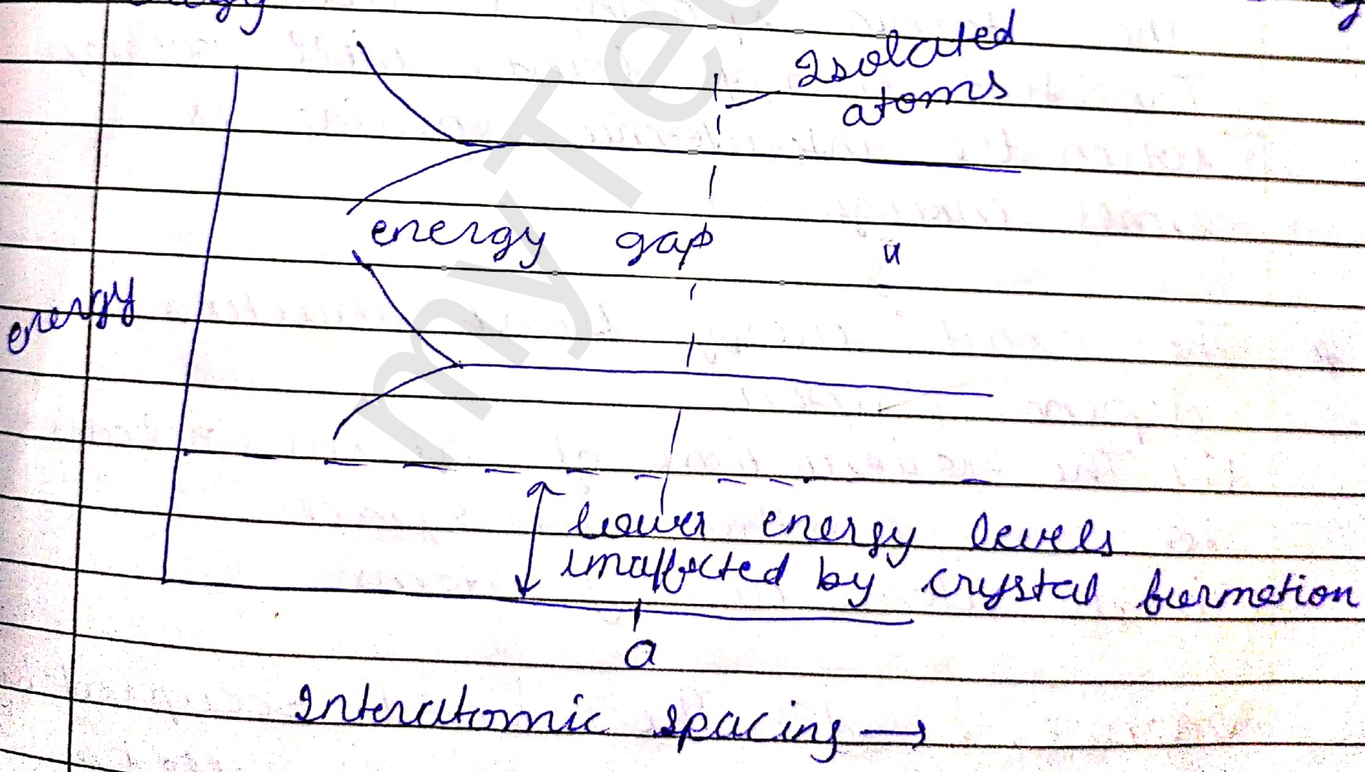
Unit I

Energy band theory of crystals

In a crystal the individual atoms are so closely packed, so that the energy levels of the inner shell electrons are not affected however the levels of outer shell electrons are altered as these electrons are shared by the adjacent atoms in crystal.

As a result the interaction b/w the outer shell electrons, the energy levels spread up to form a band of energy



- If the interatomic spacing is gradually decreased there will be gradual increase in interaction b/w neighbouring atoms and due to this interaction energy levels ($3s^2$ $3p^2$) in silicon) spread out to form band of energy

- An energy gap exist b/w the two energy bands. This energy gap is called forbidden energy gap, as no electrons can occupy states in this gap.

- Forbidden energy gap decreases as the atomic spacing is decreases, The two energy bands will overlap when the interatomic spacing is small enough.

- The exact energy band structure depends upon
  (i) The orientation of atoms relative to one another in space
  (ii) the atomic no. of atoms.

