Semiconductor Physics

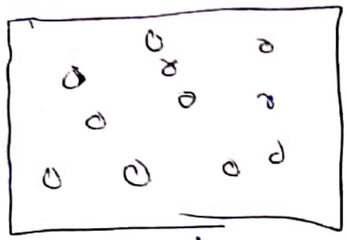
Solid — atoms — electron (outermost electrons)

↓

free electron (Unpaired electron)

↓

sea of electron (free electron gas)



→ [Quantum Mechanical analysis] → wave nature of electron motion

free electron theory (No-electron interaction, V = const)

Quantized energy states

En=-13.6/n^2;

Nearly free electron theory [Periodically varying potential]

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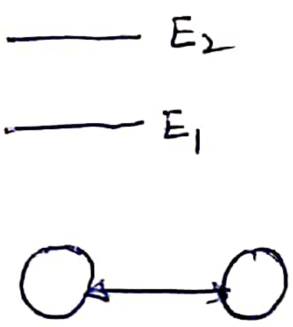
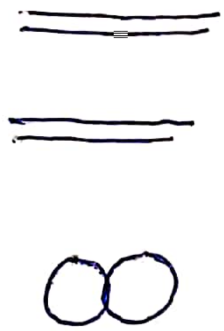
energy bands → forbidden energy states

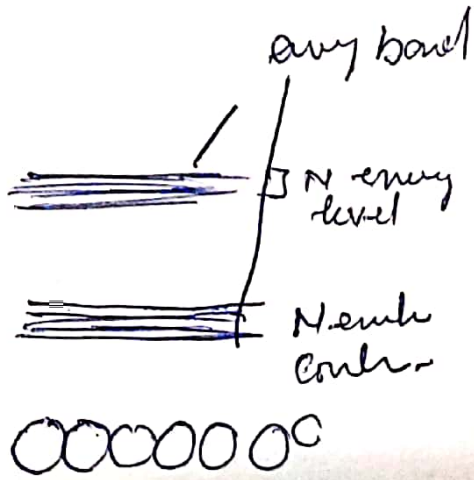
↓

Band gap

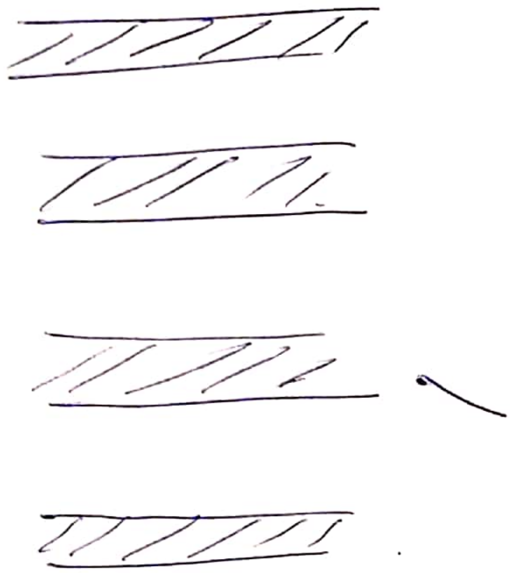
Band formation in Solid

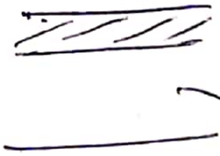






Band formation of solids





— allowed energy states

forbidden state

out of all allowed states

[* Highest filled states at T = 0K is called valence band

* lowest empty band is called conduction band]

electrons are spin ½ particles, follow Pauli's exclusion principle; distribution follows Fermi-Dirac distribution.

How energy states are going to be filled

[$S = \frac{1}{2}, \frac{3}{2}, \ldots$ particles called fermions]

[$S = 0, 1, 2 \ldots$ called Bosons]

