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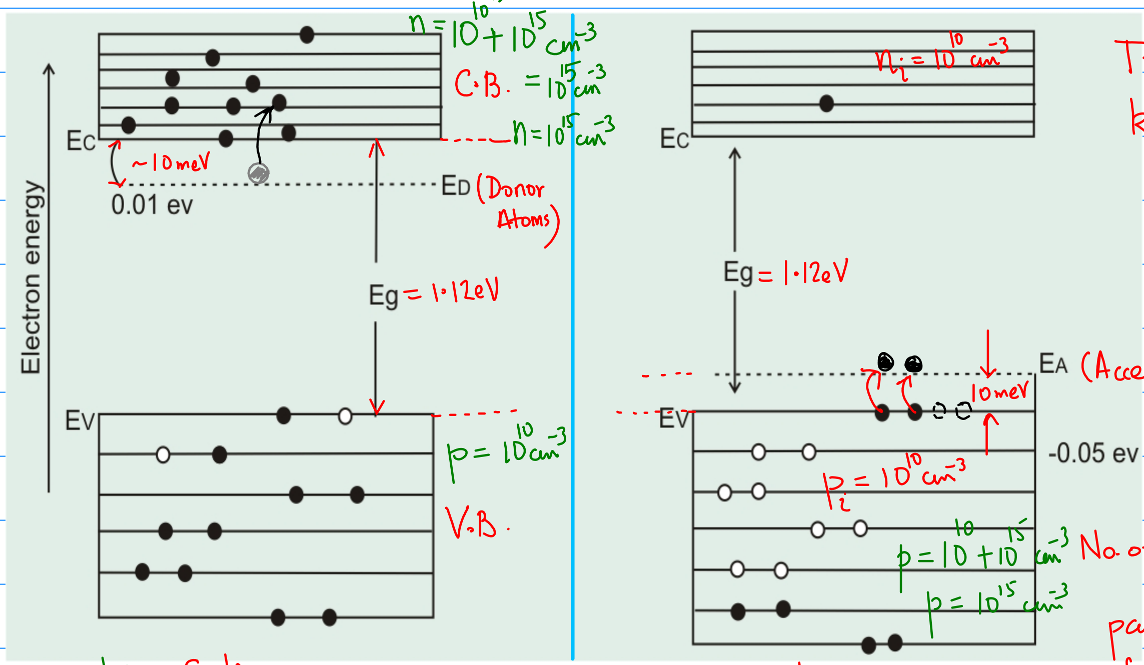
Charge-Carrier Density in Semiconductors

● → Electrons

○ → Holes



n-Type Silicon

p-type Silicon

$T = 300K$

$k_BT = 25\,meV$

$n_i = 10^{10}\ cm^{-3}$

$n = p = n_i = 10^{10}\ cm^{-3}$

No. of valance electrons participating in forming bonds $= 4\times10^{22}\ cm^{-3}$

- For Silicon :

$$n = p = n_i = 10^{10}\ cm^{-3}$$

$n_i(T)$ & varies with varying T.

- Extrinsic Semiconductor → Dopants
  - Donors
  - Acceptor

- Dopant density ≪ Atomic Density

eg: for Silicon, atomic density $\sim 10^{22}$ atoms cm^{-3}

Dopant density $\sim 10^{15}$ atoms cm^{-3}

(Moderate doping level)

⇒ Dopants are 20 parts per billion.

Note:

- Since dopant density is much-much lower than the atomic density of the solid (semiconductor); the dopants do not constitute to energy band.

$\Rightarrow$ We observe discrete energy levels of the dopant atoms within the energy-gap of the semiconductor.

At $T = 300K$, ie, $k_B T = 25\,meV$

Following observations are there:

- All donor atoms gain this thermal energy and release extra electrons to the conduction band.

$$n_{\text{Donor atoms}} \sim N_D = 10^{15}\ cm^{-3}$$

- The valance electrons gain energy & populate in conduction band.

$$n_i = 10^{10}\ cm^{-3}$$

- This means that at any instant of time, the conduction band is populated with two kinds of "FREE" electrons.

$$n_{\substack{\text{Donor}\\\text{atoms}}} = 10^{15}\ cm^{-3}$$

$$n_i = 10^{10}\ cm^{-3}$$

Comparing the two; $n_{\substack{\text{Donor}\\\text{atom}}} \gg n_i$

Therefore, we term the semiconductor as n-type since the electrons in conduction band is much-much higher than the holes in Valance band.