Valence band The band occupied by contributed electrons is called Valence band

Conduction band The upper band has unfilled states reffered to conduction band.

Energy band structures

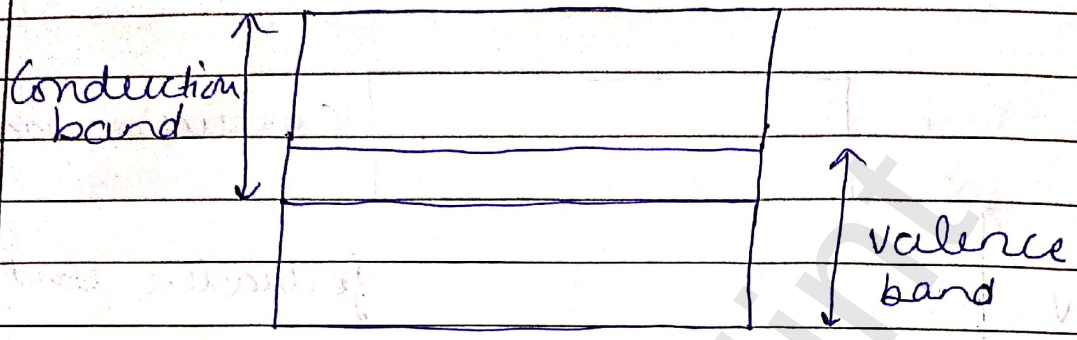
(i) Insulator

An insulator having extremely poor electrical Conductivity.

The forbidden energy gap is large. If additional energy is given to electro in the upper level of valence band, this electron attempts to cross the forbidden energy gap and enter the Conduction band. However in an insulator, the additional energy which may given to electron is much smaller than this high value of forbidden energy gap. Hence no electron Conduction possible. The no. of free electrons is very small

(ii) ⓑ Metals

The conduction in metals is only due to the electrons. A metal has overlapping valence and conduction band.



There are no forbidden levels at higher energies.

When the electric field is applied few electrons may acquire enough additional energy and move to higher energy within the conduction band. Since the additional energy ~~gain~~ ~~to~~ required for transmission from valence band to conduction band is small. Hence the conductivity of metals is excellent.

When a constant electric field E (V/m) is applied to metal the electrons would be accelerated in the direction opposite to that of electric field with velocity increase with time called drift velocity (Vd) and collisions of electrons takes place.

Drift velocity

The average velocity attained by charged particles (eg. electrons) in a metal due to an electric field.

The drift velocity is in the direction opposite to that of electric field.

$$\boxed{V_d = \mu E}$$

μ = mobility of electrons ($m^2/V\text{-}s$)

Such a directed flow of electrons constitutes a current.

n = concentration of e (e/m^3)

Current density is (A/m^2)

$$J = n V_d q$$
$$J = n q \mu E$$

$$\boxed{J = \sigma E} \qquad \boxed{\sigma = n q \mu}$$

σ = conductivity of metal $(\text{ohm-m})^{-1}$

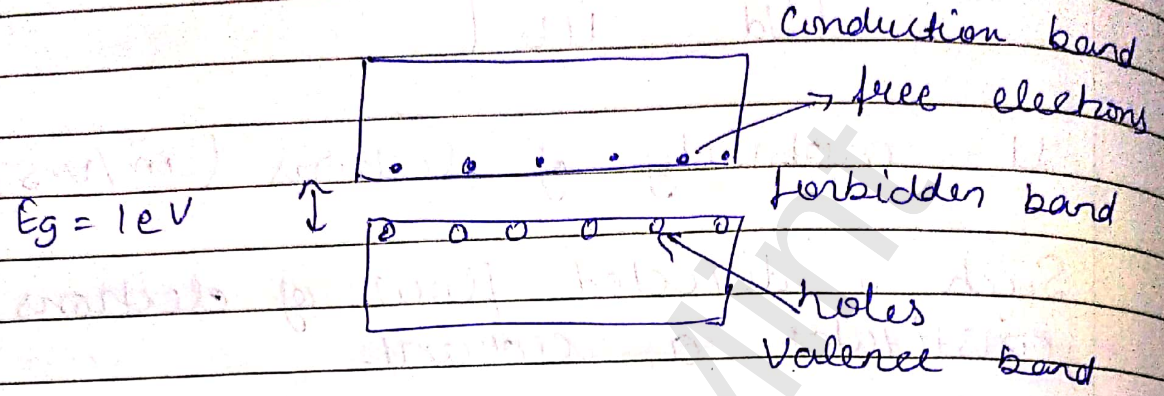
Conduction current density is proportional to the applied electric field.