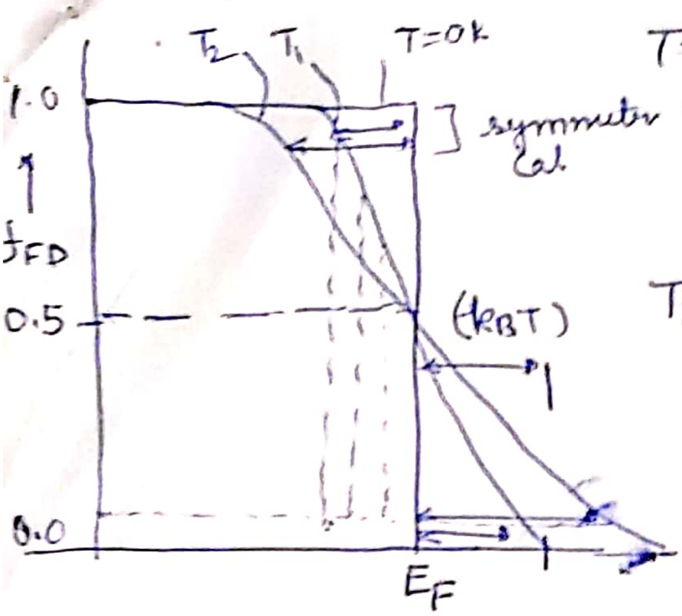
Fermi-Dirac Distribution function

$$f_{FD} = \frac{1}{1 + e^{(E-E_F)/k_BT}} \quad ; \quad f_{BE} = \frac{1}{\left(e^{(E-E_F)/k_BT} - 1\right)}$$

↓

prob. that an energy level 'E' is filled.

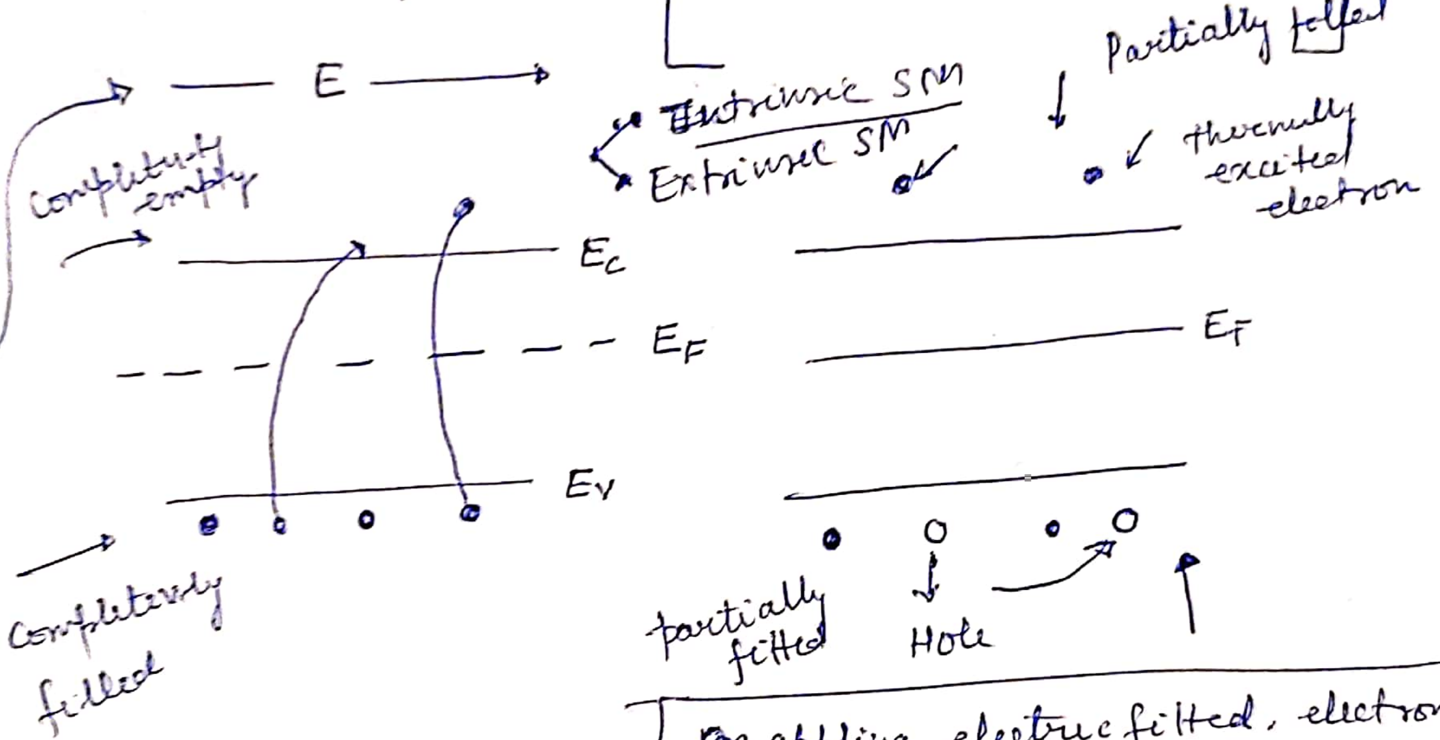
E_F = fermi energy level, this may & may not represent energy level but used as reference point and very useful in explaining various characteristics of solids.



