( $A/m^2/s$ )

$$J_p = -e D_p \frac{dp}{dx}$$

$D_p$  → diffusion constant for holes (cm<sup>2</sup>/sec)

For e<sup>⊖</sup>s

$$J_n = e D_n \frac{dn}{dx}$$

$D, \mu$  are statistically thermodynamic phenomena.

$$\left[ \frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T \right]$$

(Voltage eq. of temperature)

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

$$V_T = 1.38 \times 10^{-23} T^{1/2} K$$

At room temp.,  $\mu = 39 D$ .

Drift:-

When an electric field  $E$  is applied across the semi-conductor, the charge carriers attain a certain

drift velocity  $V_d$

$$V_d = \mu E$$

$\mu$  → mobility of charge carrier

\* The holes move toward negative terminal and e<sup>⊖</sup>s move toward positive terminal

$E$  → electric field intensity  $V/cm$

\* This combined effect of movement of charge carriers under the influence of external electric field constitutes a current called drift current. The drift current density due to charge carriers such as free e<sup>⊖</sup>s and holes are the current passing through a 1sqm perpendicular to direction of flow.

drift current density due to free e<sup>⊖</sup>s and hole concentration (A/m<sup>2</sup>)

$$J_n = \mu n e E$$

$$J_p = \mu p h E$$

$n, p \rightarrow e^{\oplus}$  and hole concentration (m<sup>-3</sup>)

$\mu_n, \mu_p \rightarrow$  mobility (m<sup>2</sup>N-sec)

$e \rightarrow$  charge of e<sup>⊖</sup>

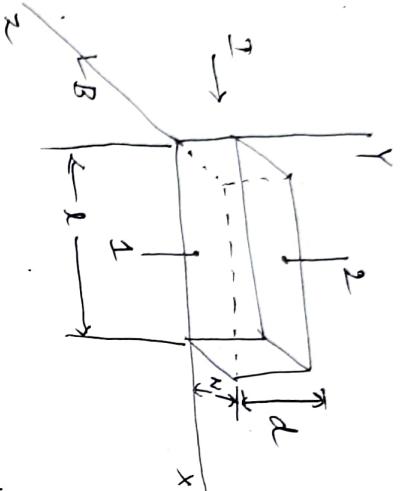
The Hall effect:-

In a specimen (or semiconductor) carrying a current  $I$  is placed in a transverse magnetic field  $B$ , an electric field  $E$  is induced in the direction of current  $I$  and it is perpendicular to both  $I$  and  $B$ . This phenomenon is called as Hall effect.

It is used to determine

- 1) type of a semiconductor (p-type or n-type)
- 2) carrier concentration and mobility
- 3) conductivity ( $\sigma$ )

\*  $I$  is in +ve  $X$  and  $B$  is in the  $-ve Y$ , then a force will be exerted in the -ve  $Z$  on the current carrier



\* If the semiconductor is n-type, current is because of  $e\text{os}$  and they are forced towards negative 'Y', i.e. side 1 will be at negative potential than side 2.

between surfaces 1 and 2.

\* In the equilibrium state the electric field intensity due to the Hall effect must exert a force on the carrier which balances magnetic force

$$eE = BeV \quad (V \rightarrow \text{mean drift speed})$$

$\Rightarrow$  magnitude of charge on carrier

$V \rightarrow \text{drift speed}$

$$\text{we have } E = \frac{V_H}{d}$$

$d \rightarrow \text{distance b/w 1 and 2}$

$J \rightarrow \text{current density}$

$P \rightarrow \text{charge "}$

$\Rightarrow \text{width of Specimen in direction of magnetic field}$

$$\Rightarrow V_H = Ed = Bwd$$

$$= \frac{BJd}{\rho} \quad \text{--- (1)}$$

\* \* \* 'P' can be measured from others from above equation

If carriers are  $e\text{os}$ ,  $\rho = ne$   $\Rightarrow e\text{o concentration}$   
" " holes,  $\rho = pe$

Now Hall Coefficient

$$R_H = \frac{1}{\rho}$$

Hence  $R_H = \frac{V_H w}{BI}$

$(\because \text{from (1)})$

\* \* \* conduction is primarily to charges of one sign / conductivity ( $\sigma = \rho \mu$ ) ( $\mu \rightarrow \text{mobility}$ )

$$\Rightarrow \boxed{\mu = \sigma R_H}$$

$$\boxed{R_H = \frac{3\pi}{8\rho}}$$

$$R_H = \frac{3\pi}{8\rho} \text{ for random thermal distribution in spec}$$

Fermi-Dirac function:

The equation  $f(E)$  is called the Fermi-Dirac probability function, and specifies the fraction of all states at energy  $E$  (ev) occupied under conditions of thermal equilibrium.

From quantum statistics it is found that

$$f(E) = \frac{1}{1 + \exp[-(E - E_F)/kT]}$$

Where

$K = \text{Boltzmann constant}, \text{ ev}/{}^\circ\text{K}$

$T = \text{temperature, } {}^\circ\text{K}$

$E_F = \text{Fermi level or characteristic energy}$

for crystal, ev.

"The 'Fermi level' represents the energy state with 50 percent probability of being filled if no

forbidden band exists.

The Fermi-Dirac distribution function  $f(E)$  gives the probability that a state of energy  $E$  is occupied.

If  $E = E_F$  then  $f(E) = \frac{1}{2}$  for any value of

temperature.

- Observe graphs  $E - E_F$  vs  $f(E)$  and  $f(E)$  vs  $E - E_F$ .
- 
- When  $T = 0^\circ\text{K}$ , two possible conditions exist:
- (1) If  $E > E_F$ , the exponential term becomes infinite and  $f(E) = 1$ .
  - (2) If  $E < E_F$ , the exponential becomes zero and  $f(E) = 0$ .
- $\Rightarrow$  There is no probability of finding an occupied quantum state of energy greater than  $E_F$  at absolute zero.

\* There are no  $e\sigma$  at  $0^{\circ}\text{K}$  which have energies in excess of  $E_F$ . i.e. Fermi energy is the maximum energy that any electron may possess at absolute zero.

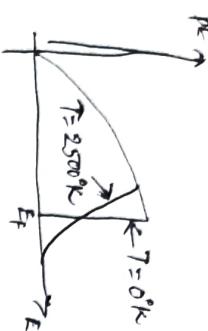


Fig: Energy distribution in metallic tungsten at 0 and  $2500^{\circ}\text{K}$ .

- \* Because of Pauli exclusion principle, no two  $e\sigma$  have the same energies even at  $0^{\circ}\text{K}$  (so only  $0$  to  $E_F$  levels)
- $\Rightarrow$  The area under the curve is total no of particles /  $\text{m}^3$ . Two areas are equal (.)
- \* Imp inference is that the distribution function changes only very slightly with temperature even temp diff is large ( $2500^{\circ}\text{K}$ ), curve change is less.  $e\sigma$  with lower energies at  $0^{\circ}\text{K}$  will have undisturbed and  $e\sigma$  with higher will have much more higher energies because of temp.

