Fermi Energy Formula for an Intrinsic Semiconductor :-

In intrinsic semiconductor the conduction is due to the intrin characteristics of the crystal without impurity. The electrons are excited from the top of the valence band to the bottom of the conduction band by thermal energy. The no. of electrons excited across the gap can be calculated by Fermi-Dirac Distribution function

$$f(E) = \frac{1}{1+\exp(E-E_F)/K_BT} \quad \text{—— (1)}$$

The fermi level E_F for intrinsic semiconductor lies midway in forbidden gap as shown in fig. The probability of finding an electron here is 50%. Then $(E-E_F)$ in eqn. (1) is equal to $E_g/2$, where E_g is magnitude of energy gap.

For exp. Silicon has $E_g = 1.1\,eV$, so $(E-E_F) = .55\,eV$, which is twen times higher than thermal energy $K_BT = .026\,eV$.

The factor unity in denominator can be ignored, so the probability $f(E)$ of an electron occupying energy level E

$$f(E) = \exp(-E_g/2K_BT) \quad \text{—— (2)}$$

So for the number of electron (n) promoted across gap

$$n = N \cdot \exp(-E_g/2K_BT) \quad \text{—— (3)}$$

where N = no. of electrons available for excitation for top of valence band.

The electron across the gap leaves some vacant electron site in valence band., These are called holes. An intrinsic semiconductor have equal no. of holes in valence band and electrons in conduction band, $n_e = n_h$.

Under externally applied field the excited electrons can accelerate using the vacant states available in conduction band.

At the same time holes in valence band also move but in opposite direction of electrons. Conductivity of intrinsic semiconductor depends upon charge carriers n_e and n_h. Like drift velocity in case of metal we have mobility of conduction electron and holes μ_e and μ_h as drift veloci(
So the conductivity σ of intrinsic semiconductor as:

$$\sigma_i = n_e e \mu_e + n_h e \mu_h \qquad \text{—— (4)}$$

where e = electronic charge and n_e and n_h are concentratio of electrons & holes.

Fermi Level :⇒ The no. of free electrons per unit volume in an intrinsic semiconductor is

$$n = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{kT}\right)$$

The no. of holes per unit volume is an intrinsic semiconducto is

$$p = 2\left[\frac{2\pi m_h kT}{h^2}\right]^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right)$$

Since $n = p$ in intrinsic semiconductor

$$2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{kT}\right) = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right)$$

$$(m_e)^{3/2} \exp\frac{(E_F - E_c)}{kT} = (m_h)^{3/2} \exp\frac{(E_V - E_F)}{kT}$$

$$e^{2E_F/kT} = \left(\frac{m_h}{m_e}\right)^{3/2} \exp\left(\frac{E_V + E_c}{kT}\right)$$

