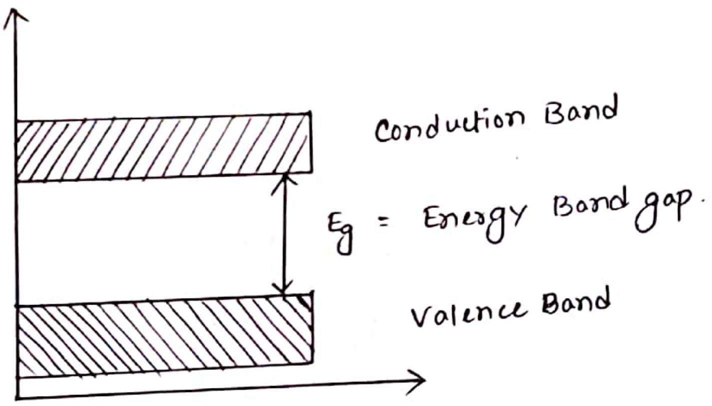
Semiconductors in Equilibrium:

* Define Bandgap.

→ **Bandgap:** In semiconductors and insulators, electrons are confined to a no. of bands of energy and forbidden from other regions. Band gap refers to the energy difference between the top of the valence band and bottom of conduction band. Electrons are able to jump from one band to another.



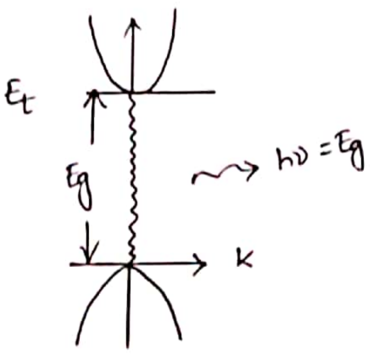
* Types of Semiconductor:

1. Direct Semiconductor
2. Indirect Semiconductor
3. Intrinsic Semiconductor
4. Extrinsic Semiconductor

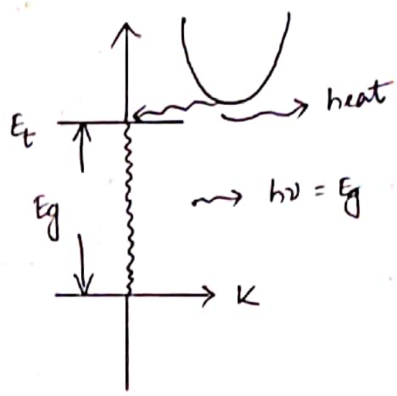
* Define - 1. Direct S.C.
2. Indirect S.C.
3. Intrinsic S.C.
4. Extrinsic S.C.

1. <u>Direct Semiconductor</u>: In a direct semiconductor, an e^- in the conduction band can fall to an empty state in the valence band, giving off the energy difference E_g as a photon of light.

The bandgap is called direct, if the momentum of e^- and holes is the same in both the conduction band and the valence band. An e^- can directly emit a photon.



Direct



2. <u>Indirect Semiconductor</u>: In an indirect semiconductor, an e^- can not fall directly to the valence band maximum but must undergo a momentum change as well as changing its energy.

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At first, it may go through some definite state (E_t) within the bandgap releasing energy as heat and then fall into valence band giving off energy as photon.

3. Intrinsic Material :

An intrinsic semiconductor is that which is pure enough that impurities do not affect its electrical behaviour. In this case, all carriers are created due to thermally or optically excited electrons from the full valence band into the empty conduction band. Thus equal no. of electrons and holes are present in an intrinsic semiconductor.

4. Extrinsic Material :

An extrinsic semiconductor is that which has been doped with impurities to modify the number and type of free charge carriers.

* Define Fermilevel

→ Fermilevel : Fermilevel is the highest energy state occupied by electrons in a material at absolute zero temparature. When temparature rises, electrons start to exist in higher energy state. At p-type, density of unfilled state is more, so more electrons can be accomodated at lower energy state.