Fermi level in an "intrinsic" semiconductor  
No of  $e\sigma$  in conduction band

$$n = N_c \exp(-(\epsilon_c - E_F)/kT) \quad (1)$$

$$\begin{aligned} N_c &\rightarrow \text{effective state density} \\ n + 200^{\circ}\text{K} N_c &= 1.02 \times 10^{19} \text{ cm}^{-3} \text{ for Ge} \\ &= 2.8 \times 10^{19} \text{ cm}^{-3} \text{ for Si} \end{aligned}$$

$N_c$  gives the concentration of free  $e\sigma$  in a semi conductor at absolute temp  $T$  and it is hypothetical density of  $e\sigma$  states placed at the bottom of conduction band energy  $E_c$  after multiplication with Fermi function  $F(E_c)$

\* Concentration

No of hole in VB

$$p = N_V \exp[-(E_F - E_V)/kT] \quad (2)$$

When multiplication with  $[1 - F(E_V)]$ , gives

hole concentrations in a semi conductor must be electrically neutral:  $N_c N_V \rightarrow$  hypothetical density placed at top of neutral band level  $E_V$ , after mul. with  $1 - F(E_V)$ , gives conc. energy  $\eta_i = p_i$  of holes in a sc @  $T_{\frac{\text{absolute}}{T}}$ , from (1) & (2).

$$\Rightarrow N_c \exp[-(\epsilon_c - E_F)/kT] = N_V \exp[-(E_F - E_V)/kT]$$

Take log on both sides

$$\ln \frac{N_c}{N_V} = \frac{E_C + E_V - 2E_F}{kT}$$

Hence

$$E_F = \frac{E_C + E_V}{2} - \frac{kT}{2} \ln \frac{N_c}{N_V}$$

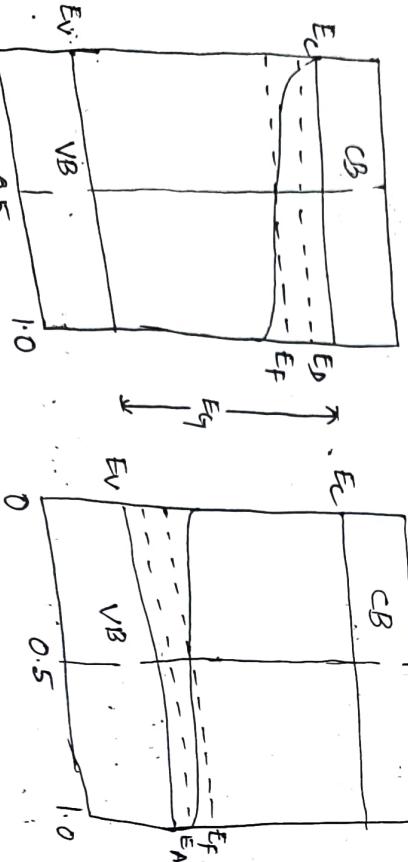
of effective masses of electron and hole are the same,  $N_c = N_V$

$$\Rightarrow E_F = \frac{E_C + E_V}{2} \quad \text{--- (A)}$$

At  $T=0K$ , even  $N_c \neq N_V$ , 'A' is valid...

Hence the Fermi level lies in the center of the forbidden energy band.

Fermi level in intrinsic semi-conductor: ( $E_F$ )



In intrinsic semi-conductor,  $E_F$  was in the middle of energy gap, indicating equal concentration of free electrons and holes.

\* If the donor impurity is added to crystal then, at a given temperature and assuming all donor atoms are ionised, the first  $N_D$  holes from VB to bridge the gap.

Stated for the electrons from VB to bridge the gap.

difficult by thermal agitation (repulsion).

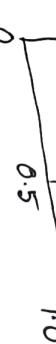
$E_F$  by thermal agitation is a measure of  $e^-$ -hole pairs thermally generated for that temp will be reduced since  $E_F$  is a measure of probability of occupancy of allowed energy states, it is clear that many of the energy states to indicate that many of the donor  $e^-$  to CB to indicate that many of the donor  $e^-$  states in that band are filled by holes exist in VB.

and fewer holes exist in VB.

\* If the temp of n-type or p-type are increased to a large extent high level (somehow) hole pairs form, finally making  $e^-$  and holes in VB almost equal and new hole pairs in VB almost equal and in CB and holes in VB almost equal and the semiconductor becomes intrinsic again.

$$E_F$$

$$f(E)$$



position of  $E_F$ :

(a) n-type

(b) p-type

position of  $E_F$ :

n-type

To calculate position of Fermi level in n-type -

we have  $n = N_c \exp [-(E_C - E_F)/kT]$

Substitute  $n \approx N_D$  ( $\because$  n-type)

$$N_D = N_c \exp [-(E_C - E_F)/kT]$$

$$\Rightarrow \boxed{E_F = E_C - kT \ln \frac{N_c}{N_D}}$$

Similarly for p-type -

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

If  $N_A = N_D$  - ,

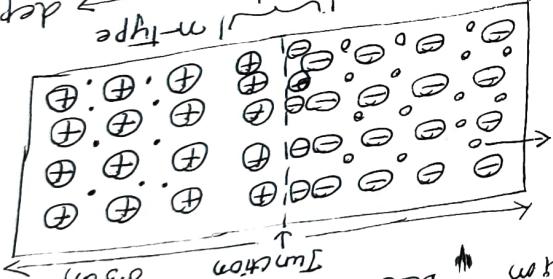
$$E_F = \frac{E_C + E_V}{2} - \frac{kT}{2} \ln \frac{N_c}{N_V} (\because \text{intrinsic})$$

The Continuity equation :-

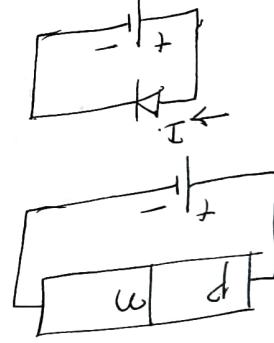
\* If we disturb the equilibrium concentration of carriers in a semiconductor, the concentration of holes and electrons will vary with time.

\* The carrier concentration in the body of a semiconductor is a function of both time and distance.

\* We will derive the differential equation which shows this relationship.

