Lec 9

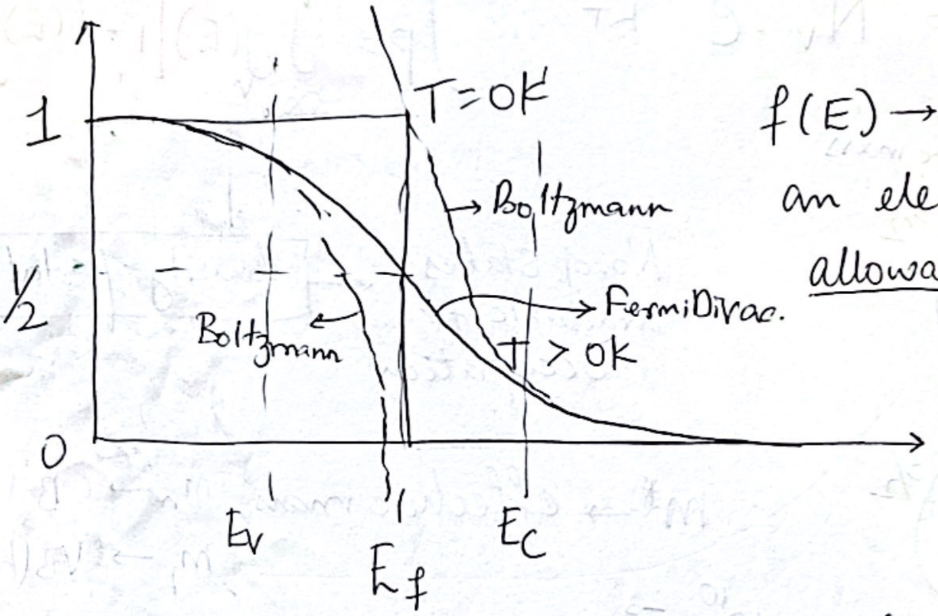
Carrier distribution

> Electrons → Fermions ⇒ Fermi Dirac Distribution.

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

$k \rightarrow$ Boltzmann const.

$1.38 \times 10^{-23} \frac{m^2 kg}{s^2 K}$ or J/K



$f(E) \rightarrow$ Probability that an electron fills an allowable Energy state E.

$E_f \rightarrow$ Fermi level $\rightarrow f(E) = \frac{1}{2}$ (doesn't mean electron will be here since there may not be an allowable state here).

> When studying conduction band we approximate with Boltzmann distribution. Same for valence band.

$CB \Rightarrow f(E) \simeq e^{-(E-E_f)/kT}$ $E - E_f > 3kT$

$VB \Rightarrow f(E) \simeq 1 - e^{(E-E_f)/kT}$ $E - E_f < -3kT$

↳ Taylor $\frac{1}{x+1} \simeq 1 - x$ when x is small.

$\Rightarrow$ number of electrons in conduction band per unit volume (aka carrier concentration)

$$n \propto e^{-(E_c - E_f)/KT}$$

$\Rightarrow$ $n = N_c \cdot e^{\frac{E_f - E_c}{KT}}$

Similarly $p = N_v \cdot e^{\frac{E_v - E_f}{KT}}$

$$\left.\begin{array}{l} n = \int_{E_c}^{\infty} g_c(E) f(E) dE \\ p = \int_{-\infty}^{E_v} g_v(E)[1 - f(E)] dE \end{array}\right\}$$

density of states $\rightarrow$ No. of states available for occupation

effective density of states at edge of CB/VB

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

effective mass

$$N_v = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2}$$

$m^* \rightarrow$ effective mass $m_n \rightarrow$ CB (electron)

$m_p \rightarrow$ VB (hole)

> Intrinsic Si $\Rightarrow$ $n = p = n_i = N_c e^{\frac{E_i - E_c}{KT}} = N_v e^{\frac{E_v - E_i}{KT}}$