In n-type, density of occupied state is more, so more electrons can be accomodated at higher state.

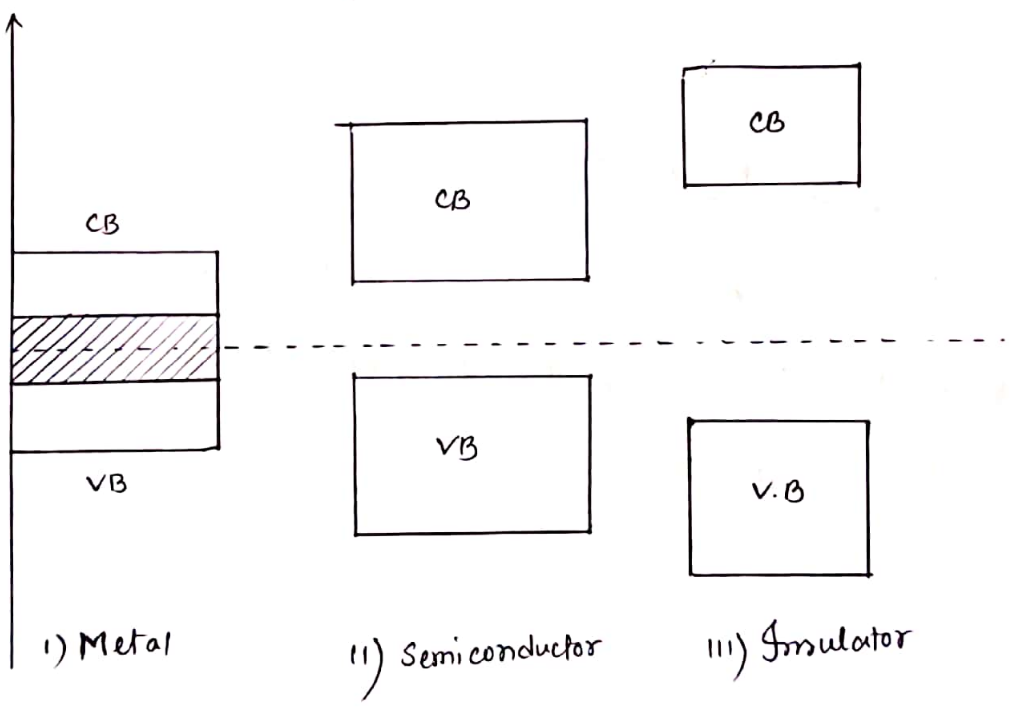


Fig. : Fermilevel in different materials.

* Fermilevel in n-type Semiconductor

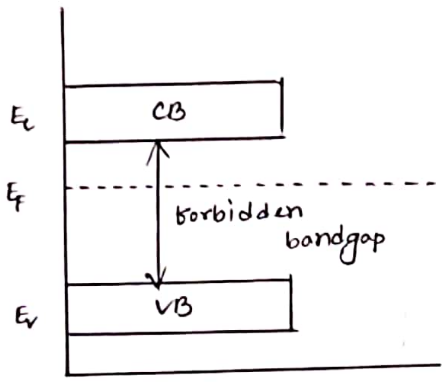
→ Pentavalent impurity is added, (doping) : each pentavalent donates a free electron.

→ Addition of pentavalent impurity creates a large no. of e^- in the conduction band.

∴ At room temparature, no. of e^-_{CB} > no. of h_{VB}

$$\therefore \quad P(e^-_{CB}) > P(h_{VB})$$

this probability of occupation of energy levels can be represented in terms of fermilevel.



Therefore, the fermilevel in the n-type lies close to the conduction band.

For n-type,

$$E_F = E_C - K_B T \log \frac{N_C}{N_D} \quad \text{—— (1)}$$

where,

N_C = effective density state of conduction band

N_D = Concentration of donor atoms

E_F = Fermilevel

E_C = Conduction Band

E_V = Valence Band

K_B = Boltzman constant

T = absolute temp.