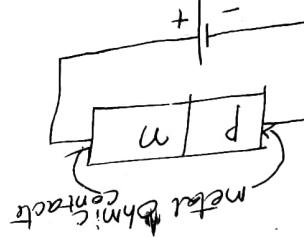
- UNIT-2
- TUNING DIODE CHARACTERISTICS
- Open-circuited PN Junction
- \* If donor impurities are introduced into one side of a semi-conductor, i.e., a P-N junction is formed and acceptors into the other side of a single crystal.
  - \* At donor impurities are introduced into the one side of a semi-conductor, i.e., a P-N junction is formed.
  - \* There are only p-type carriers to left and n-type carriers to the right. Because there is a density gradient across the junction and will diffuse to the right to the left due to displacement of charges, an electric field appears across junction - equilibrium will be established when the field becomes large enough to restrain the process of diffusion. This electric charges are confined to the neighborhood of junction, and, consist of immobile ions.
  - \* At the junction,  $\phi_A$  and holes to which are diffusing undergo recombination, finally, leaving junction free from mobile charge carriers, i.e., neutralizing  $\phi_A$  and holes and holes recombine to form mobile charge carriers.
- Diode Junctions
- Manufactured found in the neighborhood of junction of diode junctions
- could uncovered, charge. Since the region of Gunn Effect is depletion region, space-charge could be stopped by ions because of field emission (capillaries)
- Thickness =  $10^{-4} \text{ cm} = 1 \text{ micron}$
- On thickness micron
- If called the depletion region, since the region of mobile charges, it's depletion of mobile charges, i.e., Gunn Effect is depletion region, space-charge could be stopped by ions because of field emission (capillaries)
- Diffusion length  $= 0.5 \text{ cm}$
- Holes 
- p-type n-type
- $\frac{dx}{dt} = \frac{3}{\lambda P} = \frac{3}{\lambda m}$
- electric field intensity
- charge density
- depletion region
- junction barrier for  $\phi_A$
- potential barrier for  $\phi_A$
- distance from junction
- $V = - \int E dx$ , p-side.
- $E = 0$
- $V_0$
- $\phi_A$  per hole
- junction barrier for  $\phi_A$

carrier pair current  $I_c$  due to thermal generation of electron-hole pairs ( $I_0$ ) and (minority carrier flow)  $I_0 \downarrow$  with  $\downarrow$  and back scattering  $\downarrow$  when  $V$ , voltage is applied to diode or is increased by  $\Delta V$ . shown in fig. the potential barrier is balanced by electric field due to potential barrier conductors the large diffusion current should be balanced by drift current ( $I_{drift}$ )  $I_{drift} = I_c$  called concept contact potential. This contact potential is used to calculate  $V_{th}$ . Biased p-n junction and p-n junction as a diode  $\rightarrow$  permits the job of current in one direction but restricts the flow in opposite direction.



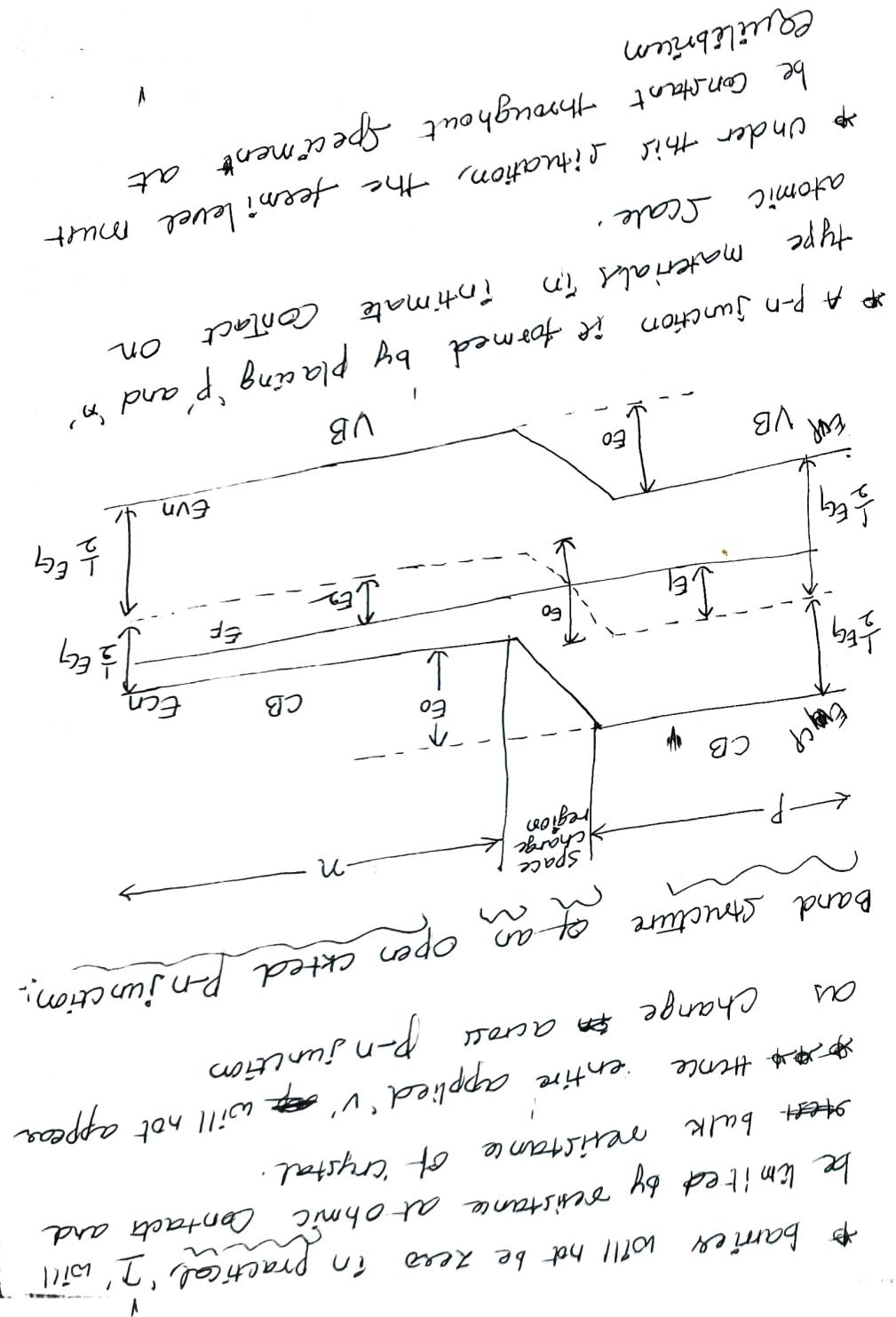
In reverse biasing, bias the direction indicated in figure. The application of voltage causes flow of carriers and minority carriers from anode to cathode. It is called reverse bias, majority carriers flow in the direction indicated in fig.  $V_{th}$  is the potential difference applied to the diode.

The depletion region offers a potential barrier for diffusion of holes and electrons. The charge density and electron concentration around the barrier is  $n$ . Due to forward bias the carriers move away from junction and  $n$ -type to p-type terminal to p-side and the terminal to n-side moves to right end due to left of junction. This process continues until holes can't be provided from the charge density and electron concentration  $n$ . The carrier flow is continued until flow.