Taking log on both sides

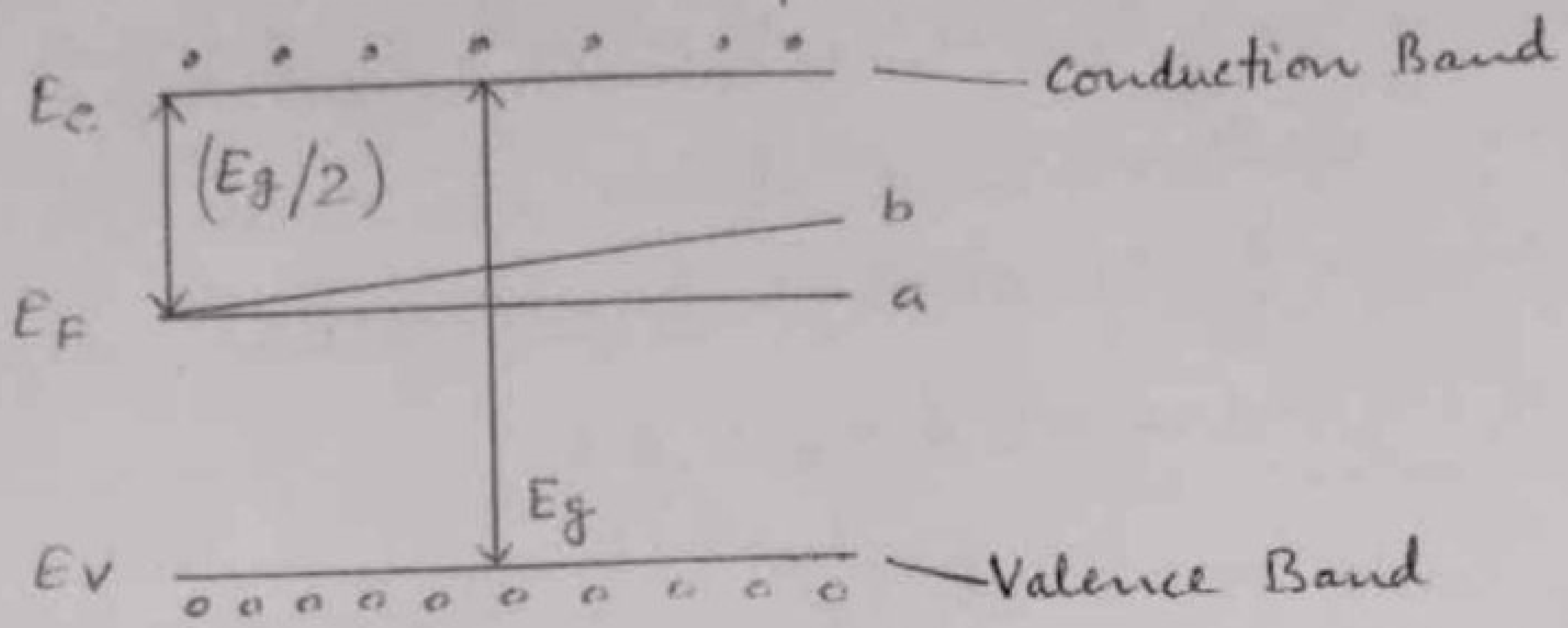
$$\frac{2E_F}{kT} = \frac{3}{2}\log_e\left(\frac{m_h}{m_e}\right) + \log_e\left[\exp\left(\frac{E_V + E_c}{kT}\right)\right]$$

$$\frac{2E_F}{kT} = \frac{3}{2}\log_e\left(\frac{m_h}{m_e}\right) + \left(\frac{E_V + E_c}{kT}\right)$$

$$E_F = \frac{3kT}{4}\log_e\left(\frac{m_h}{m_e}\right) + \left(\frac{E_V + E_c}{2}\right)$$

If we assume $m_e = m_h$ $\qquad E_F = \left(\frac{E_V + E_c}{}\right) \qquad (\log_e 1 = 0$

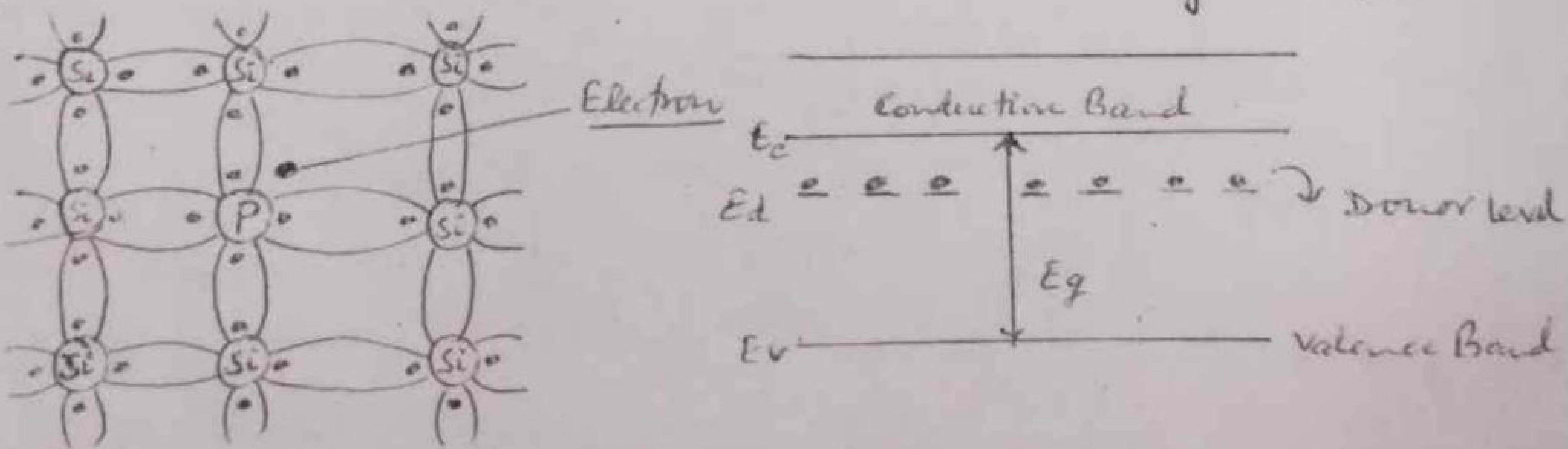
Thus the fermi level is located half way between valence and and conduction band and is independent of temperature. Since $m_h > m_e$, E_F is just above the middle and rise slightly with increase in temperature.