The power density is

$$JE = \sigma E^2 \quad W/m^3$$

(iii) Semiconductors

The conductivity of semiconductors is much greater than that of an insulator but much smaller that that of a metal. Typically semiconductor has an energy gap of about 1eV.



Energy of about 1eV can not acquired by applied field for conduction of e^-

★ At low temp. the Valence band remains full and conduction band empty, and these materials are insulators at low tem

The conductivity of these materials increa with temp. and these materials are called intrinsic semiconductors.

★ The conductivity of of these materials increase with temp. As The temp. is increased, some of e^- in valence band acquire thermal energy greater than gap energy and move into Conduction band.

These free e^- are also called conduction e^-.

The current density due to motion of e^- is

$$J_n = n \mu_n q E = \sigma_n E$$

Hole → The absence of e^- in valence band is represented by hole.

The hole conduction current density is

$$J_p = p \mu_p q E = \sigma_p E$$

Total current density J

$$J = (n \mu_n + p \mu_p) q E$$
$$= \sigma E$$

$$\sigma = (n \mu_n + p \mu_p) = \text{total conductivity}$$

For a pure semiconductor

$$n = p = n_i$$

$$J = n_i (\mu_n + \mu_p) q E$$

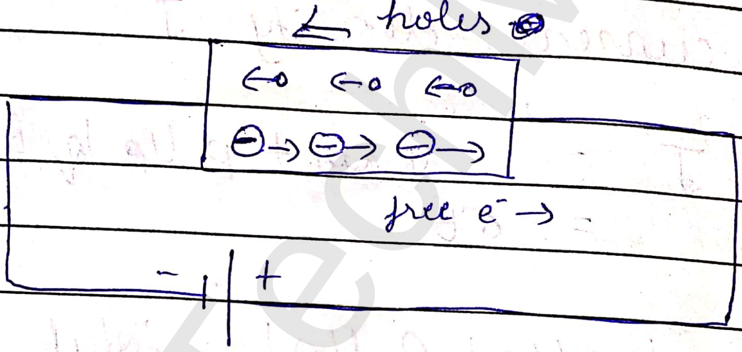
(c) The conductivity of an intrinsic semiconductor can be raised by introducing certain impurity atoms into crystal. Such semiconductors is called an extrinsic semiconductor.

Classification of Semiconductors

(i) **Intrinsic**

A pure semiconductor is called intrinsic semiconductor.

At room temp. some of valence e^- may acquire sufficient energy to enter the conduction band to form free. Under the influence of electric field, these electrons constitute electric current. holes also contribute to current



Under the influence of electric field total current through the semiconductor is the sum of currents due to free $e^\ominus$ and ~~to~~ holes.

(ii) **Extrinsic Semiconductor**

The current conduction capability of the intrinsic semiconductor should be increased by adding a small amount of impu to intrinsic semiconductor this pro is called doping. and it becomes impure or extrinsic semi conductor.

Ntype semiconductor

A small amount of pentavalent impurity such as arsenic, antimony or phosphorus is added to the pure semiconductor (germanium or silicon) to get N-type semiconductor

Germanium → 4 Valence electron
Antimony → 5 valence electron

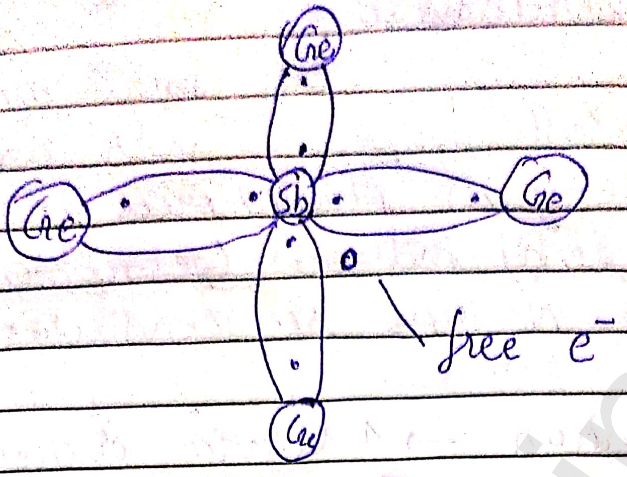
each antimony atom forms a covalent bond with surrounding 4 ~~ge~~ Ge atoms.
4 valence electrons of (Sb) form covalent bond with four valence electrons of Ge and 5th valence electron of Sb is left free which loosely bound with Sb.