Reverse bias  $\rightarrow$  -ve terminal to p-side and the terminal to n-side and the terminal to p-side and the terminal to n-side. The flow is in opposite direction.

The depletion region offers a potential barrier for diffusion of holes and electrons. The charge density and electron concentration around the barrier is  $n$ . Due to forward bias the carriers move away from junction and  $n$ -type to p-type terminal to p-side and the terminal to n-side moves to right end due to left of junction. This process continues until holes can't be provided from the charge density and electron concentration  $n$ . The carrier flow is continued until flow.



If it is not so,  $e\phi$  on one side of junction would have an avg. energy higher than that on the other side and there would be transfer of  $e\phi$  and energy until Fermi levels in two sides line up. So  $E_F$  must be constant.

\* Since  $E_F$  is closer to  $E_{Fn}$  in n-type and closer to  $E_{Fp}$  in p-side, clearly then the conduction band edge  $E_F$  in the 'p' can't be same at same level as  $E_{Fn}$  and similarly  $E_{Fn}$  &  $E_{Fp}$ .

$$E_0 = E_{Fp} - E_{Fn} = E_{Fp} - E_{Fn} = E_1 + E_2$$

$E_0 \rightarrow$  represents potential energy of the  $e\phi$  at junction

Derivation for  $V_0$ :  
 Calculation of  $V_0$  will be based on the equilibrium condition of zero resultant hole current.  
 $\text{Condition of zero resultant hole current} = \text{hole drift current}$

$$\Rightarrow -(\text{diffusion current}) = \text{hole drift current}$$

$$\Rightarrow e\frac{dp}{dx} = e\mu p E - 0$$

higher than that on the other side and there would be transfer of  $e\phi$  and energy until Fermi levels in two sides line up. So  $E_F$  must be constant.

Einstein relation is  

$$\frac{dp}{p} = \frac{V}{V_T} \quad \dots \text{Eq. 2}$$
  
 put Eq. 2 in Eq. 1 and consider ( $\because V = Ed$ )

$\frac{dp}{p} = \frac{e da}{V_T} = -\frac{dV}{V_T}$   
 when above eqn is integrated w.r.t. b/w limits from which extend across the junction hole which extend across the junction hole  
 the p-material, where equilibrium hole concentration is  $p_{po}$ , to the n-material, where hole density is  $p_n$

where

$$\Rightarrow p_{po} = p_n \exp\left(\frac{V_0}{V_T}\right)$$

( $\because E = V \theta$ )

$$\text{since } \frac{V_0}{V_T} = \frac{E_0}{K_T}$$

$$E_0 = K_T \left( \frac{V_0}{V_T} \right)$$

$$E_0 = K_T \cdot \ln \left( \frac{p_{po}}{p_n} \right) = K_T \ln \left( \frac{p_{po}}{p_n} \right)$$

$$p_n = 10^{16} \text{ cm}^{-3}, p_{po} = 10^4 \text{ cm}^{-3} \text{ and } K_T = 0.026 \text{ eV at room temp.}$$

we obtain  $E_0 \approx 0.5 \text{ eV}$ .

## Current components in a p-n diode

\* When a diode is forward biased, holes are injected to n-side and

$e^-$  to p-side.

\* The no. of injected minority current falls off exponentially with distance from junction. hence diffusion current which is proportional to concentration gradient also varies exp. with distance.

\* Two minority currents  $I_{pn}$ ,  $I_{np}$  exist

$I_{pn}(x) \rightarrow$  hole current in n-side  
 $I_{np}(x) \rightarrow e^-$  " " p-side as func. of 'x'

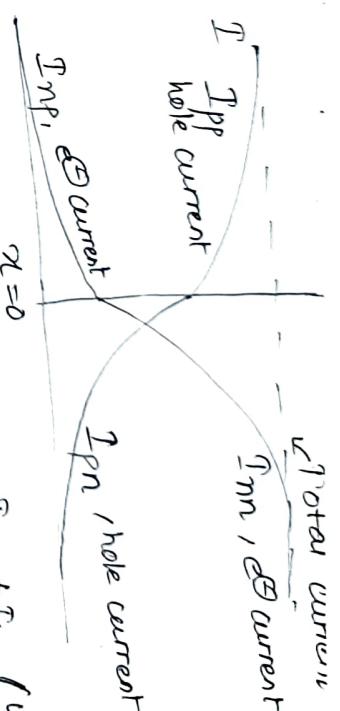
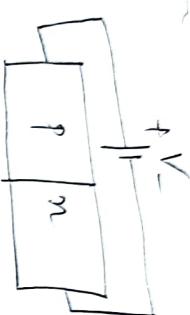
At  $x=0$ , crossing junction  $e^-$  and holes constitute current in same direction

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

\* Since 'I' is constant in series ckt, it is independent of 'x'

of 'x'  
 hence hole current in p-side (majority carrier)

$$I_{pp}(x) = I - I_{np}(x)$$



$I_{pn} \neq I_{np}$  (unsymmetrically)

$$x=0$$

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

\* In a forward biased diode, the current enters 'p' side as hole current and leaves the 'n' side as an  $e^-$  current of same magnitude

\*  $I_{pp}$  of holes is current in 'p' side. As holes approach the junc, some of them recombine with  $e^-$ , which are injected into 'p' from junction (to make current constant). what remains of  $I_{pp}$  at junction enters 'n' side and become  $e^-$  hole diffusion current  $I_{pn}$ . similarly  $I_{nn}$

\* Current in p-n diode is bipolar since it is made up of +ve and -ve carriers.

Total current is constant, but proportion due to holes and  $e^-$  vary with distance

## The law of junction :-

\* If hole concentrations at the edges of depletion region are  $P_p$  and  $P_n$  in 'p' and 'n' materials respectively and barrier potential across this depletion layer is  $V_B$ , then

$$P_p = P_n \exp(V_B/V_T) \rightarrow \begin{array}{l} \text{Boltzmann} \\ \text{relationship of} \\ \text{Kinetic gas} \\ \text{theory} \end{array}$$

(1)

The above is valid even under non equilibrium conditions as long as the net hole current is small compared with the diffusion (or drift hole current (low level injection))

