

Solid State Device

24/09/2019

① Semiconductor Physics and Devices Basic
pdf principles by Donald A. Neamen

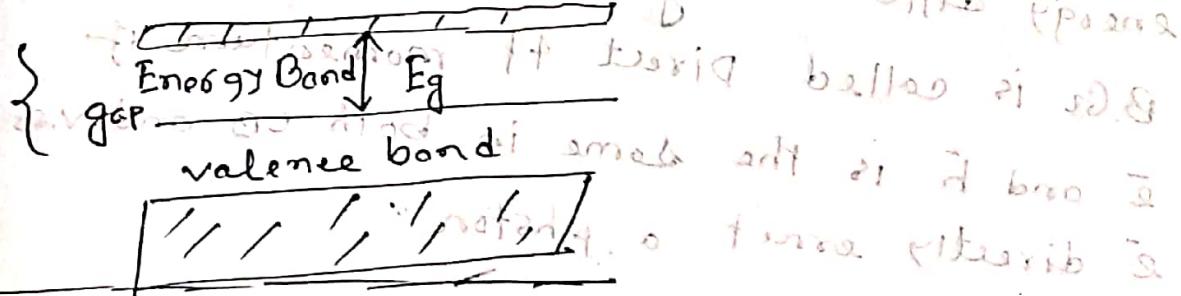
Ref. Solid State Electronic Devices (6th Edition)
Ben Streetman and Sanjay Banerjee.

Semiconductor in Equilibrium:

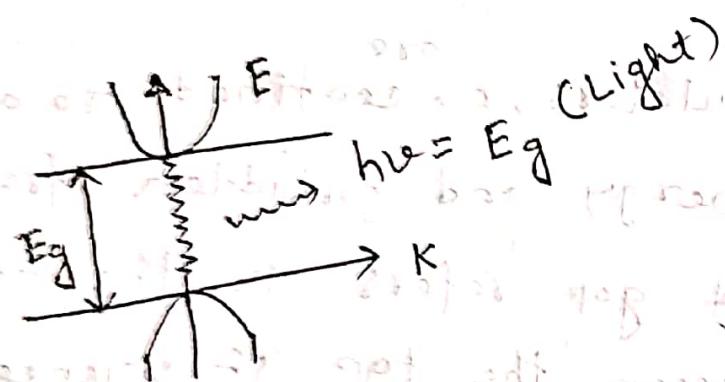
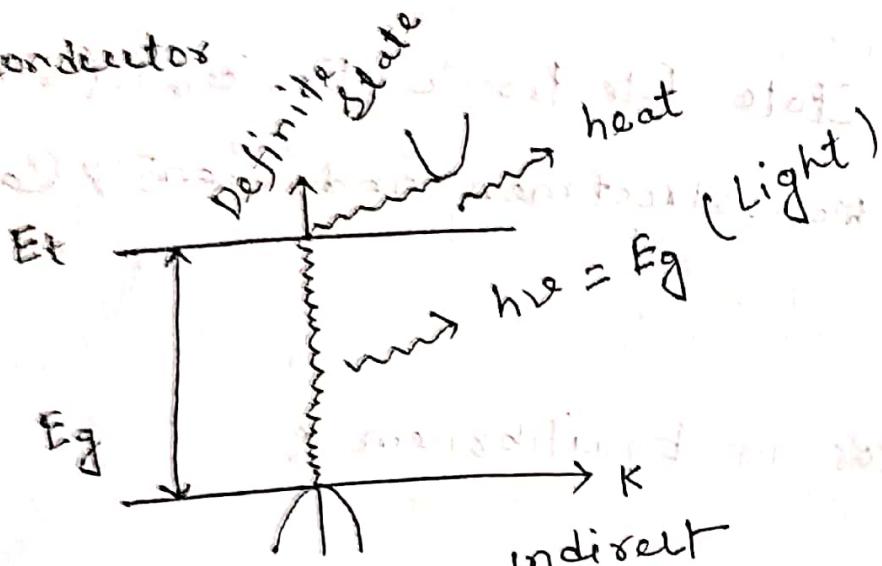
Bond gap:

In S.c and insulators, e⁻ are confined to a no. of bands of Energy and forbidden from other regions. Bond gap refers to the Energy difference between the top of valence band and the bottom of conduction band. e⁻s are able to jump from L bond to another.

Conduction Band



Direct Semiconductor, Indirect Semiconductor
Intrinsic Semiconductor, Extrinsic Semiconductor



* Direct S.C. = \bar{e} in conduction B.G. and fall to a empty state in V.B., giving off energy difference. E_g as a photon of light.

B.G. is called Direct if momentum of \bar{e} and \bar{h} is the same in both C.B. and V.B. \bar{e} directly emit a photon.

Indirect Semiconductor = \bar{e} can't fall directly to V.B maximum but must undergo a momentum changes as well as loss of energy. first go through some definite state E_f within the B.G. Releasing Energy as heat and then fall into V.B give off energy photon.