Position of Fermi level in an intrinsic Semiconductor at various temperature, (a) At T=0, (b) As temp increases E_F shift

<u>N-type of Semiconductor</u> :⇒ When small amount of pentavalent impurity such as P, As, Sb is added to the intrinsic semiconductor, n-type semiconductor is formed.

When fifth column element phosphorus substitute for a Silicon atom, four of the five electrons in the outermost orbit of Phosphorus atom take part in tetrahedral bonding with four silicon atom. The fifth electron cannot take part and it is loosely bound. It revolve around the +ve charged P ion.



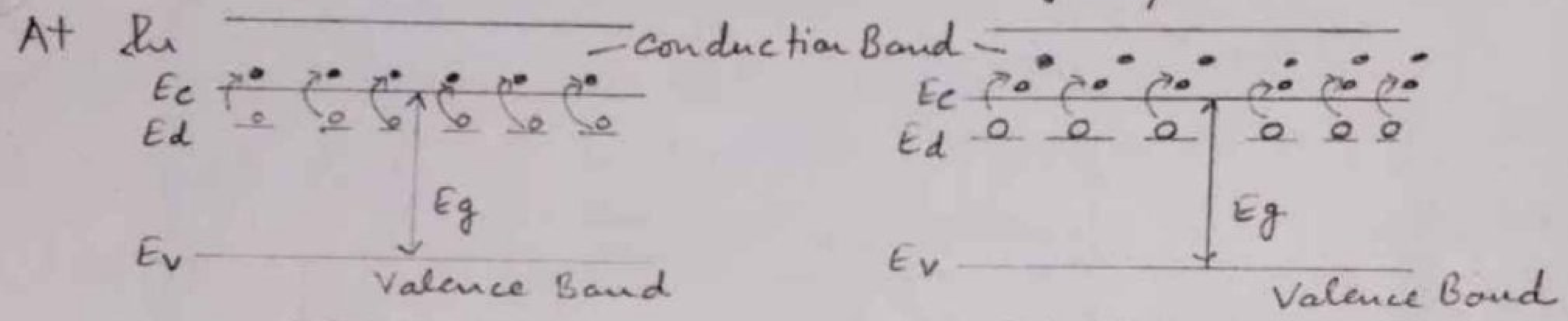
The electron of phosphorus atom is moving in the electric field of Silicon crystal and not in free space.
this brings in dielectric constant of crystal into orbit calcul and the radius of electron orbit here turn out to be very

large about 80Å. Such large orbit means fifth electron free and is at energy level close to conduction band.

At 0K the electronic system is in its lowest state, all the valence electron will be in valance band and all phosphorus atom will unionised.

In energy level digram the energy level of fifth electron is called donor level. The energy level of donor atoms are very close to bottom of conduction band.

Most of donor level electrons are excited into conduction band at room temperature & become majority carriers.



(a) At T > 0K (b) At T = 300K

At high thermal energy, in addition to ionization of donor impurity atom, breaking of covalent bond give rise to electron hole pair.