This loosely bound free electron can easily excited from valence band to conduction band by the electric field or thermal energy.

Such pentavalent impurities are called donor impurities because it donates ~~positively~~ one e^- for conduction. On giving e^- for conduction, donor atom becomes positively charges cause it lose one e^-

As a result of doping no. of free e^- far exceeds no. of holes.

So electrons → majority carriers
holes → minority carriers



P-type

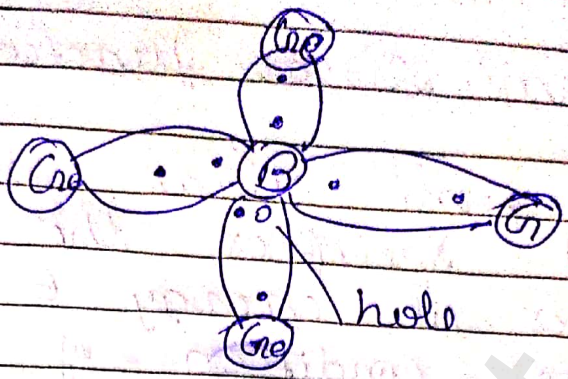
A small amount of trivalent impurity such as aluminium or boron is added to pure semiconductor to get p-type semiconductor

Ge → 4 valence e^-
B → 3 valence e^-

3 valence e^- of B make covalent bond with 4 surrounding atoms of Ge leaving one bond incomplete giving rise to ~~a~~ hole.

Thus trivalent impurity (B) added to intrinsic semiconductor introduces a large no. of holes in valence band.

Trivalent impurity such as Boron is called acceptor impurity because it accept free e^- in place of holes. As each boron donate one hole for conduction, it becomes e^-.



* Conductivity of Semiconductor

With each electron hole pair created two charge carrying particles are formed. One is negative which is free electron (n) with mobility μ_n and other is positive i.e the hole (p) with mobility (μ_p). The e^- & holes are move in opposite direction in an E. the current due to each is in the same direction.

$$J = J_n + J_p$$
$$q n \mu_n E + q p \mu_p E$$
$$(n\mu_n + p\mu_p) q E$$
$$\sigma E$$

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

if $n = p = n_i$ (no. of charge carriers in intrinsic semiconductor)

for N type $n > p$ so $\sigma = qn\mu$
for P type $p > n$ so $\sigma = qp\mu$

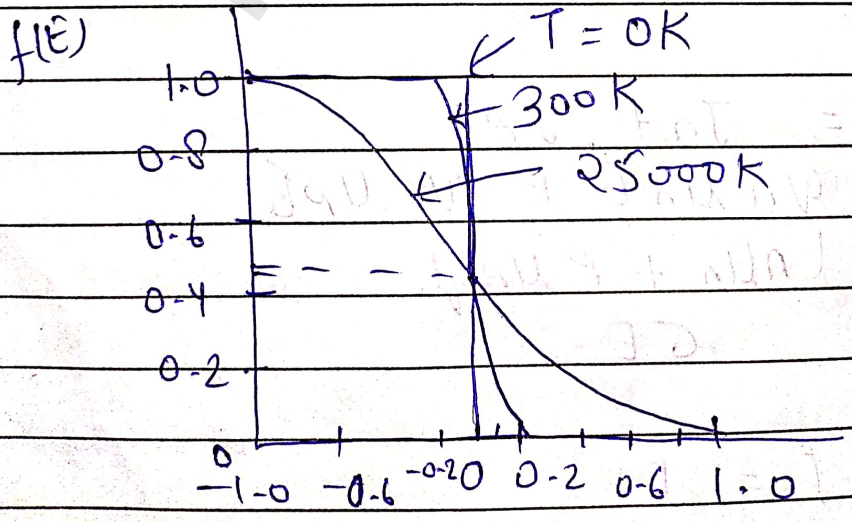
Fermi Dirac function

The fermi dirac probability function f(E) specifies the fraction of all states at energy E (in eV) occupied under condition of thermal equilibrium

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

K = Blotzman Constant in eV/K
T = temp in K
E_f = fermi level or characteristic en for crystal in eV.