- Intrinsic Materials :
— pure enough that impurities don't affect its electrical behaviour.
— carriers are created due to thermally or optically excited \bar{e} from V.B to C.B

- equal no. of \bar{e} and hole are present.

Extrinsic materials :

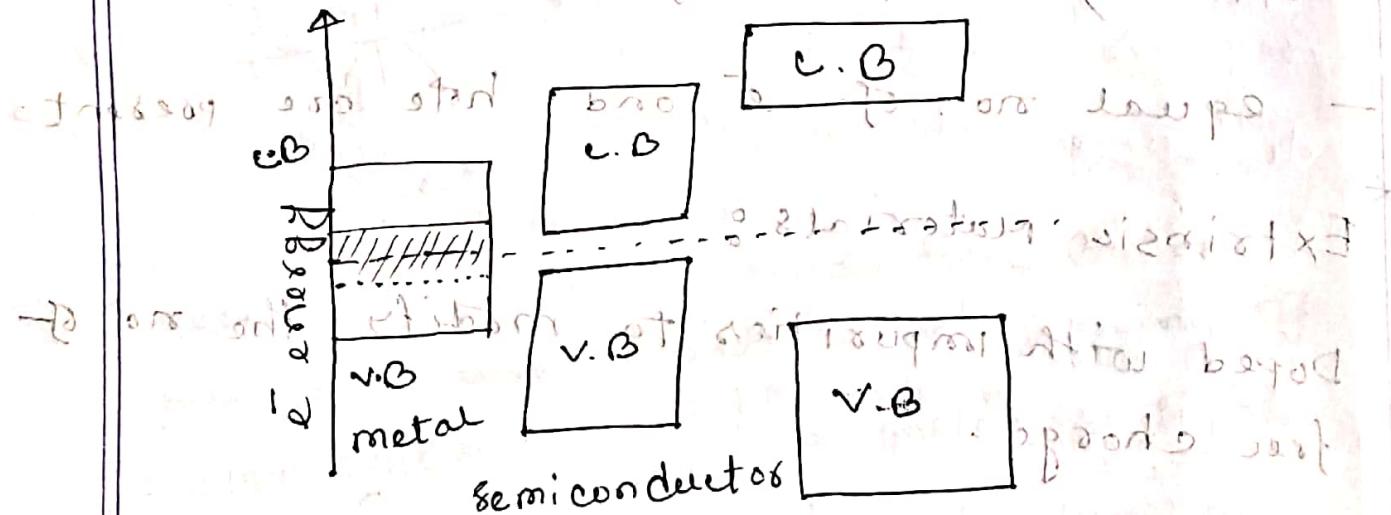
Doped with impurities to modify the no of free charge.

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~~Cherni Level~~: Fermi level is the highest energy state occupied by e^- s in a material at absolute 0 temperature. It starts to exist in higher Energy state. At p type band in the Density of unfilled state so more holes can be accommodated at lower energy state.

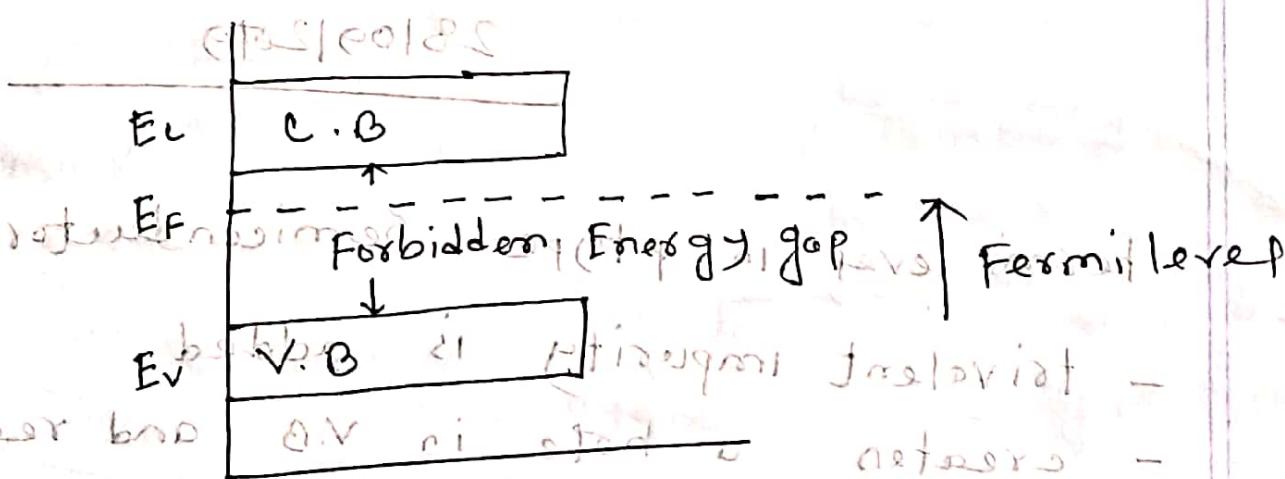
In n type \rightarrow ↑ in the density of occupied state so more e^- s can be accommodated at higher energy state.