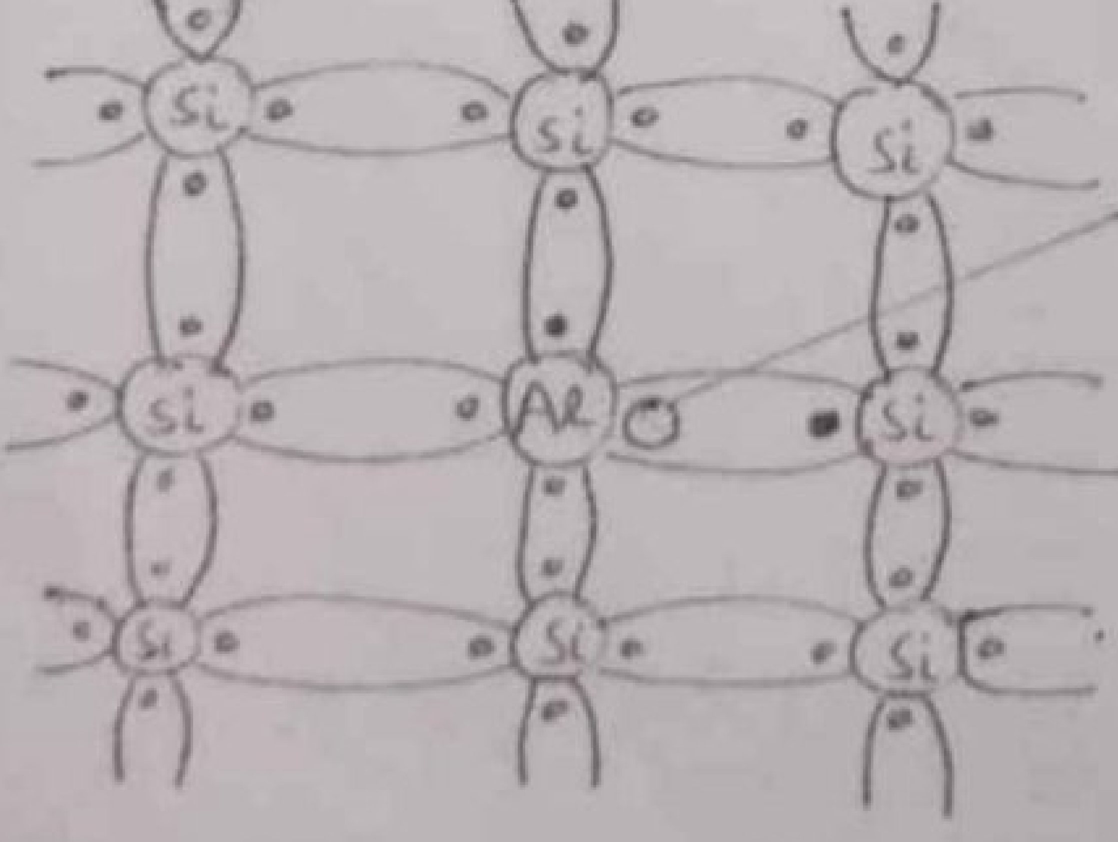
Fermi Energy :⇒

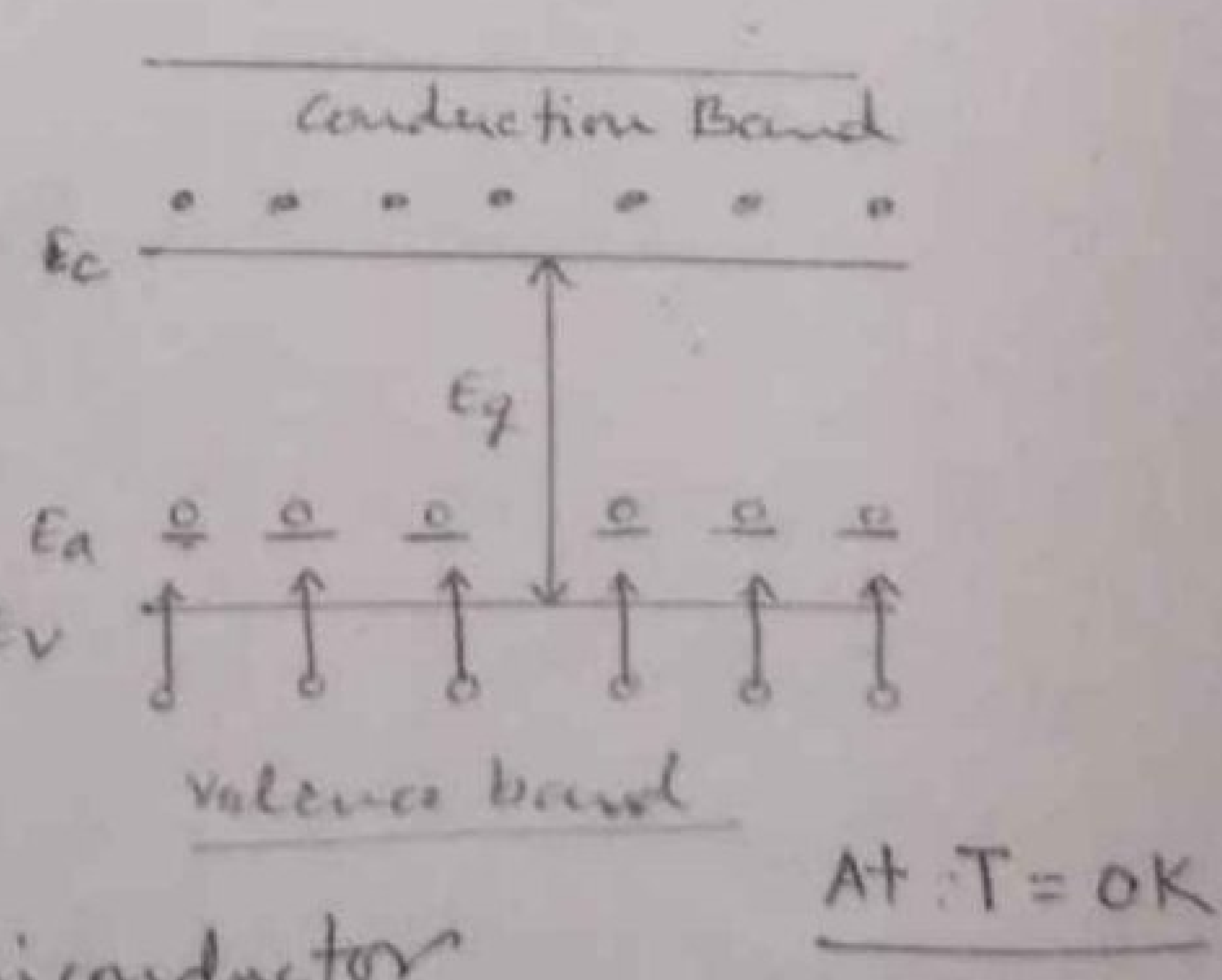
The fermi energy for n-type Semiconductor is

$$E_F = \frac{(E_c + E_d)}{2} + \frac{kT}{2} \log\left[\frac{N_d}{2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}}\right] \quad ; \quad \text{At } 0K,\ E_F = \frac{E_c + E_d}{2}$$

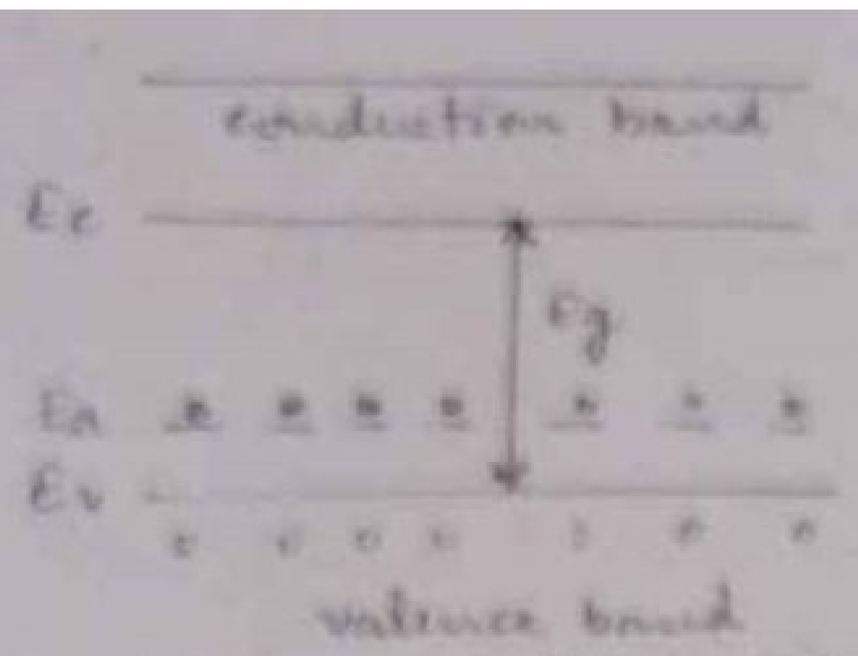
P-type Semiconductor :⇒ When trivalent impurity like Al is added to the intrinsic semiconductor, P-type semiconductor is formed. Aluminium has three electrons. While substituting for Silicon in the crystal it needs an extra electron to complete the tetrahedral bonds. The extra electron can come out only from one of the neighbouring Si atom, thereby creating a vacant electron site (hole) the Al atom with extra-electron becomes a negative charge and the holes with positive charge can considered to resolve around Aluminium atoms.