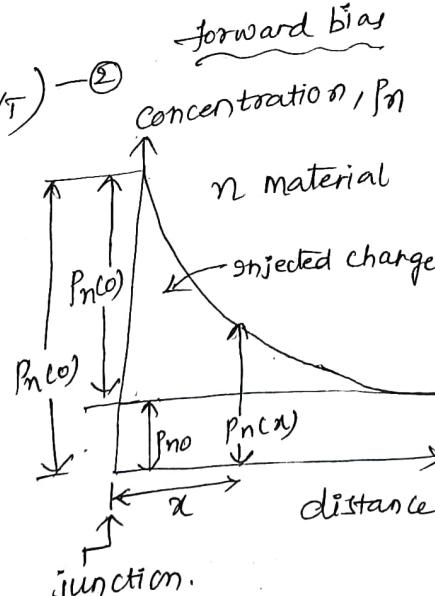
If we apply above eqn to open-circited p-n junction

then  $P_p = P_{p0}$ ,  $P_n = P_{n0}$ ,  $V_B = V_0$ , we can get contact potential

$$P_{p0} = P_{n0} \exp(V_0/V_T) \quad (2)$$

Now when this junction is forward biased by applying a voltage 'V', then the barrier Voltage  $V_B$  is decreased from its equilibrium value  $V_0$

$$\boxed{V_B = V_0 - V}$$



hole conc. throughout 'p' region is constant and  $P_p = P_{p0}$ . The hole conc. varies with distance into n side, as per diag. At the edge of depletion layer ( $x=0$ ),  $P_n = P_n(0)$

$$\Rightarrow P_{p0} = P_n(0) \exp(V_0 - V/V_T) \quad (\text{from (1)})$$

Combining with eqn (2)

$$P_n(0) = P_{n0} [\exp(V/V_T)] \quad (3)$$

This boundary condition is called "the law of junction". It indicates that, for a forward junction  $\downarrow$  be greater than  $\uparrow$  thermal equilibrium value  $P_{n0}$ . similar for e $\Theta$ s

hole concentration  $P_n(0)$  injected into the n-side at the junction is

$$P_n(0) = P_n(0) - P_{n0}$$

from (3)

$$P_n(0) = P_{n0} [\exp(V/V_T)] - P_{n0}$$

$$\boxed{P_n(0) = P_{n0} [\exp(V/V_T) - 1]}$$

## Quantitative Theory of the p-n Diode currents

Assume under forward bias, depletion-layer thickness  $\approx 0$ , holes are injected from the p-side into 'n' material. The concentration  $p_n$  of holes in the n-side is increased above its thermal-equilibrium value  $p_{no}$  and is given by

$$p_n(x) = p_{no} + p_{n(0)} \exp(-x/L_p) \quad \text{--- (1)}$$

$L_p$  → diffusion length for holes in 'n' material and the injected ion excess concentration at  $x=0$

$$p_{n(0)} = p_{n(0)} - p_{no}$$

$$p_{n(x)} = p_{no} + p_{n(0)} \exp(-x/L_p)$$

$$p_n(x) = p_{n(0)} - p_{no}$$

As shown in fig, there is exponential decrease of the density  $p_n(x)$  with distance 'x' into the 'n' material.

Diffusion hole current in the n-side is

$$I_{pn} = -Ae D_p \frac{dp_n}{dx} \quad \text{--- (2)}$$

Derivating (1) and putting in (2)

$$I_{pn}(x) = \frac{Ae D_p p_{n(0)}}{L_p} \exp(-x/L_p) \quad \text{--- (3)}$$

This eqn verifies hole current is exponentially w/<sup>111</sup> distance. The dependence of  $I_{pn}$  upon applied voltage is contained implicitly in the factor  $p_{n(0)}$  because the injected carrier conc. is a fn of voltage. we will find dependence of  $p_{n(0)}$  upon 'V'

### Diode characteristics

#### The forward currents

The hole current  $\frac{I_{pn}(0)}{I_{pn}(0)}$  crossing the junction into n-side is given with  $x=0$  in using

$$p_{n(0)} = p_{no} [\exp(V/V_T) - 1]$$

we obtain from (3)

$$I_{pn(0)} = \frac{Ae D_p p_{no}}{L_p} [\exp(V/V_T) - 1]$$

The electron current  $I_{np(0)}$  crossing junc. into p-side is  $I_{np(0)} = \frac{Ae D_n n_{po}}{L_n} [\exp(V/V_T) - 1]$

Total diode current

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

$$I = I_0 [\exp(V/V_T) - 1]$$

where

$$I_0 = \frac{A e D_p n_{p0}}{L_p} + \frac{A e D_n n_{n0}}{L_n}$$

If widths of  $p, n$  are greater than  $L_p, L_n$  then above is valid else replace  $n_{p0}, n_{n0}$  in place of  $L_p, L_n$

### Reverse saturation current

The above derivation and equation for  $I_s$  is valid even for a reverse bias voltage 'V' ie.  $-V$  for a reverse bias whose magnitude is large compared to  $V_T$ ,  $I \rightarrow -I_0$

$$\text{we know } P_n = \frac{n_i^r}{N_D} \rightarrow n\text{-type}$$

$$n_p = \frac{n_i^r}{N_A} \rightarrow p\text{-type}$$

$$I_0 = A e \left[ \frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right] n_i^r$$

where

$$n_i^r = A_0 T^3 \exp[-E_{G0}/kT] = A_0 T^3 \exp(-V_{G0}/V_T)$$

$E_{G0} \rightarrow$  magnitude of energy gap at 0K

$A_0 \rightarrow$  constant

$V_{G0} \rightarrow$  Voltage numerically equal to  $E_{G0}$  in eV

for  $G_e$ ,  $D_p$  and  $D_n$  vary approx. inversely proportional to  $T$ . Hence temperature diff. of

$I_0$  is

$$I_0 = K_1 T^2 \exp(-V_{G0}/V_T)$$

$K_1 \rightarrow$  constant independent of temp.

In the above, we neglected carrier generation and recombination in space-charge region. It is valid for Ge, not for Si. For Si, the diffusion current is negligible compared to the transition layer capacitive charge generation current which is given by

$$I_0 = I_0 (\exp(V_{G0}/V_T) - 1)$$

where  $\gamma = 2$  for small currents

$\gamma = 1$  for large "