(n_i: 10^{10} cm^{-3})

where $E_i = E_f$ for intrinsic Silicon. $\Rightarrow$ $N_c = n_i e^{\frac{E_c - E_i}{KT}}$

$N_v = n_i e^{\frac{E_i - E_v}{KT}}$

$\Rightarrow$ $n = n_i e^{\frac{E_f - E_i}{KT}}$

$p = n_i e^{\frac{E_i - E_f}{KT}}$

& $\boxed{np = n_i^2}$

$E_f > E_i \Rightarrow$ more electrons (donor) $\rightarrow$ n type sc

$E_f < E_i \Rightarrow$ more holes (acceptors) $\rightarrow$ p type sc.

Motion of free carriers

Diffusion

- Motion of charge carriers due to concentration gradient.
- Random process due to thermal energy.
- Thermal velocity $v_{th} \simeq 10^5\, m/s$ $\left[\frac{1}{2} m_n^* v_{th}^2 = \frac{3}{2} kT\right]$ in 3D

  Equipartition theorem

  m_n^* → effective mass.
- In Silicon average time between collisions
  - → mean free path $(\lambda) \rightarrow 10^{-8}\, m$
  - → mean scattering time $(\tau_c) \rightarrow 10^{-13}\, s$

  $\Rightarrow \lambda = v_{th} \tau_c$

e^-

$J_{diffusion} \propto -\frac{dn}{dx}$ → gradient of charge carrier concentration

$$\boxed{J_{n\,diff} = q D_n \frac{dn}{dx}}$$

D_n, D_p → Diffusion constant.

$$\boxed{J_{p\,diff} = -q D_p \frac{dp}{dx}}$$

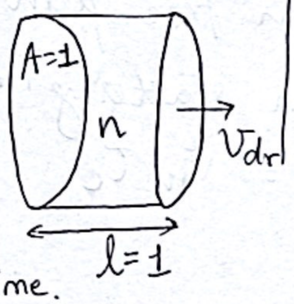
$$\boxed{D_n = \frac{kT}{q} \mu_n \,, \quad D_p = \frac{kT}{q} \mu_p}$$ → Einstein relations.

Drift

- Motion (avg) of charge carriers under an applied Electric field.
- For a free space electron $F = ma = qE$
- In a lattice, due to scattering $v_{dr} = -\mu_n E$
  mobility

$$\mu_n = \frac{q\,\tau_c}{m_n^*} \qquad v_{dr} = \left(\frac{qE}{m^*}\right)\tau_c$$

$$\Rightarrow J_{n\,drift} = (-q)\,\underbrace{n\,v_{dr}}_{\text{no. of charge carriers passing A per unit time.}}$$



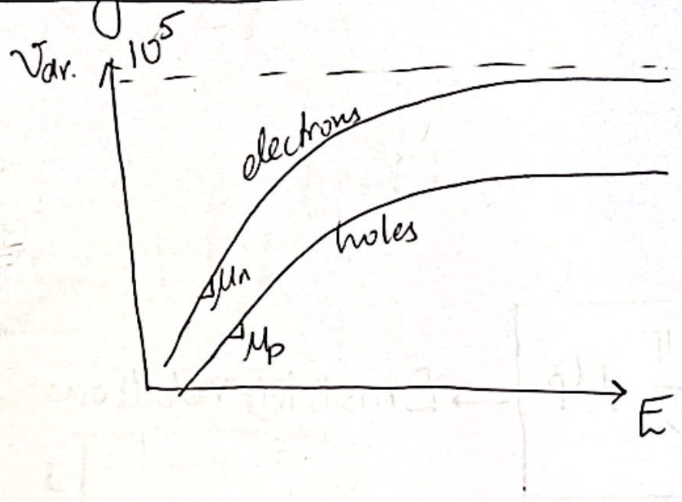
$$\boxed{J_{n\,drift} = nq\,\mu_n E}$$

Typically (1V over 1mm)