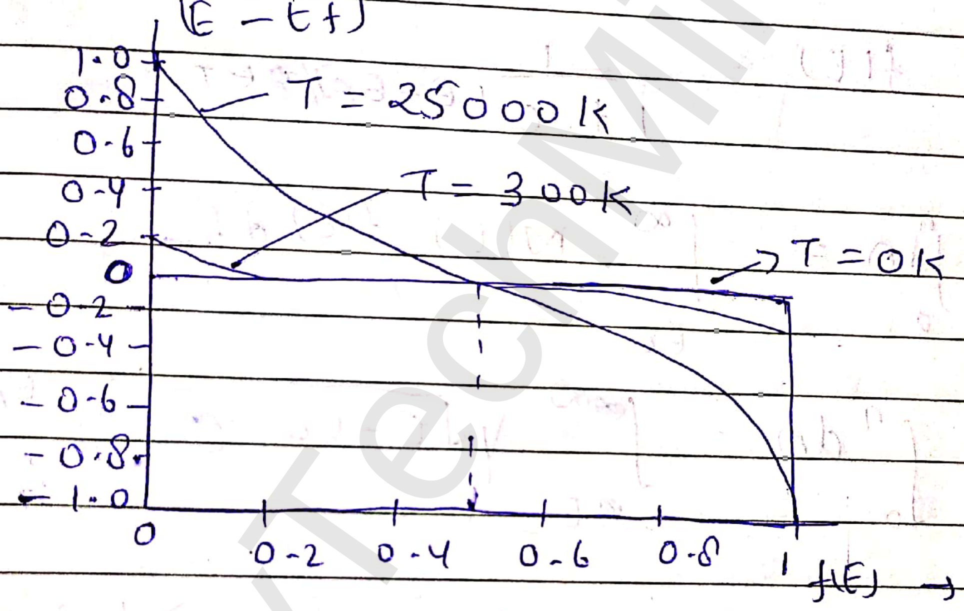
(i) If $E > E_f$
f(E) V/S $(E - E_f)$



The exp. function → infinite.
$f(E) \to 0$
there is no prob. of finding an occupied quantam State of energy greater than E_f

(ii) If $E < E_f$

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



The exponential function → 0
$f(E) = 1$
All quantum ~~no~~ levels with energies less than E_f will be occupied at T = 0K.

It implies that there are no electrons at 0K which have energies in excess of E_f. Therefore the fermi energy represents max. energy that any e^- may posses at absolute zero.

Carrier conc. in intrinsic semiconductor

To calc. conductivity of semiconductor, the conc. of free e^- & holes must be known

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

dn = no. of e^- per cubic m.

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

E_c = lowest energy in conduction band

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

$$\int_0^n dn = \int_{E_c}^{\infty} N(E)\, f(E)\, dE$$

$$\int_0^n dn = \int_{E_c}^{\infty} \gamma \sqrt{E - E_c}\; e^{-(E - E_F)/KT}$$

because $E - E_F >> KT$

$$E - E_c = x^2$$

$$\int_0^n dn = \int_0^{\infty} \gamma x\; e^{-(E_c + x^2 - E_F)/KT}\, 2x\, dx$$

ctor
the.

$$2\gamma e^{-\frac{(E_c-E_f)}{KT}} \int_0^\infty x^2 e^{-\frac{x^2}{KT}} \, dx$$

$$\sqrt{KT} = a$$

$$2\gamma e^{-\left(\frac{E_c-E_f}{KT}\right)} \underbrace{\int_0^\infty x^2 e^{-\frac{x^2}{a^2}} \, dx}_{2\sqrt{\pi}\left(\frac{\sqrt{KT}}{2}\right)^3}$$

on Solving

$$\boxed{n = N_c \, e^{-\left(\frac{E_c-E_f}{KT}\right)}}$$

$$\boxed{N_c = 2\left(\frac{2\pi m_n KT}{h^2}\right)^{3/2}(1.6\times10^{-19})^{3/2}}$$

m_n → effective mass of e^-

The Concentration of holes in valence band is

$$\int_0^p dp = \int_\infty^{E_V} N(E)\,(1-f(E))\,dE$$

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

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

$$= e^{-\left(\frac{E-E_f}{KT}\right)}$$

$E_F - E >> KT$

$$p = \int_{-\infty}^{E_v} Y (E_v - E)^{1/2} e^{-(E_F - E)/KT} \, dE$$

$$\boxed{p = N_v e^{-(E_F - E_v)/KT}}$$

$$\boxed{N_v = 2\left(\frac{2\pi m_p KT}{h^2}\right)^{3/2} (1.6\times10^{-19})^{3/2}}$$

