In Intrinsic S/c materials.

$n = p = n_i$

$$\therefore \boxed{\sigma_{ins} = n_i e (\mu_n + \mu_p)}$$

* For n-type semiconductor material -

$$\boxed{\sigma_n = n e \mu_n}$$

** for p-type semiconductor material -

$$\boxed{\sigma_p = p.e.\mu_p.}$$

***Prob:1** Assuming standard values for silicon, findout resistivity of silicon and minority carrier concentration if a donar type impurity is added to extant of 1 in 10^8 Atom

Given, $n_i = 1.5 \times 10^{10} / cm^3$

$\mu_n = 1300\ cm^2 /$ volt-sec

Density of atom in $Si = 5 \times 10^{22}$ atoms / cm3

Solution:

$$n \simeq N_D = \text{No. of donars} = \frac{5 \times 10^{22}}{10^8}$$

$$= 5 \times 10^{14}$$

$$\text{minority Carrier Conc.} = \frac{n_i^2}{N_D}$$

$$p = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{14}}$$

$$p = 4.5 \times 10^5 \ / cm^3$$

conductivity of N-Type S/c

$$\sigma_N = n \mu_n e$$

$$\therefore \rho = \frac{1}{\sigma_N} = \frac{1}{n.\mu_n.e} = \frac{1}{5 \times 10^{14} \times 1300 \times 1.6 \times 10^{-19}}$$

$$= \underline{0.117\ \Omega\, cm}$$

* **Problem 2:-** A donar type impurity is added to the extant 1 atom per 10^6 atoms of an intrinsic silicon.

Given conc. of Si. atoms $= 5 \times 10^{22} / cm^3$

$n_i = 1.5 \times 10^{10} / cm^3$

$\mu_n = 1300\ cm^2 / volt \cdot Sec$

Find.

(a) Resulting donar atom concentration.

(b) conductivity of dopped silicon sample.

(c) If silicon sample is 0.5 cm long and having cross-section area $(50 \times 10^{-4})^2\ cm^2$ find it's resistance.

* **Solution:-** (a) Resulting donar atom concentration.

$$N_D = \frac{5 \times 10^{22}}{10^6} = 5 \times 10^{16}$$

(b) conductivity of dopped silicon.

$$\sigma_n = n\,\mu_n\,e$$

$$= N_D \cdot \mu_n \cdot e$$

$$= 5 \times 10^{16} \times 1300 \times 1.6 \times 10^{-19}$$

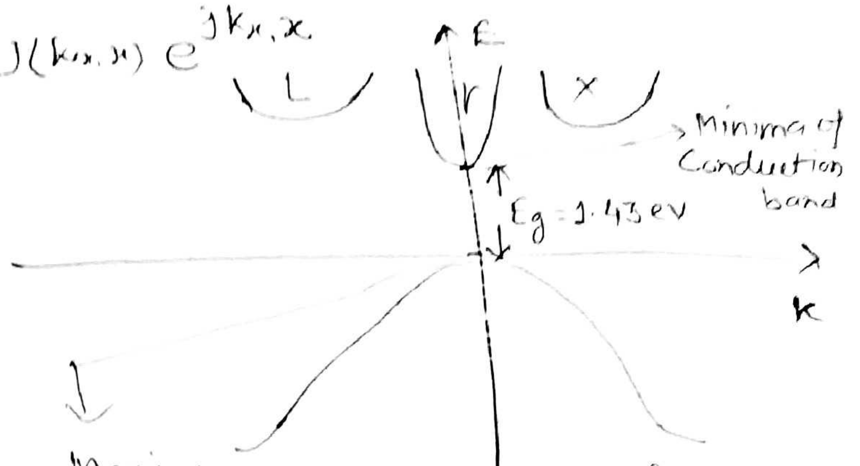
$$= 10.413\ (\Omega\,cm)^{-1}$$

(c) $$R = \frac{\rho\, l}{A} = \frac{l}{\sigma A} = \frac{0.5\,cm}{10.413 \times (50 \times 10^{-4})^2}$$

$$= 1.920\ \Omega$$

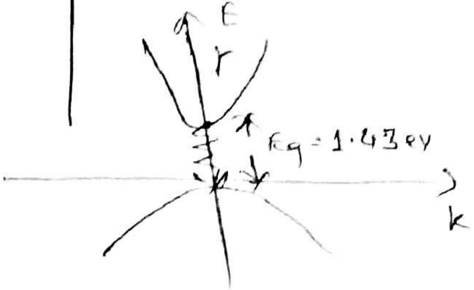
* **Direct Band gap & Indirect band gap S/C** :- The electrons moves in the crystal as a plane wave. Suppose electron moving in x- direction with a poupagation vector k. The space dependent wave equation is given by:-

$$\psi_x(x) = U(k_x, x)\, e^{jk_x.x}$$



Let us plot a curve b/n Energy E Vs. wave vector k. This diagram is called E-k diagram.