* Fermilevel in p-type Semiconductor :

- Trivalent impurity is added
- Creates a hole in VB and gets ready to accept an e^-.
- Ultimately creates a large no. of hole in V.B.

At room temp.

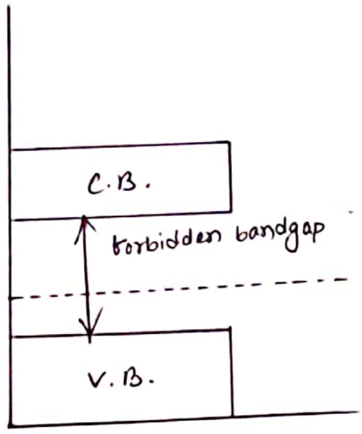
no. of hole in VB > no. of e^- in C.B.

$$\therefore P(h_{VB}) > P(e^-_{CB})$$

$\therefore$ fermilevel in the p-type lies close to V.B.

At p-type,

$$E_F = E_v + k_B T \log \frac{N_v}{N_A}$$



where,

N_v = effective density state in V.B.

N_A = concentration of acceptor atoms.

Fermi - Dirac Distribution or, Fermi - Dirac Probability Function

- Also called fermi function, provides the probability of occupancy of energy levels by ions.

So, F_E as a function of temparature is given,

$$F_E = \frac{1}{1 + e^{\frac{E - E_F}{kT}}}$$

where,

k = Boltzman constant

E_F = Fermi energy

$F_E = 1$; if energy level is filled by e^-

0 ; for empty energy level

Q. "There is no discontinuity in the equilibrium Fermi level."
— Explain

Or, show that "Fermi function is symmetrical about E_F for any temperature?

Prove : The Fermi-Dirac probability for e^- is given by,

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

where,

K = boltzman constant

$f(E)$ = Fermi-Dirac Distribution function

E_F = Fermi Energy

At $T = 0\,K$;

If $E < E_F$;

$$e^{(E-E_F)/KT} = e^{-\infty} = 0$$

$$\therefore f(E) = \frac{1}{1+0} = 1$$

If $E > E_F$;

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

$$\therefore f(E) = \frac{1}{\infty} = 0$$

So, at 0 K every available energy state up to E_F is filled with e^- and all states above E_F are empty.

At $T > 0\,K$

If $E = E_F$;

$$f(E_F) = \frac{1}{1 + e^{(E_F - E_F)/kT}} = \frac{1}{2}.$$

Thus, at fermilevel, the probability of quantum state being occupied by electrons is $\frac{1}{2}$.

Again, with $T > 0\,K$, there is a non-zero probability that, some energy state above E_F is occupied by e^- and below E_F will be empty. i.e. some electrons have jumped to higher energy level with increasing thermal energy.

Therefore, the probability of an energy level above E_F being occupied increases as the temparature increases and the probability of a state below E_F being empty increases as the temparature increase.

Hence,

at $T = 0\,K$

for $E < E_F$; $f(E) = 1$ &

$E > E_F$; $f(E) = 0$

So, w.r.t. E_F, $f(E)$ is either 1 or 0. So it is symmetric.