Q. Q of the most probable position



Fermi level in n type Semiconductor

- Pentavalent impurity is added, each pentavalent donates a free electron.
- Addition of pentavalent impurity creates a large no. of free electrons in the conductor bond.



at room temp. no of e^- \gg no of h^+

$$p(e_C) > p(h_V)$$

This probability of occupation of energy levels is represented in terms of Fermi level.

Therefore the Fermi level in the n type lies above the conduction band.

$$E_F = E_L - E_K B T \log \frac{N_e}{N_0}$$

E_F = Fermi level

E_L = conduction band

K_B = Boltzman constant.

T = absolute Temperature

N_e = effective density

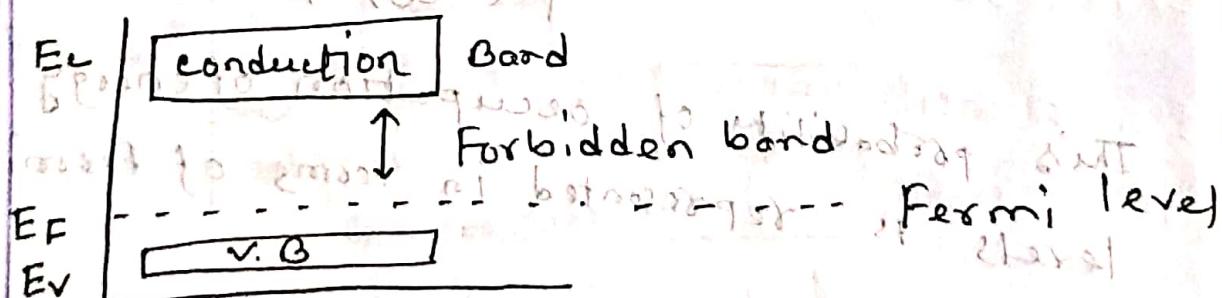
N_D = concentration of Donor atoms

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6.9	3.3
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Fermi level in N-type Semiconductor

- trivalent impurity is added
- creates a hole in V.B and ready to accept an e^-
- creates large number of holes in V.B



at room temp. no. of holes in V.B > no. of e^- in C.B
 $p(h \text{ in } V.B) > p(e^- \text{ in } C.B)$

∴ Fermi level in p type semiconductor lies close to V.B.

∴ Fermi level for p type semiconductors

$$E_F = E_V + K_B T \log \frac{N_V}{N_A}$$

~~maximum~~ N_V = effective density states in V.B
~~and~~ N_A = concentration of acceptor atoms.

~~not~~ E_F lies in intrinsic semiconductor

Intrinsic /
pure semiconductor

Extrinsic /
Impure semiconductor

Fermi - Dirac distribution probability function

→ also called Fermi function, provides the probability of occupancy of energy levels by Fermions. Fermi - Dirac distribution function F_E as a function of temp. is

$$F_E(E) = \frac{1}{1 + e^{\left(\frac{E - E_F}{K_T}\right)}}$$

$K = \text{Boltzmann constant}$

E_F = Fermi level

$F(E) = 1$; if Energy level is filled by e^-

$F(E) = 0$; for empty energy level.

* There is no discontinuity in the Equilibrium

Fermi level explanation shows that fermi function is symmetrical about E_F for any temperature.

$$F(E) = \frac{1}{1 + e^{\frac{E - E_F}{k_T}}}$$

At $T = 0^\circ K$

$$If E < E_F \quad e^{(E - E_F)/k_T} = e^{-\infty} = 0$$

$$F(E) = \frac{1}{1 + 0} = 1 \quad \text{--- (I)} \quad E < E_F$$

$$If E > E_F \quad e^{(E - E_F)/k_T} = \frac{1}{e^{\infty}} = 0 \quad \text{--- (II)} \quad E > E_F$$

So at $0^\circ K$ Every available Energy state up to E_F is filled with e^- and all states above E_F are empty.

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

$T > 0^\circ K$

$$\text{If } E = E_F, f(E_F) = \frac{1}{1 + e^{(E_F - E_F)/k_T}} = \frac{1}{2}$$

at Fermi level the probability of quantum state being occupied by e^- is $\frac{1}{2} = 50\%$

$T > 0^\circ K$

\rightarrow non 0 probability that some Energy state above E_F is occupied by e^- and $\nexists E_F$ empty i.e. some e^- jumped to a level with \uparrow of thermal energy.

At $T = 0^\circ K$

$$\text{For } E < E_F, f(E) = 1$$

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

\therefore with respect to E_F

$f(E)$ is either 1 or 0.