The distance between maxima of valence band and minima of conduction band is called energy band gap. The figure shows E-k diagram of GaAs. Here minima of conduction band and maxima of valence band are allinged. The transition of electrons occures from conduction band to valence band without any change change in the value of ($k=0$). The transition of electron is occure due to tendency of electron comming from upper state to lower state.



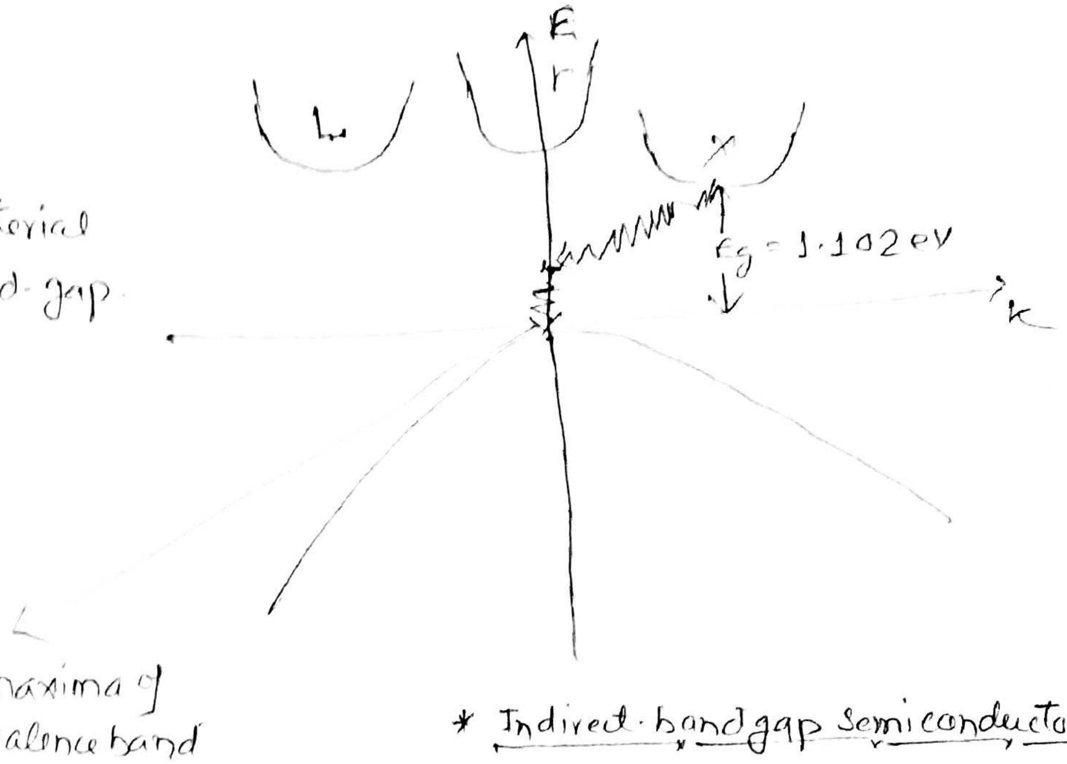
This transition is called direct transition and radiated energy is in the range of visible light. This type semiconductors are called direct band gap semiconductors or Direct Semiconductors. The compound semiconductors are always direct semiconductors. The direct semiconductors are used for optical application.

[P.T.O.]

Again we consider example of Si, the E-k diagram of silicon is shown in the figure. In this diagram we see that the minima of conduction band and maxima of valence band not alligned hence transition of electrons occur's indirectly. So this type semiconductor materials are called Indirect S/C or indirect band gap semiconductor, example.

Si, Ge.

All the elemental semiconductor material are indirect band-gap semiconductors.



* Indirect band gap Semiconductor.

Effective Mass:- The energy of charge carrier is given by as bellow-

$$E = \frac{1}{2} m v^2 \quad \ldots\ldots\ldots (i)$$

where, m = mass of charge carrier in free space
v = Velocity of charge carrier.