- Also, all acceptor atoms accept electrons from the valance band leaving behind vacancies (holes).
- In valance band, we have two kinds of vacancies,

$$p_{\substack{\text{Acceptor}\\\text{atoms}}} = N_A = 10^{15}\ cm^{-3}$$

$$n_i = p = 10^{10}\ cm^{-3}$$

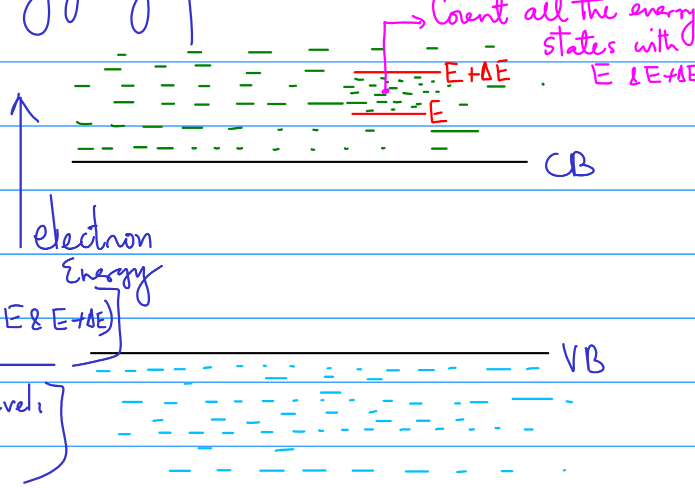
- Comparing the two, $p_{\substack{\text{Acceptor}\\\text{Atom}}} \gg n_i$

Therefore, we term the semiconductor as p-type.

Idea of Density of Energy States (DOS)

- Each energy band (ie, CB or VB) is a collection of discrete energy levels separated by very-very small energy gap.

We define, density of energy-states as,



$$D = \frac{\left[\text{The number of energy states available between two energy levels (here, } E \,\&\, E+\Delta E)\right]}{\left[\text{Difference of the two energy levels (here } \Delta E)\right]}$$

$$D = \text{Number of energy state per unit energy interval.}$$

$$D = (\ ?\ )\ \underbrace{cm^{-3}\, eV^{-1}}_{\text{unit of DOS}}$$

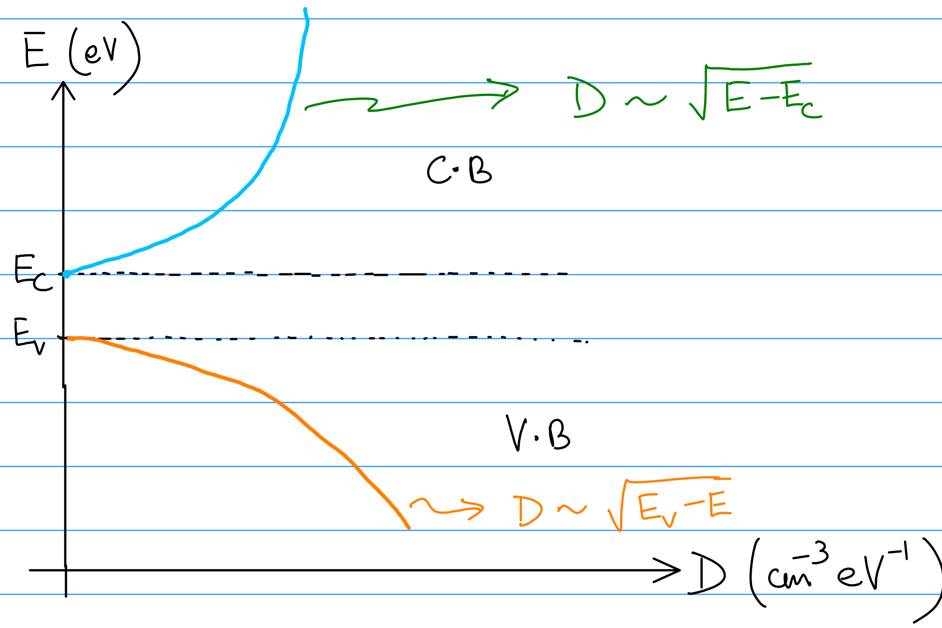
For conduction band:

$$D \propto \sqrt{(E - E_c)}$$ where E_c = Edge of CB.

depends non-linearly on the energy E

for example: if $E = E_c$; $D = 0$

if $E \gg E_c$; $D = \sqrt{E}$



$$D_c(E) = \frac{8\pi m_n^* \sqrt{2 m_n^* (E-E_c)}}{h^3}$$

where m_n^* = effective mass of the electrons in CB.

h = Planck's constant.