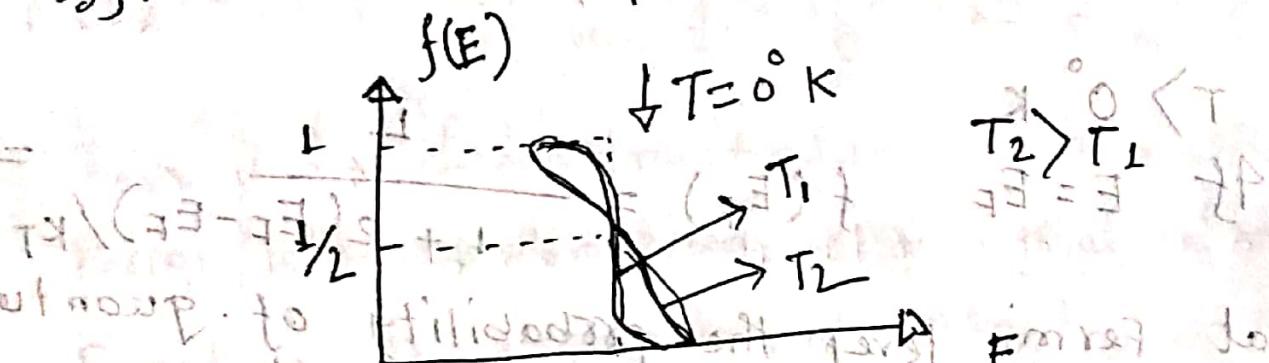
probability of an Energy state above E_F being occupied

by e^- \uparrow at temp. \uparrow

and probability of state below E_F

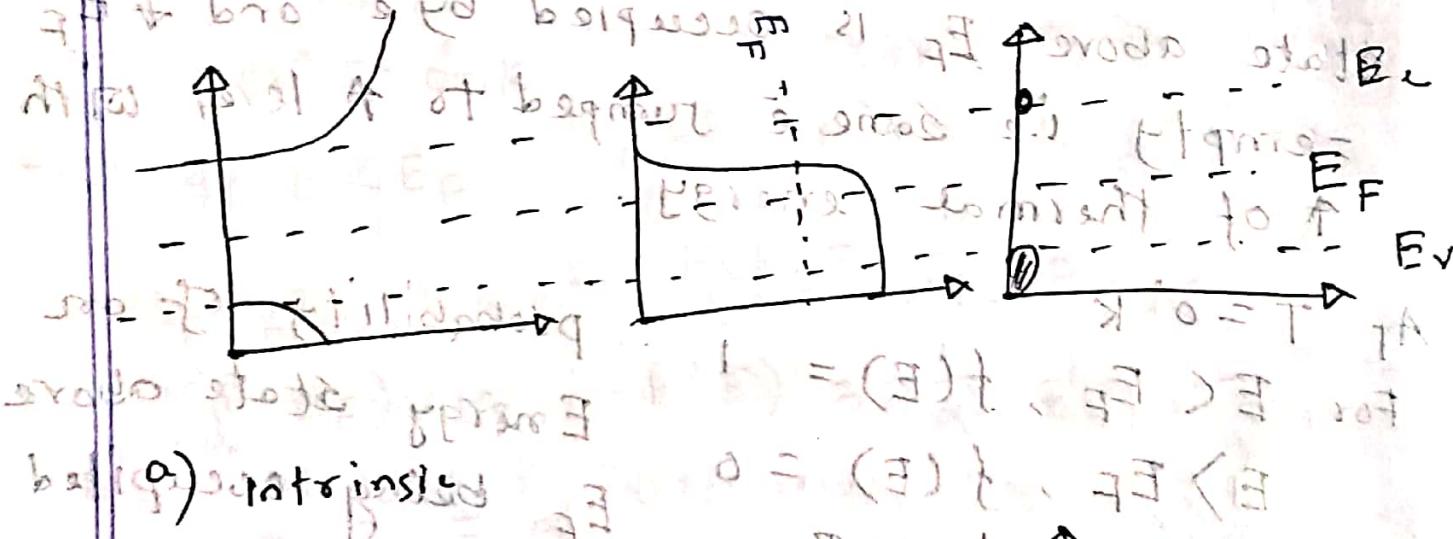
being empty \uparrow of at temperature increase.

so the Fermi level Dirac probability function is symmetrical to E_F .

