what is $p \cdot n$?

$$p \cdot n = N_C \cdot N_V \cdot \exp\left(\frac{-E_C + E_F - E_F + E_V}{kT}\right)$$

$$= N_C \cdot N_V \cdot \exp\left(\underbrace{\frac{E_V - E_C}{kT}}_{E_g/kT}\right) = n_i^2 \quad \boxed{\text{law of mass-action}}$$

thus $\boxed{p \cdot n = n_i^2}$ it is a constant!

we can rearrange the terms:

if degenerate $p \cdot n \neq n_i^2$

$$n = n_i \left(\frac{E_F - E_i}{kT}\right)$$

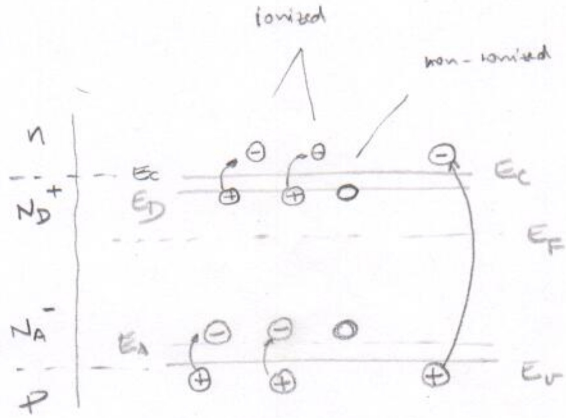
$$p = n_i \cdot \left(\frac{E_i - E_F}{kT}\right)$$

back to slides

⇒ Doping:

Donor: nutral / positive

Acceptor: nutral / negative



Not all dopants are necessarily ionized

$$N_D^+ = \frac{N_D}{1 + g_D \cdot \exp\left(-\frac{E_D - E_F}{kT}\right)}$$

g_D: degeneracy of donor level $= 2$ (spin of electrons)

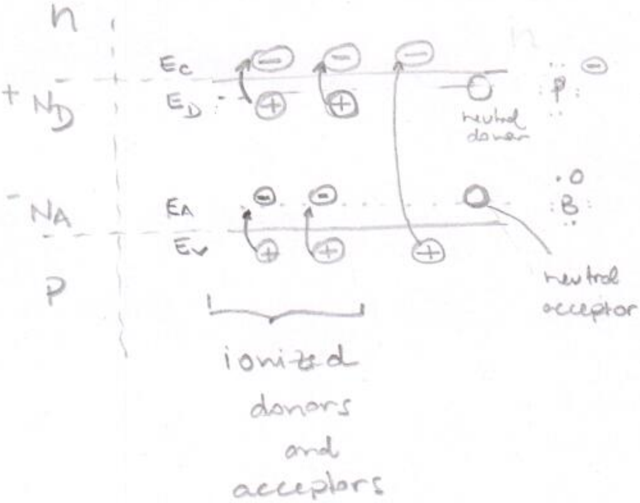
$$N_A^- = \frac{N_A}{1 + g_A \exp\left(\frac{E_A - E_F}{kT}\right)}$$

degeneracy of acceptor level $= g_A = 4$ & spin 2 × degeneracy of band at $k=0$ 2

in most semiconductors there are 2 bands degenerate at $k=0$

Due to charge neutrality :

$$n + N_A^- = p + N_D^+$$



the law of mass-action

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

still applies ! (until degeneracy)

How to calculate the Fermi level ?

- for n-type Si :

$$n = p + N_D^+$$

p : intrinsic $\sim 10^{+10}\ cm^{-3}$

N_D : doping $\sim 10^{18}\ cm^{-3}$

$$\Rightarrow n \simeq N_D^+$$

$$N_C \cdot \exp\left(-\frac{E_C - E_F}{kT}\right) \simeq N_D \cdot \frac{1}{1 + 2\exp\left(-\frac{E_D - E_F}{kT}\right)}$$

for a given N_C, N_D, T, E_D $\Rightarrow$ we can calculate $\underline{\underline{E_F}}$ and then $\underline{\underline{n}}$.

$\Rightarrow$ use graphical method.

or

- n-type

$N_D \gg N_A$: $$n \approx \sqrt{\frac{N_D N_C}{2}} \cdot \exp\left[-\frac{(E_C - E_D)}{2kT}\right]$$

- if N_A is non-negligible:

$N_D > N_A$: $$n \approx \left(\frac{N_D - N_A}{2N_A}\right) \cdot N_C \cdot \exp\left[-\frac{(E_C - E_D)}{kT}\right]$$

At relatively high temperatures, all donors and acceptors are ionized:

$$\boxed{n + N_A = p + N_D}$$

and since $n \cdot p = n_i^2 \Rightarrow n = \frac{1}{2}\left[(N_D - N_A) + \sqrt{(N_D - N_A)^2 + 4n_i^2}\right]$

$n^2 - (N_D - N_A)n - n_i^2 = 0$

in ~~n~~-type semiconductor: $N_D > N_A$

$$n_{n0} = \frac{1}{2}\left[(N_D - N_A) + \sqrt{(N_D - N_A)^2 + 4n_i^2}\right] \approx N_D$$

if $|N_D - N_A| \gg n_i$

or $N_D \gg N_A$

$$p_{n0} = \frac{n_i^2}{n_{n0}} \approx \frac{n_i^2}{N_D}$$

Fermi level:

$$n_{n0} = N_D = N_C \cdot \exp\left(-\frac{E_C - E_F}{KT}\right) = n_i \exp\left(\frac{E_F - E_i}{KT}\right)$$

we can solve numerically or graphically

for p-type semiconductor

- finish + exercices
- complete 1st list of exercices.

$$p = \frac{1}{2}\left[(N_A - N_D) + \sqrt{(N_A - N_D)^2 + 4n_i^2}\right]$$

$\simeq N_A$ $\left\{ \begin{array}{l} \text{if } |N_A - N_D| \gg n_i \\ \text{or } N_A \gg N_D \end{array}\right.$

$$n = \frac{n_i^2}{N_A}$$

fermi-level:

$$p = N_A = N_V \cdot \exp\left(-\frac{E_F - E_V}{KT}\right) = n_i \cdot \exp\left(\frac{E_i - E_F}{KT}\right)$$