Also  $I_0$  is proportional to  $n_i$  not  $n_i^r$

$$I_0 = K_2 T^{1.5} \exp(-V_{G0}/2V_T)$$

$K_2 \rightarrow$  constant

## V-I characteristics

$I$  is related to ' $V$ ' by, for a pn-junction

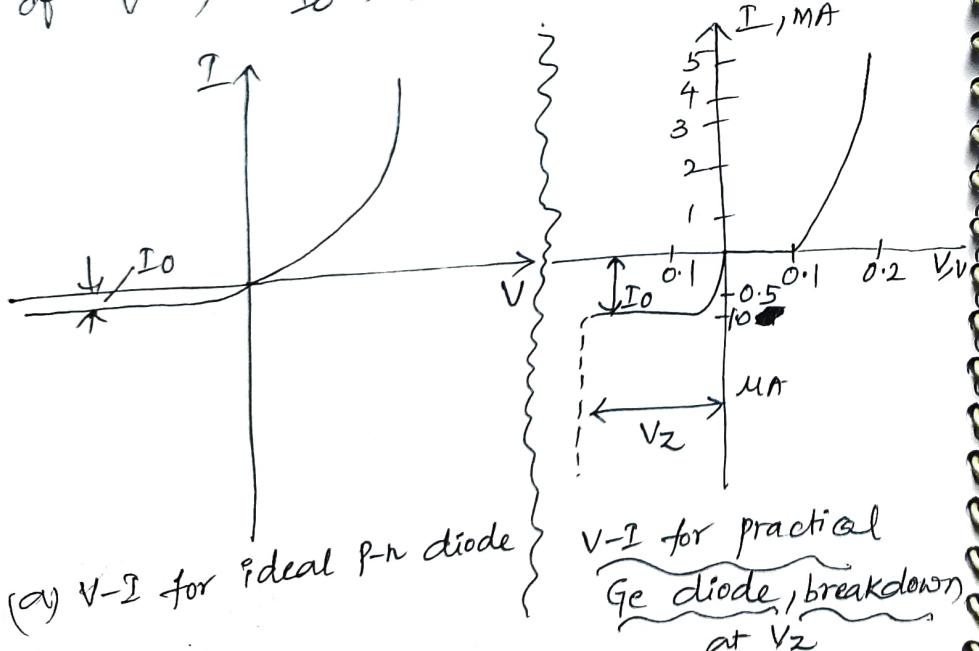
$$I = I_0 [ \exp(V/nV_T) - 1 ] \quad \text{---(1)}$$

$\eta = 1$  for Ge

$\eta = 2$  for Si

$$\begin{aligned} \text{At room temp, } V_T &= 0.26 \text{ V} \\ &\Rightarrow V_T = 26 \text{ mV} \end{aligned}$$

when ' $V$ ' is +ve (forward bias) and far greater than  $V_T$ , unity in (1) may be neglected. Except near to origin, the current ↑ exponentially with voltage. When diode is reverse biased and  $|V|$  is several times  $V_T$ ,  $I \approx -I_0$ . The reverse current is constant and irrespective of ' $V$ ',  $I_0 \rightarrow$  reverse saturation current.



forward  $I \rightarrow \text{mA}$ , reverse  $\rightarrow \text{nA}$

The dashed portion indicates that, at a reverse biasing voltage  $V_Z$ , the diode characteristic exhibits an abrupt end. At this critical voltage, a large reverse current flows and diode is said to be break down region.

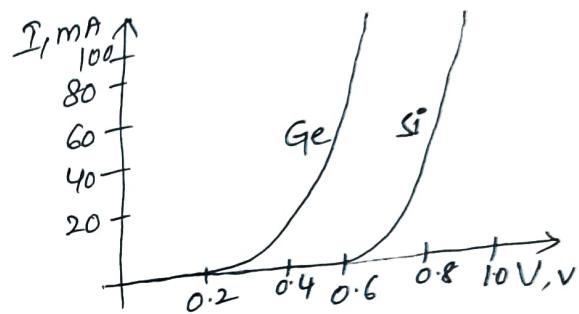


fig: V-I for Ge (1N270), Si (1N3605) at  $25^\circ\text{C}$   
cut-in voltage:- ( $V_r$ )

from fig., there exists a cutin, offset, break-point (on threshold voltage below which the current is small ( $< 1\%$  of max. rated value)). Beyond  $V_r$ , current rises rapidly

$$V_r \text{ for Ge} = 0.2 \text{ V}, \text{ Si} = 0.6 \text{ V}$$

Since  $I_0$  in Ge is  $\mu\text{A}$ , Si is  $\text{nA}$ , and  $\eta = 2$  for Si, the current rise is late compared to Ge with  $\eta = 1$

logarithmic characteristics

$V >> V_T$ , neglecting unity

from  $I = I_0 [\exp(V/\eta V_T) - 1]$  we have

$$\log I = \log I_0 + 0.434 (V/\eta V_T)$$

We therefore expect the  $\log I$  vs  $V$  plot should be linear &  $\eta \approx 2$ . At large currents, ~~exponentially~~ as when  $V \uparrow$ ,  $I$  will not ~~↑ exponentially~~ as its low currents. The reason is Ohmic resistance of diode

At low currents Ohmic drop is negligible and the externally impressed voltage simply decreases potential barrier at p-n junction. At high  $I$ , the externally applied voltage establishes an electric field to overcome the ohmic resistance of the semiconductor. At high currents diode acts ~~like a resistor~~ like a resistor than diode and current  $\uparrow$  linearly than exponentially with  $V$

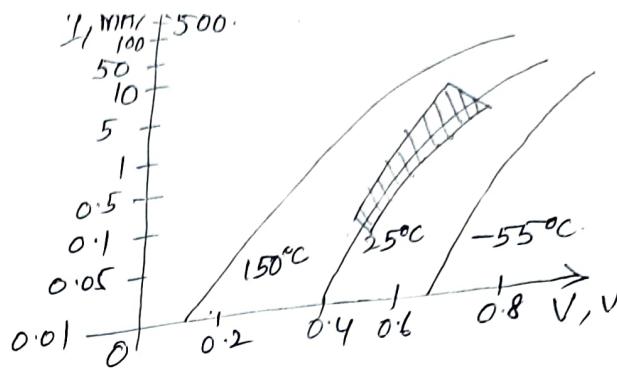


Fig: V-I characteristics at three diff temp for a Si diode. Shaded region indicates 25°C limit of control conductance. Vertical scale is log and current range is 50,000.

Temperature dependence of P-n characteristics:-

$$I = I_0 [\exp(V/\eta V_T) - 1]$$

We will now see voltage variation with temperature at fixed current. Temp. is already implicitly there in  $V_T$  and  $I_0$ .

Dependence of  $I_0$  on  $T$  is given by

$$I_0 = kT^m \exp(-V_{GO}/\eta V_T) \quad \text{---(1)}$$

where 'k' is constant,  $eV_{GO}$  is forbidden-gap energy in joules

$$\begin{array}{lll} \text{for Ge} & \eta = 1 & m = 2 \\ \text{Si} & \eta = 2 & m = 1.5 \end{array} \quad \begin{array}{ll} V_{GO} = 0.785 \text{ V} \\ V_{GO} = 1.21 \text{ V} \end{array}$$

Taking derivative of  $\ln I_0$  log of  $I_0$

$$\log I_0 = \log (KT^m \exp(-V_{G0}/\eta VT))$$

$$\log I_0 =$$

Taking derivative of log of  $I_0$

$$\ln I_0 = \ln(KT^m \exp(-V_{G0}/\eta VT))$$

$$\ln I_0 = K \left[ m \ln T - \frac{V_{G0}}{\eta VT} \right]$$

$$\frac{d}{dT} (\ln I_0) = K \frac{d}{dT} \left[ m \ln T - \frac{V_{G0} e}{\eta KT} \right]$$

$$= K \left[ \frac{m}{T} + \frac{V_{G0} e}{\eta KT^2} \right]$$

$$\frac{d}{dT} (\ln I_0) = K \left[ \frac{m}{T} + \frac{V_{G0}}{\eta VT} \right]$$

$$\Rightarrow \frac{1}{I_0} \frac{dI_0}{dT} = \frac{d(\ln I_0)}{dT} = \frac{m}{T} + \frac{V_{G0}}{\eta VT} \quad \textcircled{2}$$