Ques: What is the probability that the energy-state 'E' at temperature T is filled with the charge-carrier (electron / hole) in equilibrium?

$\Rightarrow$ The electrons/holes are FERMIONS and follow FERMI-DIRAC statistics.

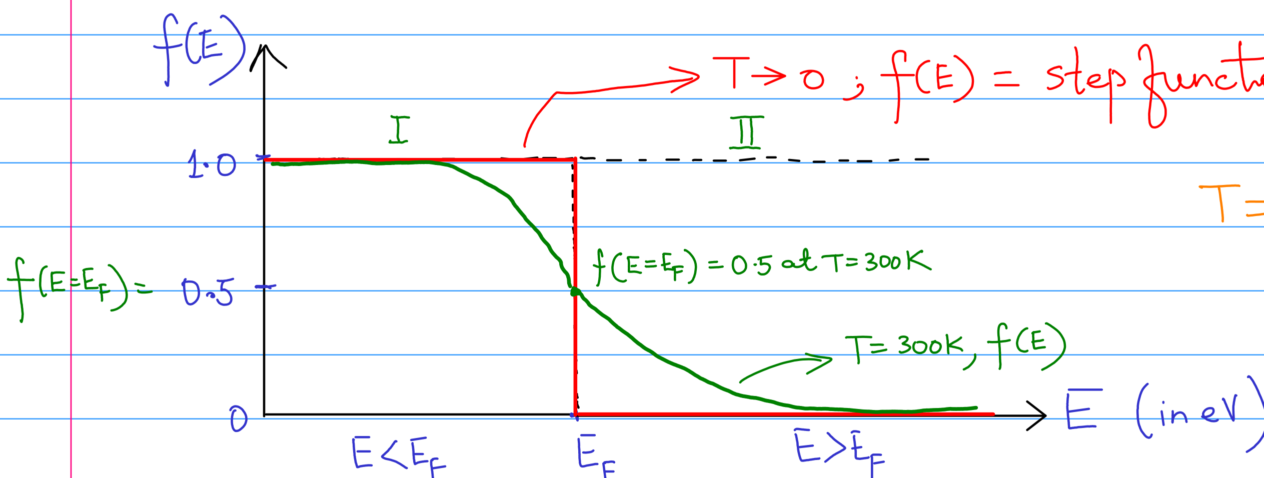
ie,

$$\boxed{f(E) = \frac{1}{1 + \exp\left(\frac{E-E_F}{k_B T}\right)}}$$

here, E_F is termed as "FERMI-ENERGY"

$f(E)$ = Probability that an available energy state at energy E and at Temp. T is occupied with the electron.

$$f(E) = \frac{1}{1+\exp\left[\frac{E-E_F}{k_B T}\right]}$$



i) at $T \to 0K$

a) $E < E_F$ (Region-I)

$$\underbrace{\exp\left[\frac{-(E_F-E)}{k_B T}\right]}_{\to 0} \to 0$$

$$f(E) \to 1$$

b) $E > E_F$ (Region-II)

$$\exp\left(\frac{E-E_F}{k_B T}\right) \to \infty$$

$$f(E) \to 0$$

ii) at $T = 300K$ $\quad k_B T = 25\,meV$

a) $E < E_F$

$$\exp\left(\frac{-(E_F-E)}{k_B T}\right)$$

Vary 'E' from 0 to E_F

b) $E = E_F$

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

c) $E > E_F$ $\quad \exp\left(\frac{E-E_F}{k_B T}\right)$

- Now, we know the DOS in CB and how the electrons occupy the available energy-states.

Therefore, we can calculate the electron density in the conduction band at temp 'T' as

$$n(E,T) = \int_{E_C}^{\infty} \underbrace{f(E)}_{\text{Probability of occupancy}} \cdot \underbrace{D(E)}_{\text{Number of electrons in CB in } cm^{-3}} dE$$

$$n = \int_{E_C}^{\infty} \frac{1}{1+\exp\left(\frac{E-E_F}{k_B T}\right)} \cdot K\sqrt{E-E_C} \cdot dE$$

"FERMI-INTEGRAL"