$T = 0\,K$ all energy levels below E_F all filled and all energy level above E_F are empty

T_1 $(T_1 > 0K)$

some Numerical example.



$E_g = E_C - E_V$ = Band gap

$E_g = 0$ conductor

$E_g \sim$

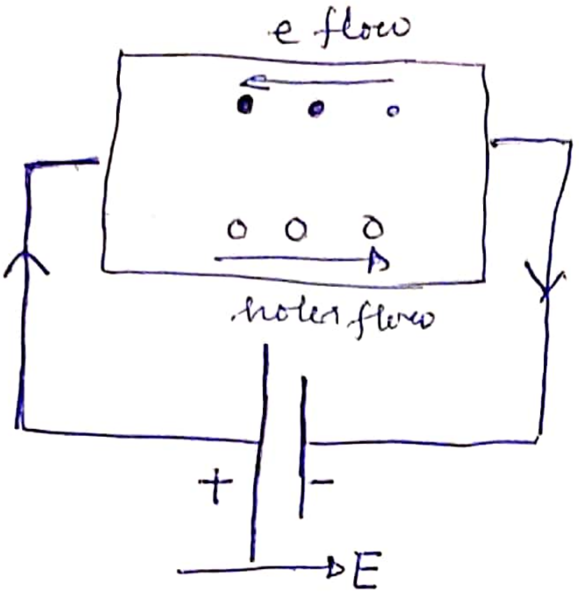
E_g large - insulator

On appling electric filled, electron and ~~no~~ holes moves into respective bands as the bands are partially filled. Motion of electron in opposite to external field while hole in direction of applied field. Thus motion of both charges carriers constitutes currents.

Conductivity $\sigma = ne\mu_e + pe\mu_p$

μ_e = mobility of electron. μ_p = hole

$$\boxed{\sigma = ne(\mu_e + \mu_p)} \qquad \boxed{n = p}$$



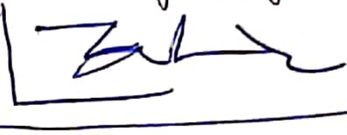
Drift velocity

$v_d \propto E$

$v_d = \mu E$, $\boxed{\mu = \frac{v_d}{E}}$

ease with which e^- moves in the effect of applied external field.

* After external field, e^- gets energy moves loose all energy with atom interaction again gets acceleration..



Density of states :- No. of density states per unit energy is defined as density of states

$$\boxed{D(E) = dN/dE}$$

$E \rightarrow E+dE$

$(dN) \rightarrow$ No. density of ~~energy~~ states (No. of states per unit volume)

* We are taking case of 3D solid.

in 2D - dN = # of states / area

1D - dN = # of states / length

3D — dN = # of states / volume

(for 3D case only)

$$D(E) = \frac{1}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2}\sqrt{E}$$

[m_e = effective mass of electron]

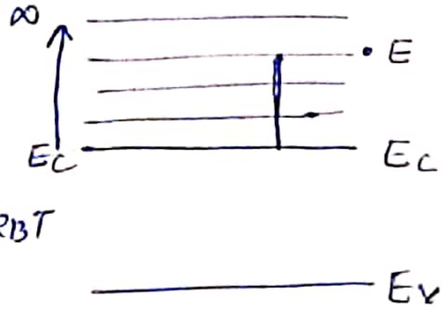
of electron (charge carriers) in Conduction Band

n = # density of electron in conduction band

$$n = \int_{E_c}^{\infty} f_{FD}\, D(E)\, dE = \int_{E_c}^{\infty} f_{FD}\, D(E)\, dE$$