At room temp,  $\frac{d(\ln I_0)}{dT} = 0.08^\circ/\text{C}$  for Si  
 $= 0.11^\circ/\text{C}$  for Ge

From experimental data,  $I_0 \uparrow$  approx.  $7\%/\text{C}$  for Si & Ge. Since  $(1.07)^0 \approx 2.0$ . we conclude that

"To double approx. for every  $10^\circ\text{C}$   $\Delta T$  in temp."  
 from  $I = I_0 [\exp(V/\eta VT) - 1]$ , for constant  $I$   
 ( $=$  neglecting unity)

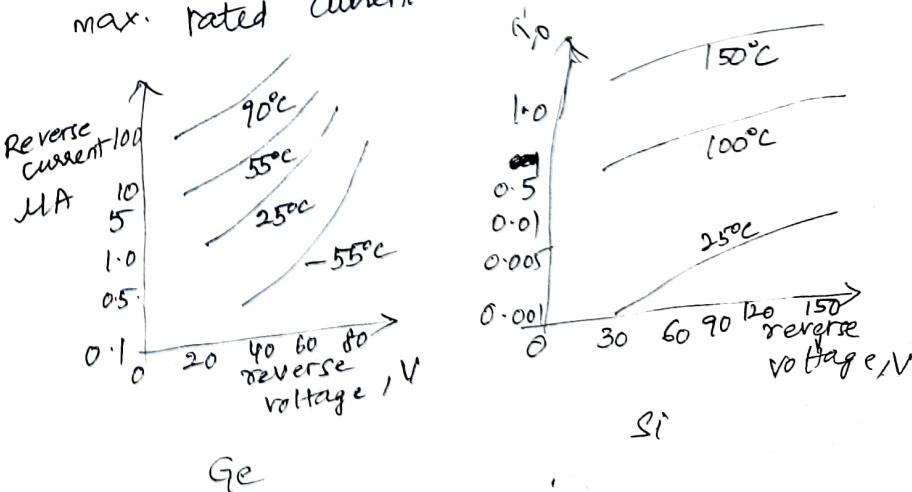
$$\frac{dV}{dT} = \frac{V}{T} - \eta VT \left( \frac{1}{I_0} \frac{dI_0}{dT} \right) = \frac{V - (V_{G0} + m\eta VT)}{T} \quad \textcircled{3}$$

$$\frac{dV}{dT} = \begin{cases} -2.1 \text{ mV}/\text{C} \text{ for Ge} \\ -2.3 \text{ mV}/\text{C} \text{ for Si} \end{cases} \quad (\text{from } \textcircled{2})$$

$$\Rightarrow \boxed{\frac{dV}{dT} = -2.5 \text{ mV}/\text{C}}$$

from  $\textcircled{3}$  \*

$\left| \frac{dV}{dT} \right| \downarrow$  with  $\uparrow T$  . first term in  $\textcircled{3}$  is b'coz of  $V_T$  depending on  $T$  and second  $I_0$  depending on  $T$  but not on  $V$ . Also, as  $V \uparrow$ ,  $\frac{dV}{dT}$  becomes less negative and zero at  $V_{G0} + m\eta VT$  and further positive. The reversal takes place at a level higher than max. rated current



$I_D$  will not be constant for  $\uparrow$  reverse voltage because of leakage current and new carrier generation due to collision in transition region at junction for Ge more  $I_D$  than Si.

### Diode Resistance:-

An ideal diode offers zero resistance under forward and infinite under reverse bias. But for practical there are two resistances

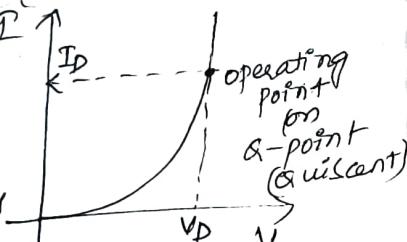
- 1) Static (or DC resistance)
- 2) Dynamic (or AC resistance)

#### Static R ( $R$ )

$$R = \frac{V}{I}$$

At any point on V-I characteristic curve,  $R$  is equal to reciprocal of the slope of a line joining the operating point to the origin.

$$R = \frac{V_D}{I_D}$$



since the static resistance varies widely with  $V$  and  $I$ , it is not a useful parameter. It doesn't consider shape of characteristic. The rectification property of diode is given on specification sheet by giving the max. forward voltage  $V_F$  required to attain a given forward

current  $I_F$  and max reverse current  $I_R$  at a given reverse voltage  $V_R$

$$\text{Si}, V_F = 0.8V \text{ at } I_F = 10mA \Rightarrow R_F = 80\Omega$$

$$I_R = 0.1mA \text{ at } V_R = 50V \Rightarrow R_R = 500M$$

\* for low current, high is ' $R$ '

2) Dynamic (or incremental) or AC resistance :- (g)

for small signal operation,  $g$  is imp and is defined as reciprocal of slope of V-I characteristic

$$g = \frac{dV}{dI}$$

The dynamic resistance is not a constant and depends on operating voltage.  
we have

$$I = I_0 [exp(V/nVT) - 1]$$

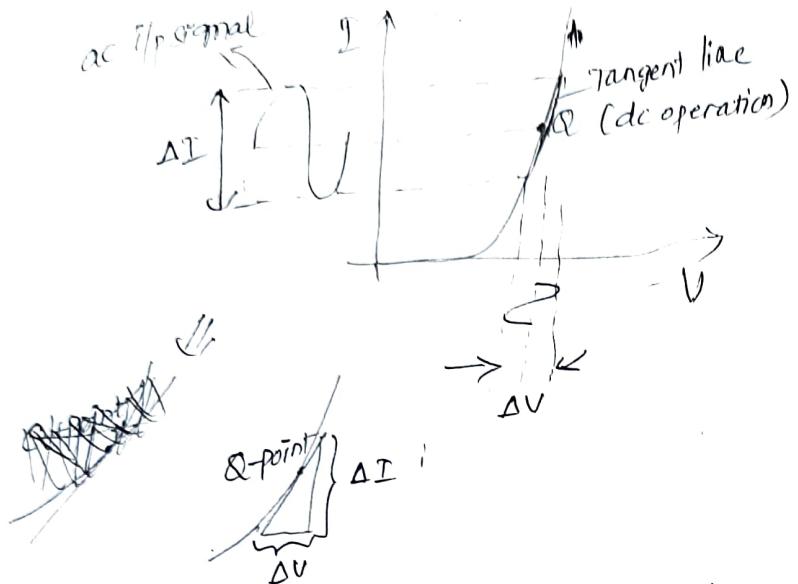
$$\text{dynamic conductance } g = \frac{1}{nVT}$$