Approximate Sol^n:

$$n = N_C\, e^{-(E_C-E_F)/k_B T} \quad (\text{in } cm^{-3})$$

where, N_C = effective density of energy states

$$N_C = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2}$$

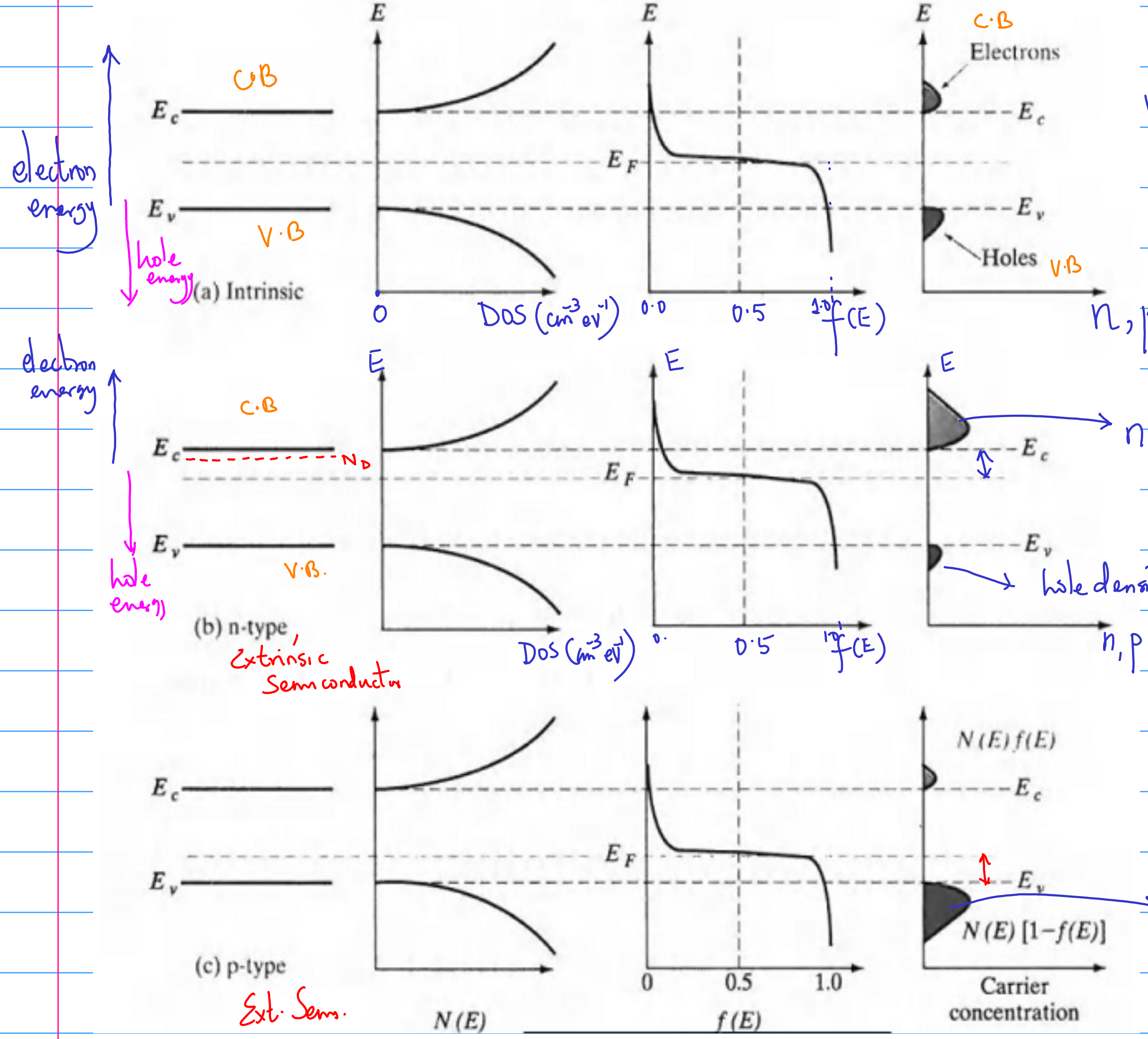
$\sim 10^{19}\ cm^{-3}$ for n-type Silicon at 300K

Density of charge-carriers in Intrinsic & Extrinsic Semiconductors

$n = \int_{E_c}^{\infty} f(E) \cdot DOS \, dE$

$n = N_c e^{-(E_c - E_F)/k_B T}$

$n = p = n_i$



$n = N_c e^{-(E_c - E_F)/k_B T}$

$n \gg p$

$p \gg n$