$D(E) \longrightarrow E \longrightarrow \sqrt{E - E_c}$

$$n = \int_{E_c}^{\infty} \frac{1}{1+e^{(E-E_F)/k_BT}} \frac{1}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2} \sqrt{E-E_c}\, dE$$



for $(E-E_F) \gg k_BT$; $\frac{1}{1+e^{(E-E_F)/k_BT}} \approx e^{-(E-E_F)/k_BT}$

$$n = \int_{E_c}^{\infty} e^{-(E-E_F)/k_BT} \left(\frac{1}{2\pi^2}\right)\left(\frac{2m_e}{\hbar^2}\right)^{3/2} (E-E_c)^{1/2}\, dE$$

$$n = \frac{e^{E_F/k_BT}}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2} \int_{E_c}^{\infty} e^{-E/k_BT} (E-E_c)^{1/2}\, dE$$

let $E-E_c = x$; $dE = dx$

$$n = \frac{e^{E_F/k_BT}}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2} \cancel{\int_0^{\infty} e^{-E_c/k_BT} e^{-x/k_BT} x^{1/2}} \int_0^{\infty} e^{-E_c/k_BT} e^{-x/k_BT} x^{1/2} dx$$

$$n = \left(\frac{1}{2\pi^2}\right)\left(\frac{2m_e}{\hbar^2}\right)^{3/2} e^{(E_F-E_c)/k_BT} \int_0^{\infty} x^{1/2} e^{-x/k_BT}\, dx$$

Standard Integral

$$\boxed{\int_0^{\infty} x^n e^{-\alpha x} dx = \left(\frac{1}{\alpha^{n+1}}\right)\Gamma(n+1)}$$

$$\int_0^{\infty} x^{1/2} e^{-\alpha x} dx = \frac{\sqrt{\pi}}{2}(k_BT)^{3/2}$$

$\boxed{\alpha = \frac{1}{k_BT}}$ $\boxed{n = \frac{1}{2}}$.

$$n = \frac{1}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2} e^{(E_F-E_c)/k_BT} \frac{\sqrt{\pi}}{2}(k_BT)^{3/2}$$

$$n = \frac{1}{4}\left(\frac{2 m_e k_B T}{\pi \hbar^2}\right)^{3/2} e^{(E_F - E_C)/k_B T}$$

$$n = \frac{2}{2^3}\left(\frac{2 m_e k_B T}{\pi \hbar^2}\right)^{3/2} e^{(E_F - E_C)/k_B T}$$

$$\boxed{n = 2\left(\frac{m_e k_B T}{2\pi \hbar^2}\right)^{3/2} e^{(E_F - E_C)/k_B T}}$$

similarly

$$p = \int_{-\infty}^{E_V} D(E) (f_{FD})_h \, dE$$

$$(f_{FD})_h \downarrow (1 - f_{FD})$$

$$D(E) = \frac{1}{2\pi^2}\left(\frac{2 m_h}{\hbar^2}\right)^{3/2} \sqrt{(E_V - E)}$$

$$\boxed{p = 2\left(\frac{m_h k_B T}{2\pi \hbar^2}\right)^{3/2} e^{(E_V - E_F)/k_B T}}$$

* <u>Position of Band gap</u>

since the $n = p$ (for ~~extrinsic~~ semiconductor)

$$n = p$$

$$2\left(\frac{m_e k_B T}{2\pi \hbar^2}\right)^{3/2} e^{(E_F - E_C)/k_B T} = 2\left(\frac{m_h k_B T}{2\pi \hbar^2}\right)^{3/2} e^{(E_V - E_F)/k_B T}$$

$$\left(\frac{m_e}{m_h}\right)^{3/2} = e^{(E_V - E_F - E_F + E_C)/k_B T} = e^{(E_C + E_V - 2E_F)/k_B T}$$

$$\frac{(E_C + E_V - 2E_F)}{k_B T} = \frac{3}{2}\log\left(\frac{m_e}{m_h}\right); \quad E_C + E_V - 2E_F = \frac{3}{2} k_B T \log\left(\frac{m_e}{m_h}\right)$$

$$2E_f = (E_c + E_v) - \frac{3}{2}k_BT \log\left(\frac{m_e}{m_h}\right)$$

$$E_f = \frac{(E_c + E_v)}{2} - \frac{3k_BT}{4}\log\left(\frac{m_e}{m_h}\right)$$

$$\boxed{m_e \approx m_h}$$

since $m_h \neq m_e$ is insignificant Fermi level in an intrinsic SM may be considered as independent of temperature

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

* Intrinsic semiconductor; fermi level lie inbetween conduction and valence band.
~~* not function of temperature~~