Momentum of charge carrier can be given by

$$p = mv$$
$$= \hbar k$$

where, $\hbar$ = Planck's Constant
k = wave Vector.

Hence equation (i) becomes:-

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

$$\therefore \frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

$$\therefore m = \frac{\hbar^2}{d^2E/dk^2} \Rightarrow \boxed{m^* = \frac{\hbar^2}{d^2E/dk^2}}$$

Effective mass :-

d^2E/dk^2 = Carvalue of valley

Ge.	Si.
$m_n^* = 0.55\, m_o$	$m_n^* = 1.1\, m_o$
$m_p^* = 0.37\, m_o$	$m_p^* = 0.56\, m_o$

$m_o = 9.1 \times 10^{-31}$ kg

Donar & Acceptor Binding Energy :-

for donar:-

$$E = \frac{m_n^* q^4}{8(\epsilon_o \epsilon_r)^2 \hbar^2}$$

where,
ϵ_o = Permittivity of free space
ϵ_r = Relative Permittivity
$= 8.85 \times 10^{-12}$

for Acceptor :-

$$E = \frac{m_p^* q^4}{8(\epsilon_o \epsilon_r)^2 \hbar^2}$$

$\hbar$ = Plank constant = 6.63×10^{-34}.

Prob: 3 Calculate approximate donar binding energy for germanium.

Given,

$\epsilon_r = 16$, Effective mass of electron,

$m_n^* = 0.12\, m_0$

$m_0 = 9.11 \times 10^{-31}$ Kg

$$E = \frac{m_n^* q^4}{8(\epsilon_0 \epsilon_r)^2 \hbar^2}$$

$$= \frac{0.12 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19}}{8(16 \times 8.85 \times 10^{-12})^2 \times 6.63 \times 10^{-34}}$$

$$= 1.02 \times 10^{-21}\ \text{J}$$

$$= 0.0064\ \text{eV}$$

* **Fermi - Dirac distribution** :- The distribution of electrons over a range of allowed energy levels at thermal equilibrium is given by -

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

where,

E_f = fermi energy of electron

E = Energy of electron

k = Boltzman Constant = 1.38×10^{-23} J/k

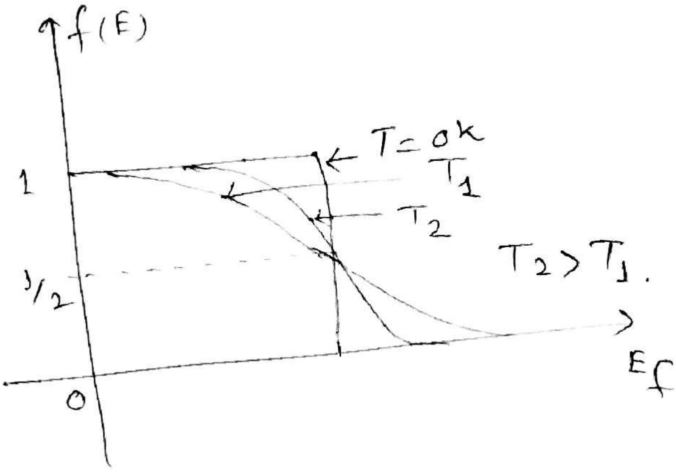
$F(E)$ = fermi - Dirac distribution function.

Fermidirac distribution function is a probability function that gives the probability that an avialable energy state at E will be - occupied by an electron at absolute temperature T.

[P.T.O.]

The fermidirac distribution Functionis Symmetrical at $E = E_f$ for any temperature

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



if $E = E_f$

$$F(E) = \frac{1}{1+e^0} = \frac{1}{1+1} = \frac{1}{2}$$

Electrons and Holes Concentration :- fermi-dirac distribution function can be used to calculate the concentration of electrons and holes in a semiconductor. The concentration of electron in conduction band can be given by as bellow -

$$n = F(E)\, N(E)\, dE \quad \text{------ (i)}$$

Hence concentration of electrons inWhole conduction band

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

$$= \int_{E_c}^{\infty} F(E)\, N(E)\, dE \quad \text{---------- (ii)}$$

where,
F (E) = fermi-Diracdistribution function
N (E) = No. of states Avialable = Density of states
d (E) = Small energy difference.

Similarly we can calculate concentration of Holes in the valence band.

$$P = \int_{-\infty}^{E_v} [1 - F(E)]\, N(E)\, dE \quad \text{...... (iii)}$$

[P.T.O.]

where $1-f(F) =$ Probability of finding of Holes.