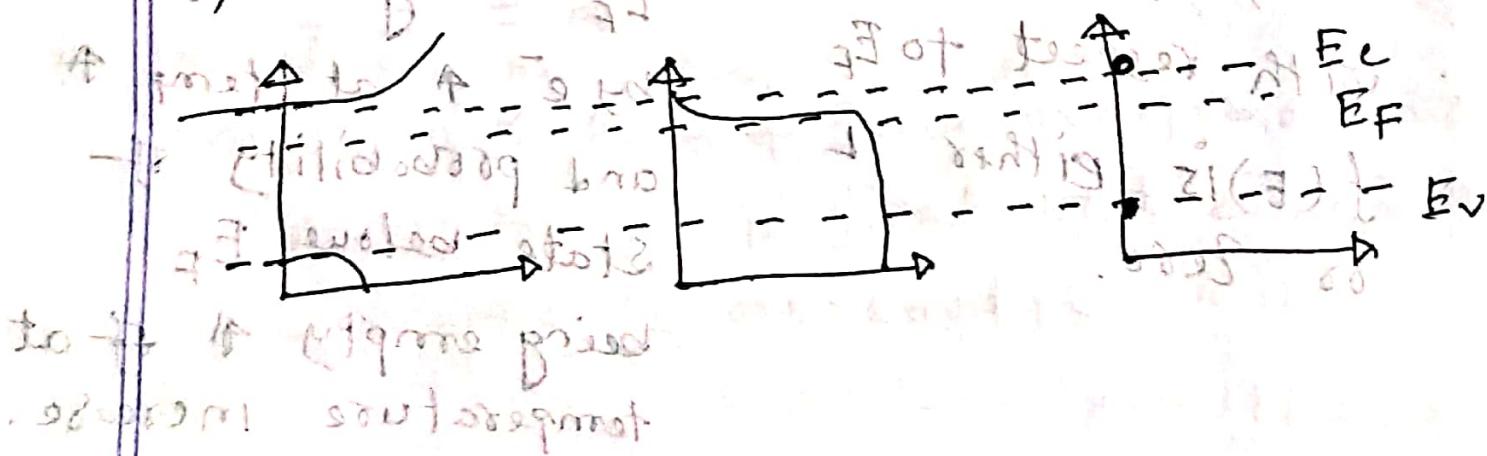


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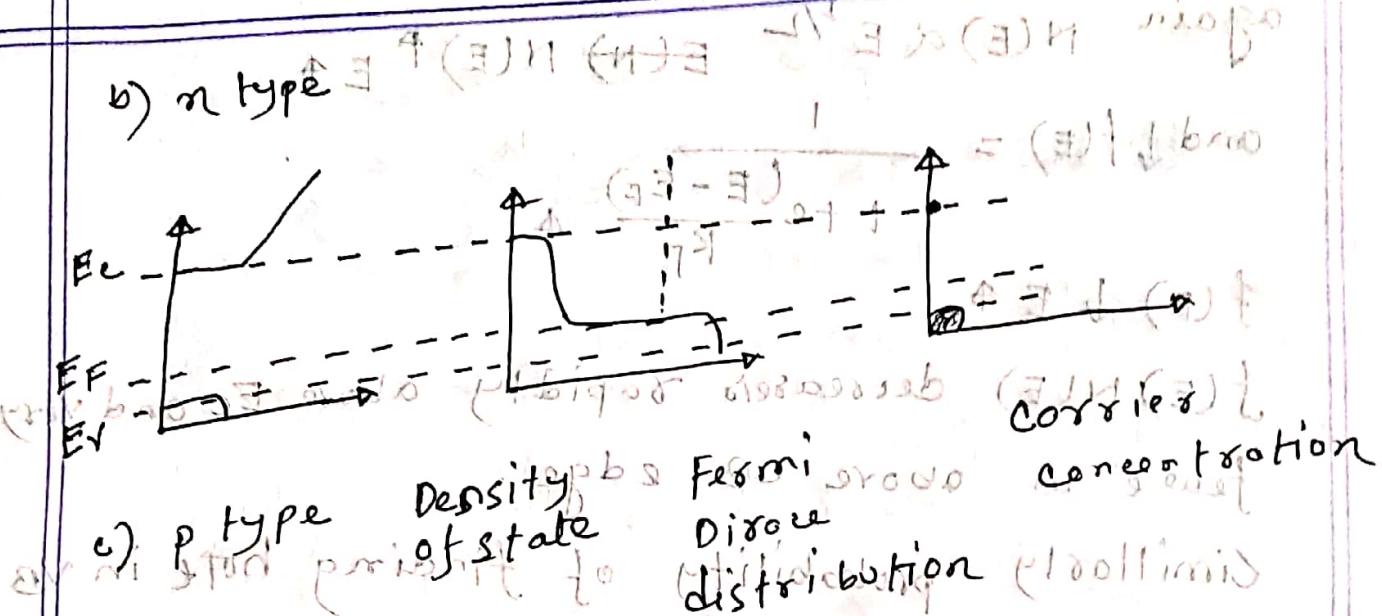
$K^\circ \text{K} < T$



b) Intrinsic



b) n type



c) p type Density of state: Fermi group concentration

Band diagram

Detailed schematic band diagram. Densities of states, Fermi (Dirac) distribution and carrier concentrations for n-type as well as p type materials

$$\Delta \quad n_0 p_0 = n_i^2$$

$$\text{concentration of } e^- \text{ in conduction band } n_0 = \int_{E_C}^{\infty} f(E) N(E) dE \quad \text{①}$$

where $N(E) d(E) = \text{Density of States } (\text{cm}^{-3})$ in energy range dE .