Law of Mass action

$$np = 2\times 2\left(\frac{\cancel{m_e m_h}\, k_BT}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2}\, e^{(\cancel{E_f} - E_c + E_v - \cancel{E_f})/k_BT}$$

$$np = 4\left(\frac{k_BT}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2}\, e^{-(E_c - E_v)/k_BT}$$

$$E_c - E_v = E_g$$

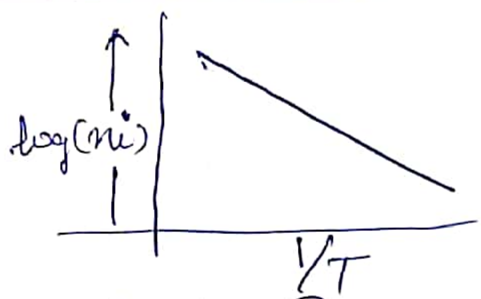
$$np = 4\left(\frac{k_BT}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2}\, e^{-E_g/k_BT}$$

$n = p = n_i$ (intrinsic semiconductor)

$$\boxed{n_i = 2\left(\frac{k_BT}{2\pi\hbar^2}\right)^{3/2} (m_e m_h)^{3/4}\, e^{-E_g/2k_BT}}$$

$n_i = n_i(T)$

$$\boxed{n_i = A\, T^{3/2}\, e^{-E_g/2k_BT}}$$



n_i mainly depends on exponential factor. I mean $e^{-E_g/2k_BT}$ is dominating factor.

Conductivity of Intrinsic Semiconductor (Measurement of Band gap)

$$\sigma = \sigma_e + \sigma_h = ne\mu_e + pe\mu_p \quad n = p = n_i$$

$$\sigma = n_i e(\mu_e + \mu_p)$$

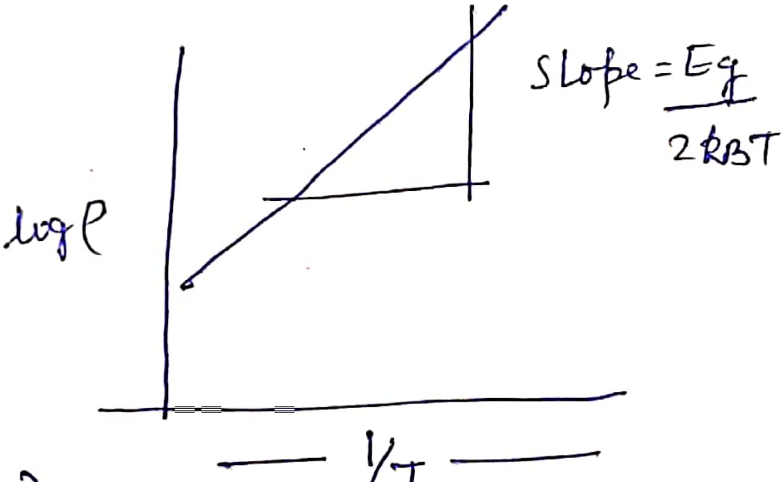
$$\sigma = \underbrace{e(\mu_e + \mu_p) A T^{3/2}}_{\sigma_0} e^{-E_g/2k_BT}$$