fermi level in intrinsic Conductor

$$n_i = p_i$$

$$N_c e^{-\frac{(E_c - E_F)}{KT}} = N_v e^{-\frac{(E_F - E_v)}{KT}}$$

$$\frac{N_c}{N_v} = \frac{e^{-\left(\frac{E_F - E_v}{KT}\right)}}{e^{-\left(\frac{E_c - E_F}{KT}\right)}}$$

$$\frac{N_c}{N_v} = e^{\frac{-E_F + E_v - E_F + E_c}{KT}}$$

$$\frac{N_c}{N_v} = e^{\frac{E_v + E_c - 2E_F}{KT}}$$

$$\ln\left(\frac{N_c}{N_v}\right) = \frac{E_c + E_v - 2E_F}{KT}$$

$$KT \ln\left(\frac{N_c}{N_v}\right) = E_c + E_v - 2E_F$$

$$E_f = \frac{E_c + E_v}{2} - \frac{KT}{2}\ln\left(\frac{N_c}{N_v}\right)$$

if effective mass of e^- = effective mass of hole

$$m_n = m_p$$

$N_c = N_v$ at given temp.

$$\boxed{E_f = \frac{E_c + E_v}{2}}$$

At the centre of forbidden energy gap fermi level is present.

Fermi level in n-type semiconductors

$$n = N_D$$

$$N_C\, e^{-\left(\frac{E_C - E_F}{KT}\right)} = N_D$$

$$\frac{N_C}{N_D} = e^{\frac{E_C - E_F}{KT}}$$

$$\ln\left(\frac{N_C}{N_D}\right) = \frac{E_C - E_F}{KT}$$

$$\boxed{E_F = E_C - KT\ln\left(\frac{N_C}{N_D}\right)}$$

Fermi level is just below the conduction band.

fermi level in p-type semiconductor

$$p = N_A$$

$$N_V \, e^{-\left(\frac{E_F - E_V}{KT}\right)} = N_A$$

$$\frac{N_V}{N_A} = e^{\frac{E_F - E_V}{KT}}$$

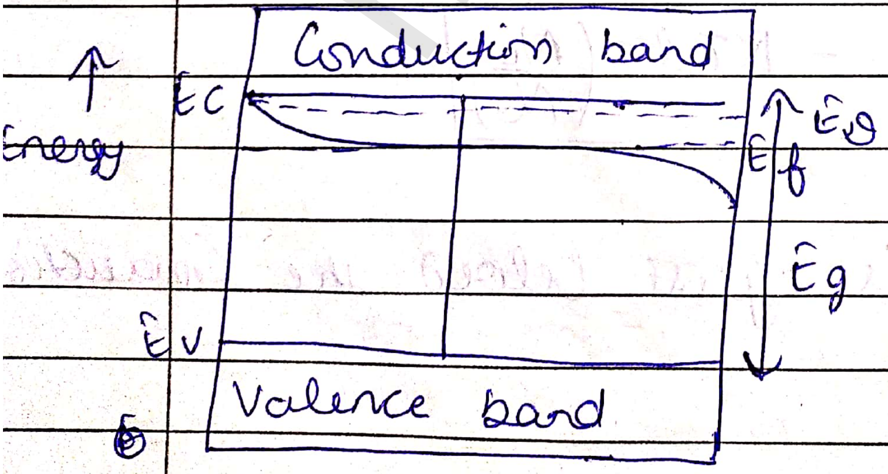
$$\ln\left(\frac{N_V}{N_A}\right) = \frac{E_F - E_V}{KT}$$

$$KT \ln\left(\frac{N_V}{N_A}\right) = E_F - E_V$$

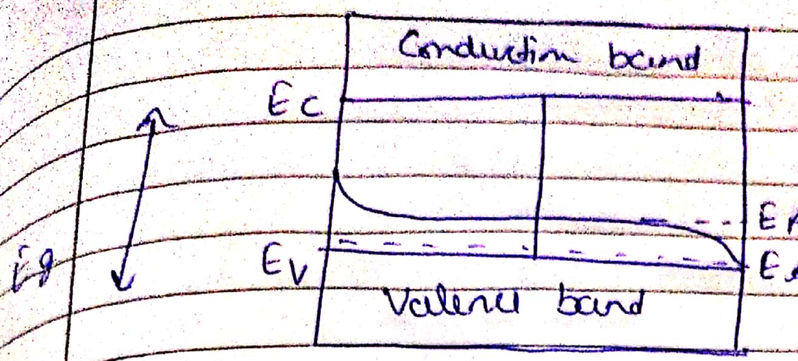
$$\boxed{E_F = E_V + KT \ln\left(\frac{N_V}{N_A}\right)}$$

fermi level is above the valence band

(c) It is concluded that as the temp. of p-type & N-type semiconductor increases E_F progressively move towards the middle of the forbidden energy gap.