$$g = \frac{dI}{dV} = \frac{I_0 exp(V/nVT)}{nVT}$$

$$g = \frac{I + I_0}{nVT}$$

For reverse bias ( $>$  few tenths of a volt)  $\Rightarrow |V/nVT| > 1$ ,  $g$  is extremely small and ' $g$ ' is very large. On the other hand, for a forward bias  $I \gg I_0$

$$g \approx \frac{nVT}{I}$$



$g_v$  varies inversely with current, at room temp  $\beta \approx 1$

$$r = \frac{26}{I}$$

$$I \rightarrow \text{mA}$$

$$r \rightarrow \text{ohms}$$

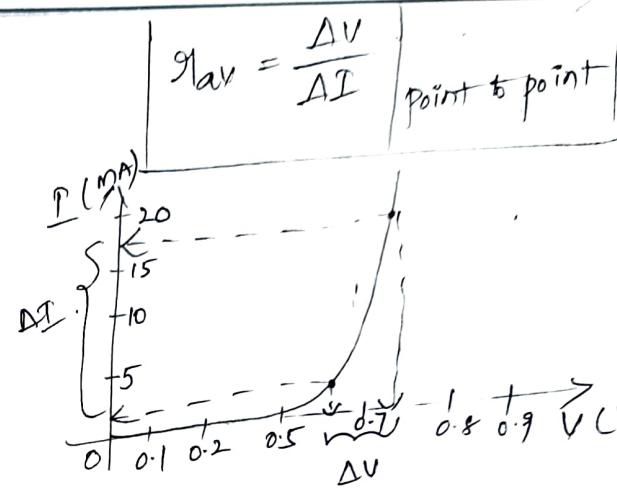
For a forward current of  $26\text{mA} \Rightarrow r = 1/\text{mA}$ . It is lesser than ohmic resistance and even  $r$  varies with  $I$ ,

for a small signal model ' $r$ ' is taken constant  
\* lower the Q-point, high is ' $r$ '

Avg. AC resistance:-

If input signal is large to produce a broad swing as shown in fig., the resistance associated with the device for this region is called avg ac resistance. It is determined by a straight line drawn b/w two intersections established by max and min. values of i/p voltage.

\* lower the level of current used to determine  $r_{av}$ , the higher is resistance level



A piece wise linear diode characteristic

A large signal approximation leads to piece wise linear characteristic

diode is open ckt,  $V < V_r$  and has constant incremental resistance

$$r = \frac{dV}{dI} \text{ if } V > V_r$$



$V_r, R_f$  depends on type of diode and  $V, I$  swings

e.g.: Ge diode for current swing from cut off to 10mA

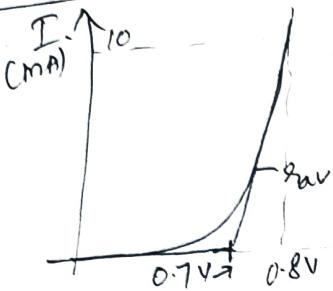
$$\Rightarrow V_r = 0.6V, R_f = 15\text{m}\Omega$$

for swings upto 50mA

$$\text{Ge}, V_r = 0.3V, R_f = 6\text{m}\Omega$$

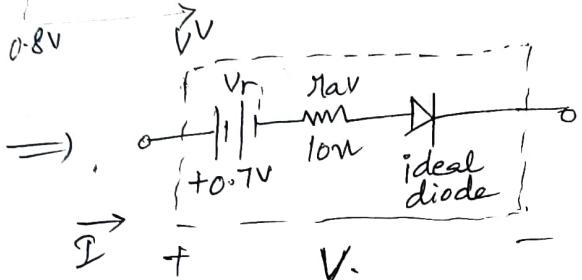
$$V_r = 0.65V, R_f = 5.5\text{m}\Omega$$

Piecewise

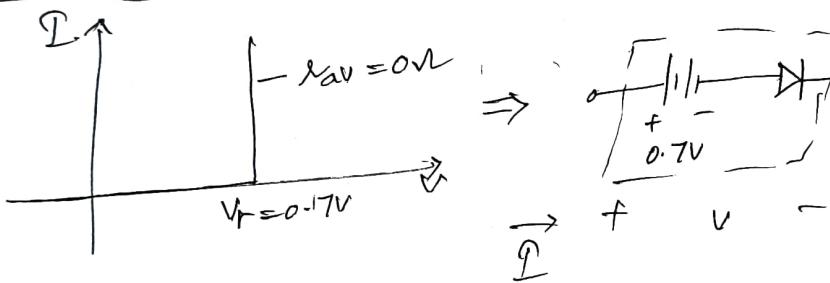


An ex-CKT is a combination of elements properly chosen to best represent the actual terminal charac. of a device or system in a particular operating region.

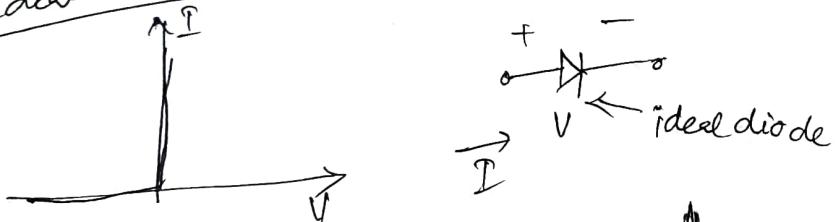
Practical diode



Simplified ex-CKT



Ideal ex-CKT



$$R_{AV} = \frac{\Delta V_d}{\Delta I} = \frac{0.8 - 0.7}{10 - 0} = \frac{0.1V}{10mA} = 10V$$

Diode capacitance:

Space charge  $\rightarrow$  transition capacitance,  $C_T$  :-  
 + Capacitance in reverse bias  $\rightarrow$  transition capacitance  
 forward "  $\rightarrow$  Diffusion "

\* a reverse bias causes majority carriers to move away from junction, thereby uncovering more immobile charges. Hence the thickness of space charge layer at junc.  $\uparrow$  with reverse voltage. This increase in uncovered charge with applied voltage may be considered a capacitive effect we can define an incremental capacitance

$$C_T = \left| \frac{dQ}{dV} \right| \quad (A)$$

where  $dQ$  is increase in charge caused by a change  $dV$  in the voltage. Also a change in voltage  $dV$  in a time  $dt$  will result in a current  $i = dQ/dt$ ,

$$i = C_T \frac{dV}{dt}$$

"  $C_T$  depends on reverse voltage and not constant