$\Rightarrow v_{dr} \simeq 100$ m/s

$$J_{drift} = \underbrace{q(n\mu_n + p\mu_p)}_{\sigma}E \quad \text{(Microscopic picture of } \sigma\text{)}$$

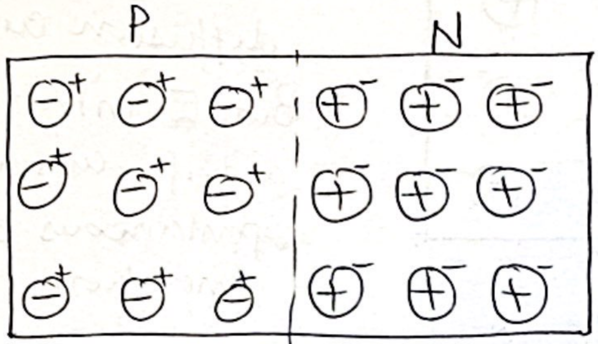
Velocity Saturation



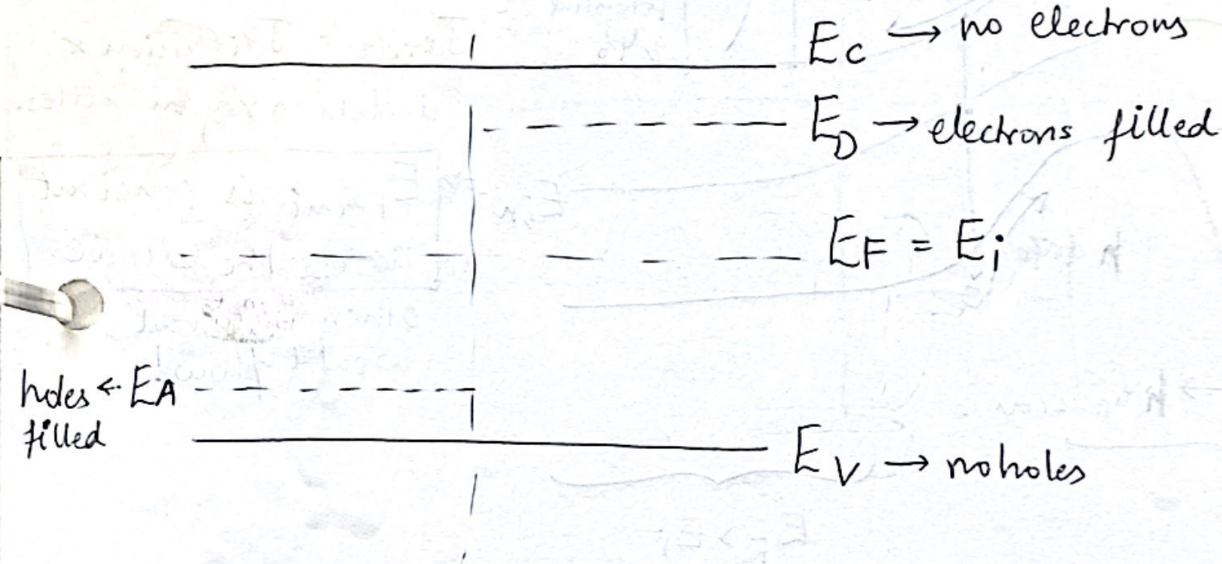
- At high fields $\mu \to 0$.
  Modern MOSFETs operate in this regime since E is very high in short channel devices.

PN Junction

At T = 0K



> Charge neutral
> Frozen!
> Note the large gradient in carrier concentration ⇒ Diffusion (but T = 0K)



> When T > 0K, electrons in E_D are "released" to E_c, i.e. they become free electrons in the lattice. Similarly $E_V \rightarrow E_A$ electrons leave behind "free holes" & start moving around.

> At the boundary these free electrons & holes recombine, leaving behind ions in a so called Depletion region.

> This process happens very rapidly and a "built in" potential develops across the boundary.