N-type



Law of Mass action

Under thermal equillibrium for any semiconductor, the product of the no. of holes and no. of electrons is constant and is independent of the amount of donor and acceptor impurity doping. This relation is known as law of mass action.

$$\boxed{n \cdot p = n_i^2}$$

while considering the conductivity of the doped semiconductors, only the dominant majority charge carriers have to be considered.

N_D = no. of donor atoms in an N-type semiconductor

$$n_N = N_D$$

$$p_N = \frac{n_i^2}{n_N}$$

$$= \frac{n_i^2}{N_D}$$ (in N type)

$p_p = N_A$

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

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

$\sigma_N = q n_n \mu_n$

$\boxed{\sigma_N = q N_D \mu_n}$

$\sigma_P = q p_p \mu_p$

$\boxed{\sigma_P = q N_A \mu_p}$

The doping of intrinsic semiconductor increases its conductivity.

Variation in semiconductor parameters with temp.

$n = N_C e^{-(E_C - E_F)/KT}$

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

$np = N_C N_V e^{-(E_C - E_V)/KT}$

$E_G = E_C - E_V$

$np = N_C N_V e^{-E_G/KT}$

$np = n_i^2$ (Acc. to mass action law)

$$n_i^2 = A_0 T^3 e^{-E_G/KT}$$

A_0 = a constant
T = temp in K
E_G = forbidden energy gap
K = boltzman's constant

In an intrinsic semiconductor, as the temp. rises the intrinsic concentration (n_i) increases & conductivity (σ) also increases.

The increase in n_i^2 with temp. has an effect on the charge densities in extrinsic semiconductor.

(i) In N type no. of holes increases with temp.
(ii) In P type no. of free e^- increases with temp.

(·) The mobility of semiconductors decreases with rise in temp.

(·) No. of hole electron pair increases with rise in temp., while its mobility decreases and conductivity increases

(·) ~~energy~~ The conductivity of extrinsic semiconductor decreases with temp. as the no. of majority carriers are almost constant and mobility decreases

(c) The energy gap decrease with increase in temp.

$$E_G(T) = E_{G(0)} - \beta T$$

β is a constant whose value depends on nature of material.

Drift Current

The drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

$$J_n = \underline{q n \mu_n E} \text{ A/cm}^2$$
$$J_p = \underline{q p \mu_p E} \text{ A/cm}^2$$

diffusion current

In a semiconductor material, the charge carriers have the tendency to move from the region of higher concentration to that of lower concentration of the same type of charge carriers.

Thus, the movement of charge carriers takes place resulting in current called diffusion current diffussion current density due to holes:

$$J_p = -q \mathcal{D}_p \frac{dP}{dx} \quad A/cm^2$$

due to electrons

$$J_n = q \mathcal{D}_n \frac{dn}{dx} \quad A/cm^2$$

where $\frac{dP}{dx}$ & $\frac{dn}{dx}$ are concentration gradients for electrons & holes.

$\mathcal{D}_n$ & $\mathcal{D}_p$ are diffussion coefficients in cm^2/s

Total Current

Sum of drift current + diffussion current

total current density due to holes

$$J_p = qP\mu_p E - q\mathcal{D}_p \frac{dP}{dx}$$

total current density due to e^-

$$J_n = qn\mu_n E + q\mathcal{D}_n \frac{dn}{dx}$$

$$\boxed{V_T \text{ (thermal voltage)} = \frac{KT}{q}}$$

$$\boxed{\frac{\mathcal{D}_P}{\mu_P} = \frac{\mathcal{D}_N}{\mu_n} = \frac{KT}{q} = V_T}$$

Einstien's relationship

Carrier life time

It is defined as the time for which a charge carrier will exist before recombination with a carrier of opposite charge.