$$\sigma = \sigma_0 e^{-E_g/2k_BT}$$

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

$$\rho = \rho_0 e^{+E_g/2k_BT}$$

$$\log \rho = \log \rho_0 + \frac{E_g}{2k_B}\left(\frac{1}{T}\right)$$



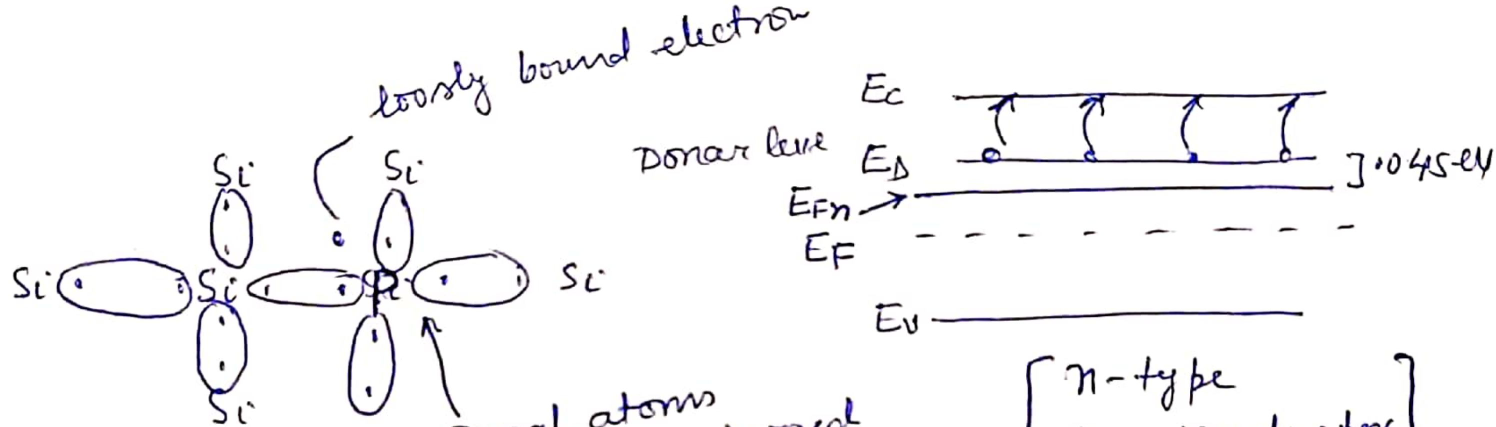
conductivity of intrinsic semiconductor increase with temperature which is reverse case to conductor.

Extrinsic Semiconductor (Doped Semiconductor)

Ge – Si (group IV element)

Add impurity during the growth of crystal it will provid extra electrons or holes.

Pentavalent Impurity (P, As, Sb; Phosphorous, Arsenic Antimony)



[n-type semiconductor]

Donal atoms gets +vely charged by giving e^- just with very small energy ~ in comparision to Bandgap

→ Donar impurity provids hudge no. of free electrons with small energy (~0.045 eV). This can be understand with the concept of Donar level close to conduction Band. Position of fermi level shift towards conduction band. Its position (actual) will depends upon the doping concentration.

Low doping → E_{Fn} between (E_F & E_D)

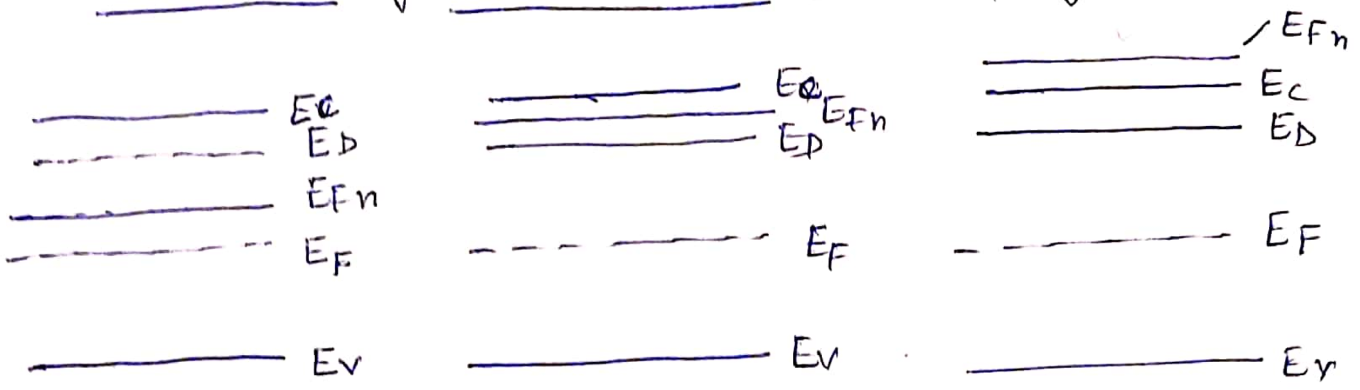
Medium doping → E_{Fn} between (E_D & E_C)

Heavy doping → E_{Fn} between (Inside the conduction band) equivalent- semiconductor

↓ case of laser diode. Called population inversion conduction.