$N(E)$ can be calculated by quantum mechanics and pauli exclusion principle

again $N(E) \propto E^{1/2}$ $E \leftarrow N(E) \uparrow E \uparrow$

$$\text{and } f(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}$$

$f(E) \downarrow E \uparrow$

$f(E), N(E)$ decreases rapidly above E_F and very

slowly in above E_F edge states

Similarly probability of finding hole in VB

decreases rapidly below E_V

$\therefore n_0 = N_f(E_V)$, N_f = Effective density of states

$f(E_V)$ is probability of occupation at E_V

$n_0 = 9.05 \times 10^{22} \text{ cm}^{-3}$

E_F hole states exist

$$V_{IN} = 9.05$$

For broad distributions n_0 to no holes

$\exists b(\beta) H(\beta)$

①

n_0 (final) add to n_0 initial $\exists b(\beta) H(\beta)$ or

$\exists b$ open $H(\beta)$ or
outgrouped holes add to n_0 $\exists b(\beta) H(\beta)$
allowing holes may have less than

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$$n_0 p_0 = n_i^2 \text{ (at } T=0 \text{ K)}$$

$$\therefore n_0 = \int_{E_c}^{\infty} f(E) N(E) dE \rightarrow ①$$

$$N(E) \propto E^{1/2} \cdot N(E) \uparrow \Rightarrow E \uparrow$$

$$f(E) = \frac{1}{\pi \sqrt{(E - E_F)^2 + \epsilon^2}} = \frac{(E)^{1/2}}{\pi}$$

$$f(E) \downarrow = E \uparrow$$

$$\Rightarrow n_0 = N_c f(E_c) \rightarrow ②$$

At room temperature, $kT = 0.026 \text{ eV}$

$$\therefore f(E_c) = \frac{1}{\pi \sqrt{(E_c - E_F)^2 + \epsilon^2}} \gg kT$$

$$\therefore f(E_c) = \frac{1}{\pi \sqrt{(E_c - E_F)^2 / kT}}$$

$$= \frac{1}{\pi \sqrt{(E_c - E_F)^2 / (kT)}}$$

putting the value in equation ②

$$n_0 = N_c e^{-(E_c - E_F)/kT} - ③$$

$$\text{again, } N_c = 2 \left(\frac{m_e \pi^2 k T}{h^3} \right)^{3/2}$$

where, m_e^* = effective mass for e^-
 similarly, the concentration of hole in N.O

$$P_0 = N_v e^{-(E_F - E_v)/kT} \\ = N_v [1 - f(E)] \rightarrow ①$$

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

$$\therefore P_0 = N_v e^{-(E_F - E_v)/kT} \rightarrow ②$$

$$N_v = 2 \left(\frac{2\pi m_p^* k T}{h^2} \right)^{3/2} \rightarrow ⑤$$

equation ① and ② both valid for
 i.e. Intrinsic and Extrinsic. For
 Intrinsic E.F lies near the middle
 of B.G called E_i

Intrinsic (e^- and hole) concentration

$$n_i = N_v e^{-(E_i/kT)} \rightarrow 6$$

$$P_i = N_v e^{- (E_L - E_V) / kT} \rightarrow ⑦$$

$$n_i p_i = N_c N_v e^{- (E_L - E_V) / kT}$$

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

$$\Rightarrow n_i = \sqrt{N_c N_v} e^{- \frac{Eg}{2kT}} \text{ for intrinsic } [N_i =$$

$$\text{and } n_0 p_0 = N_c N_v e^{- Eg / 2kT}$$

$$\therefore n_i^2 = n_0 p_0$$

from equation ① and ⑥
 $e^{- (E_L - E_F) / kT}$

$$\frac{n_0}{n_i} = \frac{e^{- (E_L - E_i) / kT}}{e^{- (E_F - E_i) / kT}}$$

$$\Rightarrow n_0 = n_i e^{(E_F - E_i) / kT}$$

from equation ② and ⑦
 $\rho_0 = P_i e^{(E_i - E_F) / kT}$

calculate the probability that a state in the conduction band is occupied by an electron and calculate the thermal equilibrium electron concentration in Silicon at $T = 300\text{ K}$

Assume the Fermi level is 0.2 eV below the conduction band. The value of N_e for silicon at $T = 300\text{ K}$ is $N_e = 2.8 \times 10^{19} \text{ cm}^{-3}$