- Since the trivalent impurity accepts an electron, the energy level of this impurity atom is called acceptor level. This acceptor level lies just above valence band.
- Even at relatively low temperature, these acceptor atoms get ionized taking electrons from valence band and thus giving to holes in valence band for conduction.
- Due to ionization of acceptor atoms, only holes and no electron are created. If the temperature is sufficiently high, in addition to above process electron and holes pairs are generated due to breaking of covalent bonds. Thus holes are majority carriers and electrons are minority carriers for p-type Semiconductor

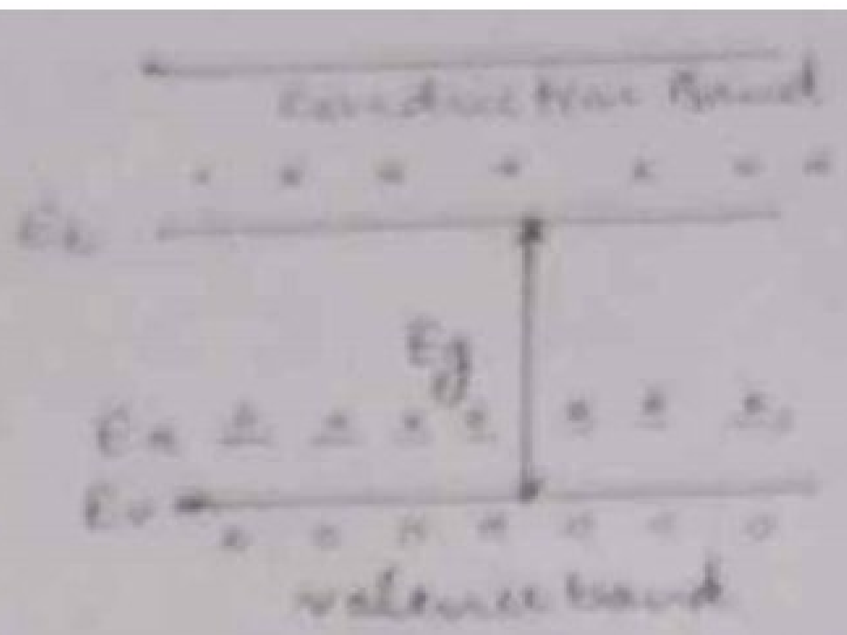




P-type Semiconductor



(a) At T > 0K



(b) At T = 300K

Fermi Energy :⇒ The Fermi energy for p-type semiconductor is

$$E_F = \left(\frac{E_v + E_a}{2}\right) + \frac{kT}{2} \log \left[\frac{N_a}{2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}}\right]$$

At 0K , $E_F = \frac{E_v + E_a}{kT}$

i.e at 0K, Fermi level is exactly at the middle of the acceptor level on the top of valence band.

Q. :⇒ Explain with sketch the variation of Fermi Level and carrier concentration with temperature in case of P and N type semiconductor for high and low doping levels.

Ans:- Variation of Fermi Level with temperature (N-type) :⇒

The Fermi Energy is given by

$$E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{kT}{2} \log \frac{N_d}{2\left[\frac{2\pi m_e kT}{h^2}\right]^{3/2}},$$