Scanned with CamScanner

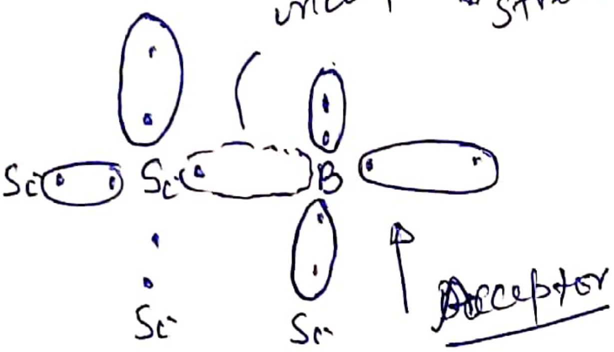
Variation of Fermi-level with Doping Concentration.

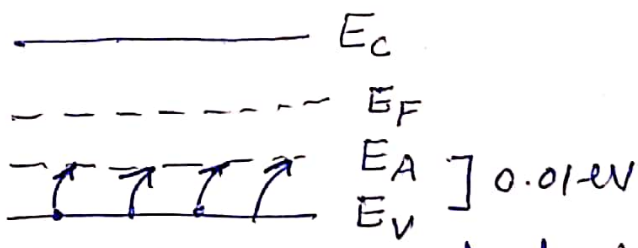


(low doping) (Medium doping) (Heavily doped)

p-type semiconductor :- Addition of trivalent impurity during crystal formation provides excess holes [Al, B, Ga, In]

incomplete bond ↓ stress] vacancy of electron, any stress electron can come to this position leaving the Acceptor doping (-vely) charged.





(p-type semiconductor)

holes – Majority carriers]
electron – Minority carrier] p-type semiconductor

electron – Majority carrier]
hole – Minority carrier] n-type semiconductor

Variation of Fermi level with doping conc. follows the same pattern.

1. At what temperature we can expect a 10% prob that electron in silver have an energy which is 1% above the fermi level $E_F = 5.5\ eV$

$$\frac{E-E_F}{E_F} = 1\%, \quad E-E_F = 0.055\ eV$$

Valence band

$$f_E = 0.1$$

$$0.1 = \frac{1}{1+e^{(E-E_F)/k_BT}}$$

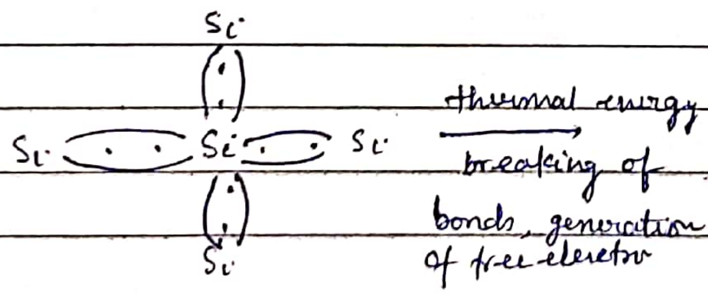
$$\boxed{T = 290\ K}$$

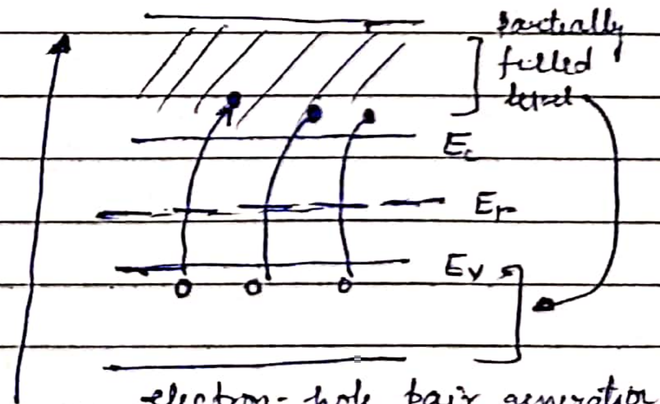
At room Temp. (300 K) – $1.5\times10^{16}\ m^{-3}$

(1.5×10^{16} electron/m^3) – silicon

in conduction band at room temp.

Intrinsic Semiconductor :- Group IV – element (Germinium, Silicon)
(Ge, Si)





On appling electric field – electric conductivity takes place.

hole – fictitious particle (+e) (m_h)

$$\boxed{\sigma = \mu_e n e + p e \mu_p}$$

$$\boxed{\sigma = n(\mu_e+\mu_p)e}$$

n = # density of e in conduction Band

p = # density of holes in Valence band

$$\boxed{n=p}$$