Ques 5.0 is a pure important question
Ques 5.0: The probability that an energy state at $E = E_0$ is occupied by an electron is given by

$$f_E(E_0) = \frac{1}{1 + \exp\left(\frac{E_0 - E_F}{kT}\right)}$$

$$\approx \exp\left[-\frac{E_0 - E_F}{kT}\right]$$

$$= \exp\left(-\frac{0.25}{0.0259}\right)$$

$$= 6.43 \times 10^{-5}$$

$$K_T = 0.0259 \times \frac{T_1}{T_2}$$

$$= 0.0259 \times \frac{100}{300}$$

$$= 0.0259$$

$$= 7.4 \times 10^{-5}$$

$$= 7.4 \times 10^{-5} \times 2.8 \times 10^{19} = 2.08 \times 10^{15}$$

The electron concentration is given by

$$n_0 = N_c \exp \left[-\frac{(E_F - E_F)}{KT} \right]$$

$$n_0 = 2.81 \times 10^{19} \exp \left(\frac{-0.25}{0.0259} \right)$$

$$2.81 \times 10^{19} \exp \left(\frac{-0.25}{0.0259} \right) = 1.8 \times 10^{15}$$

$$1.8 \times 10^{15} \text{ cm}^{-3}$$

calculate the thermal equilibrium hole concentration in silicon at $T = 400 \text{ K}$.

Assume that the Fermi energy is 0.27 eV

above the valence band. The value of N_c for silicon at $T = 300 \text{ K}$ is $N_c = 1.04 \times 10^{19} \text{ cm}^{-3}$

$$N_c = \frac{(2\pi m_e k T)^{3/2}}{3 \epsilon^2}$$

$$N_c = \left(\frac{400}{300} \right)^{3/2} = 1.60 \times 10^{19} \text{ cm}^{-3}$$

$$N_c = (1.04 \times 10^{19}) \left(\frac{400}{300} \right)^{3/2} = 1.60 \times 10^{19} \text{ cm}^{-3}$$

$$N_c = 1.60 \times 10^{19} \text{ cm}^{-3}$$

$$kT = 0.0259 \times \frac{400}{300}$$

$$= 0.03453 \text{ eV}$$

$$P_0 = Nv \exp \frac{-(E_F - E_v)}{kT}$$

$$= 1.60 \times 10^{19} \exp \frac{-0.27}{0.03453}$$

$$= 6.43 \times 10^{15} \text{ cm}^{-3}$$

E4.1 calculate the thermal equilibrium electron concentration in silicon at $T = 300\text{K}$ and here concentration in silicon at $T = 300\text{K}$ for the case when the Fermi energy level is 0.22 eV below the conduction band energy E_c .

$$E_g = 1.12\text{ eV}$$

from Appendix B.4

$$Nv = 1.04 \times 10^{19} \text{ cm}^{-3}$$

$$Nc = 2.8 \times 10^{19} \text{ cm}^{-3}$$

$$P_0 = Nv \exp \frac{-(E_F - E_v)}{kT}$$

$$= 1.04 \times 10^{19} \exp \frac{-(1.12 - 0.22)}{0.0259}$$

$$= 1.04 \times 10^{19} \exp \frac{-0.90}{0.0259}$$

$$= 8.43 \times 10^{13} \text{ cm}^{-3}$$

we know, $n_{e0} = \frac{N_e N_h}{P_0} \exp^{-E_g/kT}$

$$n_{e0} = \frac{N_e N_h}{P_0} \exp^{-E_g/kT}$$

$$\Rightarrow n_{e0} = \frac{N_e N_h}{P_0} \exp^{-E_g/kT}$$

$$= \frac{2.8 \times 10^{19} \times 1.04 \times 10^{19}}{8.43 \times 10^3} \exp^{-\frac{1.12}{0.0259}}$$

$$= 5.73 \times 10^{15} \text{ cm}^{-3}$$

$$P_0 = 8.43 \times 10^{13} \text{ sub} \quad \text{cm}^3 \text{ water}$$

$$n_0 = 5.73 \times 10^{15}$$

E9.2 electron and hole concentration in
GaAs at $T = 300K$ for the case when
Fermi level is 0.30 eV above the V. B.

from Appendix

$$E_g = 1.42 \text{ eV}$$

$$N_c = 4.7 \times 10^{17} \text{ cm}^{-3}$$

$$N_v = 2.0 \times 10^{18} \text{ cm}^{-3}$$

$$\frac{P}{P_0} \times e^{-E_F - E_V} = 74$$

$$\frac{SOT\%}{240.0} = P_0 \times \left(\frac{N_V N_C}{P_0 T} \right) \times \exp \left(\frac{-(E_F - E_V)}{kT} \right)$$

$$= 7 \times 10^{18} \times \exp \left(\frac{-1.30}{0.0259} \right)$$

$$= 6.53 \times 10^{13} \text{ cm}^{-3}$$

$$n_0 = \frac{N_V N_C}{P_0 T} \times \exp \left(\frac{-E_g}{kT} \right)$$

$$= \frac{7 \times 10^{18} \times 4.7 \times 10^7}{6.53 \times 10^{13}} \times \exp \left(\frac{-1.42}{0.0259} \right)$$