Consider N type semiconductor having thermal equillibrium concentration P_o and n_o of holes & e^-. When a specimen is illuminated electron-hole pairs are generated uniformly throughout the medium This causes the concentration of holes and electrons to increase from P_o and n_o.

$$\frac{dP}{dt} = G - R$$

G is the generation rate of minority carriers & which is a function of temp. So at constant temp. G is constant

R = decreases in hole (minority) concentration

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

τ_p = mean life time of hole

under steady state conditions $\frac{dP}{dt} = 0$

$$\& \quad G = \frac{P_o}{\tau_p}$$

$$\text{So} \quad \boxed{\frac{dP}{dt} = \frac{P_o - P}{\tau_p}}$$

A similar eqⁿ can be derived for P type Semiconductor

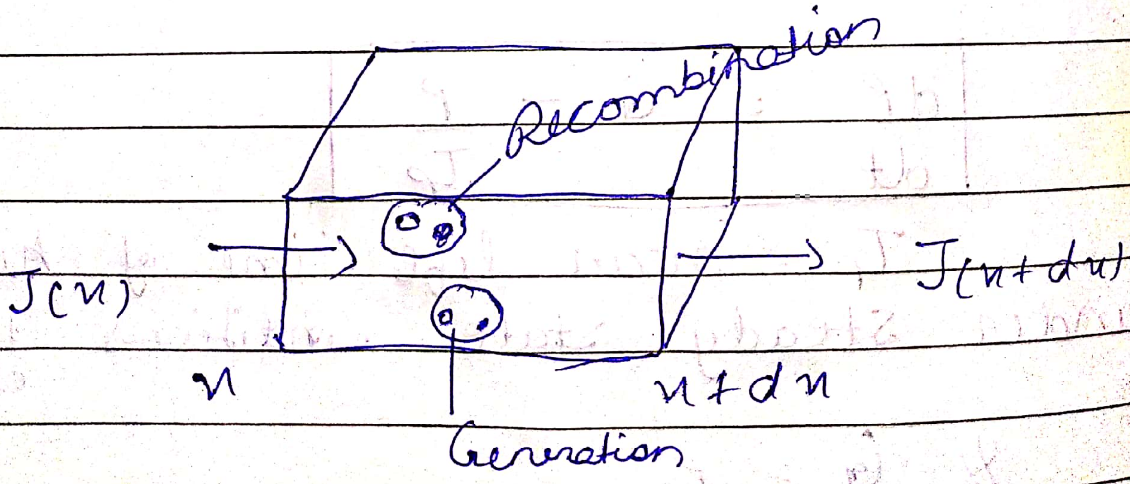
$$\boxed{\frac{dn}{dt} = \frac{n_0 - n}{\tau_n}}$$

τ_n = mean life time of electrons

Continuity Equation
The fundamental law governing the flow of charge is called the continuity equation.
law of conservation of charge

drift → electric field
Diffussion of charge Carriers - concentration gradient
generation → thermal energy, Illumina
Recombination → of electrons & holes.

n - type semiconductor material



$J_{n(x)}$ = rate of e^- flow into the block
$J_{n(x+dx)}$ = rate of e^- flow out of block
G_n = Rate of generation of e^-
R_n = Rate of e^- recombination

overall rate of e^- increase/charge carriers

$$G_n = \frac{n_0}{\tau_n}, \quad R_n = \frac{n_r}{\tau_n}$$

increase in no. of charge carriers/sec

$$= \frac{\partial n}{\partial t} \times A\,dx = J_{(x+dx)} - J_{(x)} + G - R$$

$$\frac{\partial n}{\partial t} \times A\,dx = \frac{J_{n(x)} \times A}{-q} - \frac{J_{n(x+dx)} \times A}{-q} + (G_n A\,dx - R_n A\,dx)$$

$$J_{n(x+dx)} = J_{n(x)} + \frac{\partial J_n}{\partial x} dx$$

$$\boxed{\frac{\partial n}{\partial t} = \frac{\partial J_n}{\partial x(q)} + (G_n - R_n)}$$

$$\boxed{\frac{\partial p}{\partial t} = -\frac{1}{(q)} \frac{\partial J_n}{\partial x} + (G_p - R_p)}$$

J_n = total e^- current density
= drift current density + diffussion current density

$$\boxed{J_n = q \mu_n n E + q D_n \frac{\partial n}{\partial x}}$$

Total hole current density

$$\boxed{J_p = q\mu_p p E - q D_p \frac{\partial p}{\partial x}}$$