let $2\left[\frac{2\pi m_e kT}{h^2}\right]^{3/2} = N_x$

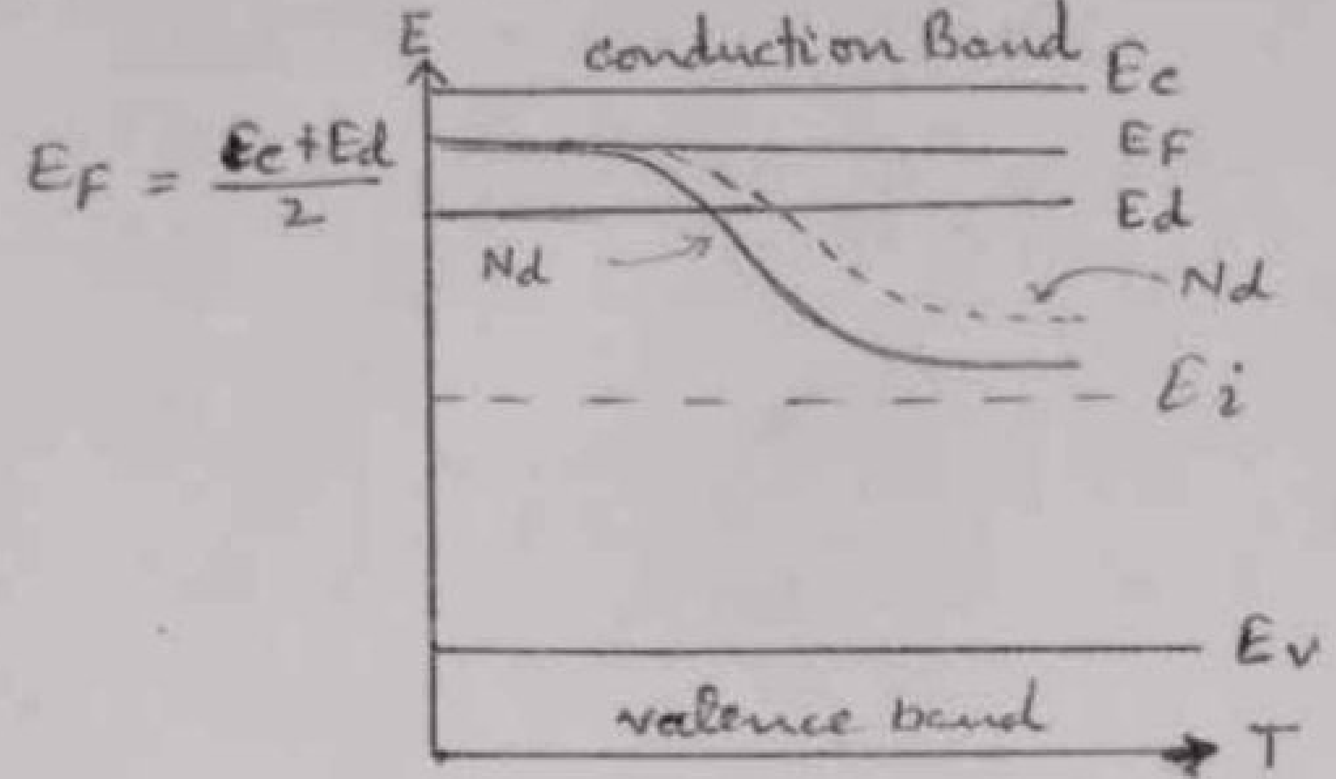
$$\therefore E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{kT}{2} \log\left(\frac{N_d}{N_x}\right) = \left(\frac{E_d + E_c}{2}\right) - \frac{kT}{2} \log\left(\frac{N_d}{N_x}\right)^{-1}$$

$$= \left(\frac{E_d + E_c}{2}\right) - \frac{kT}{2} \log\left(\frac{N_x}{N_d}\right)$$

→ As T increases, Fermi level drops. For a given temperature the Fermi level shift upward as concentration increases.

→ Above eqn. show that E_F decreases with increases as tempt.

→ As the temperature increased, more donor atom are ionized. For a particular temperature all donor atom are ionized. Further increase in temperature generate electron-hole pair due to breaking of covalent bond, & material behave as intrinsic semiconductor.



Variation of Fermi level with donor concentration with temperature.

Variation of Fermi level with temperature (P-type) :⇒

The fermi energy is given by

$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{kT}{2}\log\left[\frac{N_a}{2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}}\right] = \left(\frac{E_v+E_a}{2}\right) - \frac{kT}{2}\log\left(\frac{N_a}{N_y}\right)$$

where $N_y = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$

$$E_F = \left(\frac{E_v + E_a}{2}\right) + \frac{kT}{2}\log\left(\frac{N_a}{N_y}\right)$$

→ The above eqn. shows that E_F increases as the temperature increase. As the tempt. increases more & more acceptor atom are ionized.

→ For a particular temperature all the acceptor atoms are ionized.

→ Further increases in temperature generates the electron-hole pair due to breaking of covalent bond and the material behave as intrinsic semi-conductor.