$$= 0.0779 \text{ cm}^{-3}$$

EQ.3 Find the intrinsic carrier concentration

in silicon a) $T = 200\text{K}$ b) $T = 400\text{K}$

SOT%: From appendix,

$$E_g = 1.12$$

$$\rightarrow N_V = 1.04 \times 10^{19} \text{ cm}^{-3}$$

$$\rightarrow N_C = 2.8 \times 10^{19} \text{ cm}^{-3}$$

$$n_i = 2.8 \times 10^{19} \times 1.04 \times 10^{19} \times \left(\frac{200}{300} \right)^3 \times \exp \left(\frac{-1.12}{0.01726} \right)$$

$$n_i = 7.68 \times 10^{19} \text{ cm}^{-3}$$

$$\therefore K_T = 0.0259 \times \frac{4}{3}$$

$$n_i = 2.8 \times 10^{19} \times 1.04 \times 10^{19} \times \left(\frac{400}{300}\right)^3 \times \exp \frac{-1.12}{0.0345}$$

$$= 5.5 \times 10^{24}$$

$$n_i = 2.38 \times 10^{12} \text{ cm}^{-3} \times 2 \times 10^3 =$$

$$\therefore n_i = 2.38 \times 10^{12} \text{ cm}^{-3}; \text{ at } T = 200\text{K}$$

$$n_i = 2.38 \times 10^{12} \text{ cm}^{-3}; \text{ at } T = 400\text{K}$$

Ans

$$\left. \begin{array}{l} 1000 \text{ STP} \text{ (at } 200^\circ\text{C) with } 1 \text{ atm} \\ \text{and } 1000 \text{ g/m}^3 \text{ density} \end{array} \right\} \begin{array}{l} \text{Volume } V = \frac{1000}{1000} = 1 \text{ m}^3 \\ \text{Temperature } T = 200^\circ\text{C} = 473 \text{ K} \\ \text{Pressure } P = 1 \text{ atm} \end{array}$$

$$\frac{1.12}{0.0345} = \frac{e^{1.12 \times 473}}{e^{1.12 \times 473} + e^{1.12 \times 82.5}}$$

$$\frac{1.12}{0.0345} = \frac{e^{1.12 \times 473}}{e^{1.12 \times 473} + e^{1.12 \times 82.5}} = 1.0000000000000002$$

chapter 5

Drift current : An electric field is the net movement of charge due to an electric field is called drift. The net drift of charge gives rise to a drift current.

$$\text{① } \frac{dq}{dt} = qbE = qb^2(nA) = j_{\text{drift}}$$

Drift current density :

If we have a positive volume density of moving charges having a positive volume density moving at an average drift velocity

$$j_{\text{drift}} = (p \cdot d) (nA) = ab^2q = j_{\text{drift}}$$

If the volume charge density is due to positively charged holes, then

$$j_{p \text{ drift}} = (eP) v_{dp}$$

v_{dp} = Average drift velocity

The equation of motion of a positively charged hole into the presence of an electric field is non-zero and zero.

$$F = m_p a = eE \quad m_p = \text{effective mass}$$

It takes $t = \frac{d}{v_{dp}}$ seconds to drift from one terminal to the other. $e = \text{magnitude of electronic charge}$

To indicate current

Average drift velocity is \propto to electric field

in drift space $v_{dp} = \mu_p E$ where μ_p = carrier mobility in drift space

carries charge to drift factor $\mu_p = \text{carrier mobility}$

$$J_{pdif} = (\rho_p) v_{dp} = e \mu_p p E \quad \text{---(1)}$$

The same discussion of drift applies to electrons

$$J_{ndif} = p v_{dn} = (-e n) v_{dn} = (-e n) (-\mu_n E) = j_{drift} \quad \text{---(2)}$$

$$J_{drift} = (e \rho) v_{drift} = (e \rho) \mu_p p E$$

$$\rho = q b r$$

This is called carrier diffusion

and so

Diffusion is the process whereby particles move from a region of high concentration toward a region of low concentration

and so

If the gas molecules were electrically

charged, the net flow of charge would result in a diffusion current.

Diffusion current Density :

[F.O]

The net rate of electron from F_n ,

$$F_n = \frac{1}{2} n(-e) v_{th} - \frac{1}{2} n(+e) v_{th} = \frac{1}{2} v_{th} [n(-e) - n(+e)] \quad \text{-①}$$

If we expand equation ① into taylor series.

$$F_n = \frac{1}{2} v_{th} \left\{ \left[n(0) - e \frac{dn}{dx} \right] - \left[n(0) + e \frac{dn}{dx} \right] \right\}$$

$$= -v_{th} e \frac{dn}{dx}$$

each electron has a charge ($-e$) , so the current is

$$J = -e F_n = + e v_{th} e \frac{dn}{dx}$$

$$J_{ndrif} = e D_n \frac{dn}{dx} \quad , D_n \text{ is called electron diffusion coefficient}$$

$$J_{pdif} = -e D_p \frac{dp}{dx} \quad , D_p \text{ hole diffusion coefficient}$$