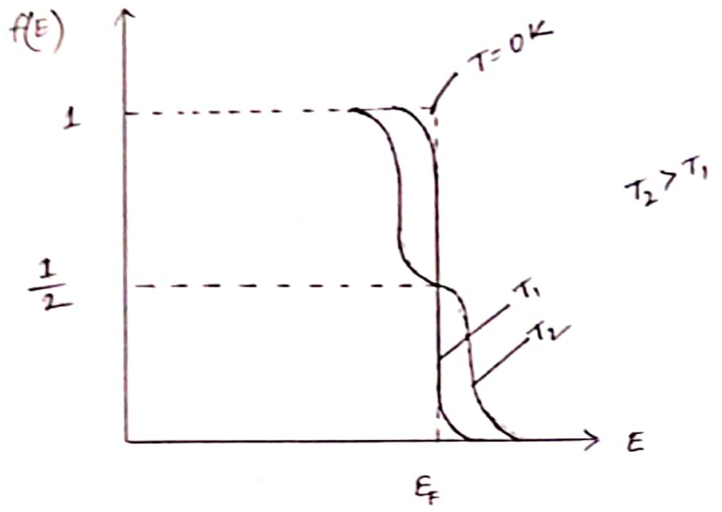
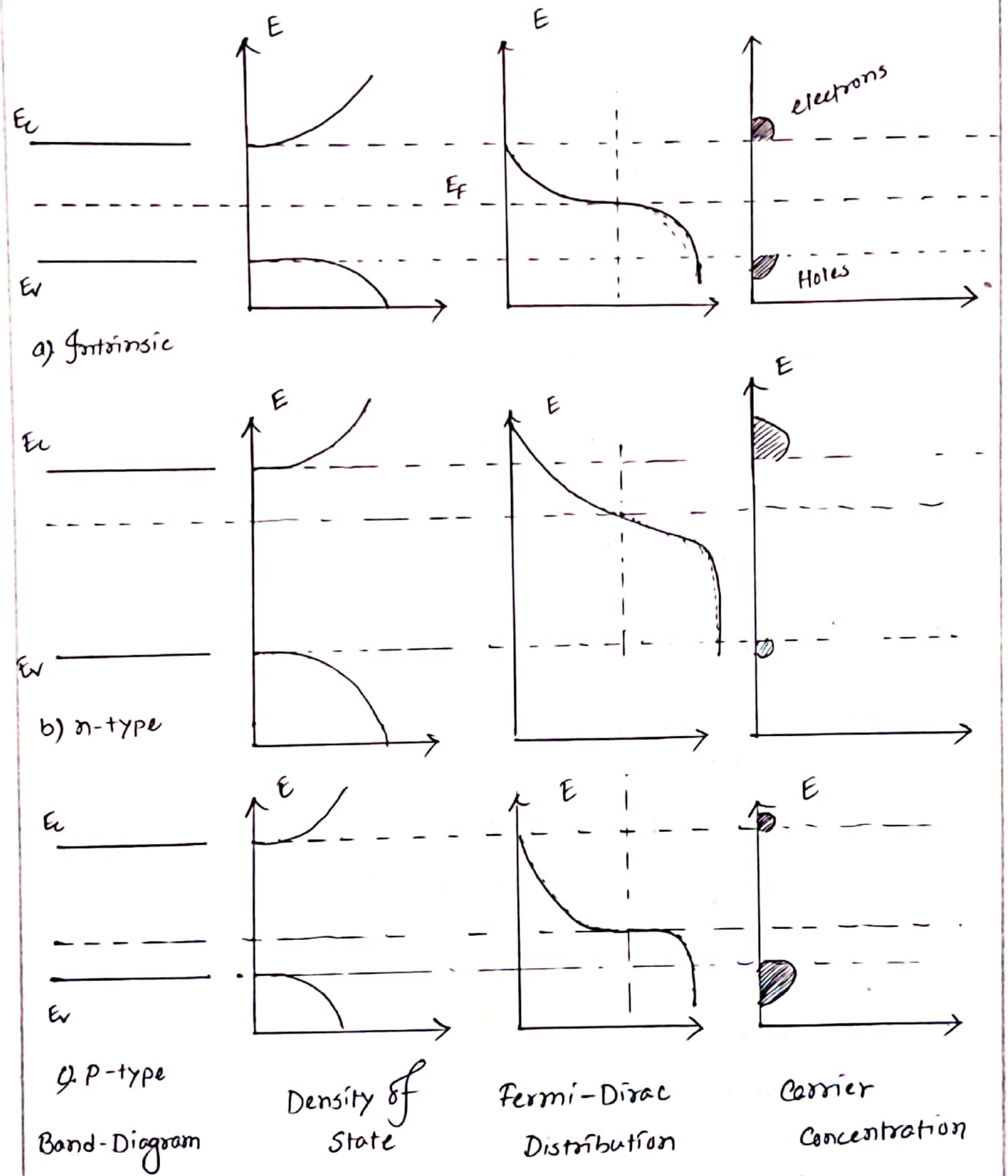


Fig. : The Fermi-Dirac Distribution function.