Quanlative analysis:- Carrier concentration in different type semiconductor material

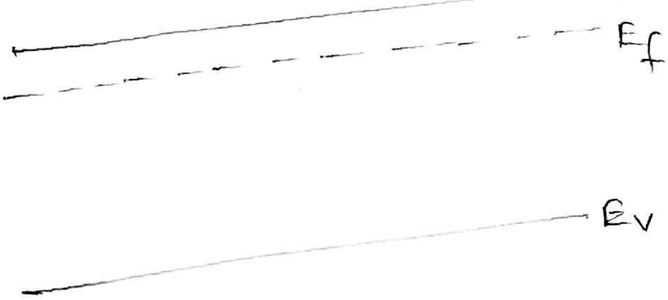
N.Type:- Concentration of electrons in conduction band can be given by.

$$n=\int_{E_c}^{\infty} F(E)\,N(E)\,dE \quad \text{- - - - - - - - (i)}$$

where $F(E)$ = fermi-Dirac distribution function &

$N(E)$ = Available states or Density of states.

The function $\int_{E_c}^{\infty} N(E)\,dE$ reffered as effective density of states & represented by N_c and located at the bottom of conduction band.



when donor type impurity is added in the intrinsic S/c material then N-Type Extrinsic S/c is formed. In this situation fermi level shifted upward.

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

$$= \frac{1}{1+e^{(E_c-E_f)/kT}}$$

Here $(E_c-E_f)/kT \gg 1$

$$\therefore F(E) = \frac{1}{e^{(E_c-E_f)/kT}}$$

$$\text{or } F(E) = e^{-(E_c-E_f)/kT}$$

The the value of $F(E)$ in equation (i), becomes

$$n = N_c \cdot e^{-(E_c-E_f)/kT} \quad \text{. . . . . (ii)}$$

The value of N_c can be calculated by using Quantum mechanics.

$$N_c = 2\left\{\frac{2\pi m_n^* kT}{h^2}\right\}^{3/2}$$

[P.T.

Hence conc. of electrons in conduction band -

$$\boxed{n = 2\left\{\frac{2\pi m_n^* KT}{h^2}\right\}^{3/2} e^{-(E_c-E_f)/KT}}$$

where, m_n^* = Effective mass of electron

K = Boltzman constant.

T = absolute temperature

2. P-Type Semiconductors :- The concentration of Holes in the valence band can be given by -

$$p = \int_{-\infty}^{E_V} [1-F(E)]\, N(E)\, dE \quad \ldots\ldots (i)$$

$[1-F(E)]$ = No. of unoccupied states.

$$\int_{-\infty}^{E_V} N(E)\, dE = N_V$$

= Effective density of states.

The p-Type Semiconductor material is formed when we added a trivalent impurity in intrinsic semiconductor. In this condision fermi level shifted bellow towards Ev.

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

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

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

[P.T.O]

or

$$n_i^2 = n \cdot p$$

$$n = N_c \cdot e^{-(E_c - E_f)/KT}$$

$$p = N_v \, e^{-(E_f - E_v)/KT}$$

$$\therefore \; n_i^2 = N_c \cdot N_v \, e^{-(E_c - E_v)/KT}$$

or $n_i^2 = N_c \cdot N_v \cdot e^{-E_g/KT}$ $\because$ $(E_c - E_v) = E_g$ = Energy band gap

$$\Rightarrow \boxed{n_i = \sqrt{N_c N_v}\, e^{-E_g/2KT}}$$

$$n_i = \left\{ 2\left[\frac{2\pi m_n^* KT}{h^2}\right]^{3/2} 2\left[\frac{2\pi m_p^* KT}{h^2}\right]^{3/2} \right\}^{1/2} e^{-E_g/2KT}$$

or

$$\boxed{n_i = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4} e^{-E_g/2KT}}$$

Problem 4:- A silicon sample is dopped with $10^{17}/cm^3$ Arsanic atoms. What is equilibrium Hole concentration at 300K & where E_i related to E_f. Given $n_i = 1.5 \times 10^{10}/cm^3$.

Solution:-

$$N_d \approx n = 10^{17}$$

$$p = \frac{n_i^2}{n} = \frac{(1.5 \times 10^{10})^2}{10^{17}}$$

$$= 2.25 \times 10^3/cm^3.$$

Now using relation,

$$n = n_i \, e^{(E_f - E_i)/KT}$$

$$\log\left(\frac{n}{n_i}\right) = \frac{E_f - E_i}{KT}$$

[P.T.O]