Draw the schematic band diagram, density of states, Fermi-Dirac Distribution & carrier concentration for n-type as well as p-type materials.



Derive the relation, $n_0 p_0 = n_i^2$.

Prove: The Fermi Distribution function can be used to calculate the concentration of e^- and holes in a semiconductor if the densities of available states in the valence and conduction bands are known.

The concentration of e^- in conduction band,

$$n_0 = \int_{E_c}^{\infty} f(E)\, N(E)\, dE \qquad \text{—— (1)}$$

Where,

$N(E)dE$ = density of states (cm^{-3}) in energy range dE.

$N(E)$ can be calculated by quantum mechanics and Pauli's exclusion principle.

Again, $N(E) \propto E^{1/2}$

so; $N(E) \uparrow$; when $E \uparrow$

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

so, $f(E) \downarrow$; when $E \uparrow$

So, $f(E)N(E)$ decreases rapidly above E_c and very few e^- occupy energy states for above CB edge.

Similarly, probability of finding hole in VB decreases rapidly below E_v and most holes occupy states near the top of VB.

so. from equ (1) ;

$$n_0 = N_c f(E_c) \quad \text{--- (2)}$$

N_c = effective density of state

$f(E_c)$ = probability of occupancy at E_c.

At room temp.

$$KT = 0.026 \text{ eV}$$

$$\& \quad E_c - E_F >> KT$$

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

Putting the value in eqn (2) ;

$$n_0 = N_c e^{-(E_c - E_F)/KT} \quad \text{--- (A)}$$

Again, $$N_c = 2\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2} \quad \text{--- (3)}$$

where, m_n^* = effective mass for e^-.

Similarly the concentration of holes in V.B.,

$$P_0 = N_v e^{-(E_F - E_v)/KT}$$

$$= N_v [1 - f(E)] \quad \text{--- (4)}$$

Now, $$1 - f(E_c) = \frac{1}{1 + e^{(E_F - E_v)/KT}} = e^{-(E_F - E_v)/KT}$$

$$\therefore P_0 = N_v e^{-(E_F - E_v)/KT} \quad \text{--- (B)}$$

and, $$N_v = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} \quad \text{--- (5)}$$

Now, eqn A & B are valid for intrinsic and extrinsic both.

For intrinsic material,

E_F lies near the middle of B.G. and called E_i.

Therefore, intrinsic e^- & hole concentration,

$$n_i = N_c e^{-(E_c - E_i)/kT} \quad \text{—(6)}$$

$$p_i = N_v e^{-(E_i - E_v)/kT} \quad \text{—(7)}$$

$$\therefore n_i p_i = N_c N_v e^{-(E_c - E_v)/kT}$$

$$\Rightarrow n_i p_i = N_c N_v e^{-E_g/kT}$$

$$\Rightarrow n_i^2 = N_c N_v e^{-E_g/kT} \quad [\because n_i = p_i \text{ for intrinsic}]$$

$$\therefore n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT}$$

Again, $\because n_o p_o = N_c N_v e^{-E_g/kT}$

So, $n_i^2 = n_o p_o$ —— (Proved)

From A & 6 ; $\dfrac{n_o}{n_i} = \dfrac{e^{-(E_c - E_F)/kT}}{e^{-(E_c - E_i)/kT}} = e^{(E_F - E_i)/kT}$

$$\therefore n_o = n_i e^{(E_F - E_i)/kT}$$

From B & 7 ;

$$p_o = p_i e^{(E_i - E_F)/kT}$$