ⓑ N-type and P-type Semiconductors

a semicond. containing donor atoms is called N-type
// // // acceptor atoms is called P-type.

N-type semicond has ~~more~~ more free e^- than hole.
P-type // // // // holes than e^-

the material is, however, charge neutral. $\boxed{n+N_A = p+N_D}$

- ~~of N type~~ We call N_D the donor concentration
  N_A the acceptor concentration.

~~$n = N_D$ N_D = doping concentration of donor~~

for non-degenerate semicond.

$$\Rightarrow \quad n = N_c \exp\left[-\beta(E_c - E_F)\right]$$

$$= N_c \exp\left[-\beta(E_c - E_i)\right] \exp\left[(E_F - E_i)\beta\right]$$

$$\boxed{n = n_i \exp\left[\beta(E_F - E_i)\right]}$$

$$\Rightarrow \quad \boxed{p = \frac{n_i^2}{n} = n_i \exp\left[-\beta(E_F - E_i)\right]}$$

The Fermi-level adjusts itself to ensure charge neutrality in the semiconductor.

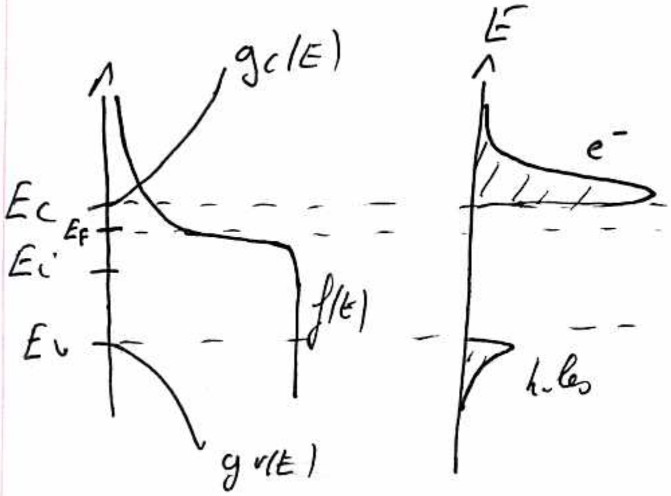
⇒

* if N-type   charge neutrality $n \simeq N_d$ (complete ionization)

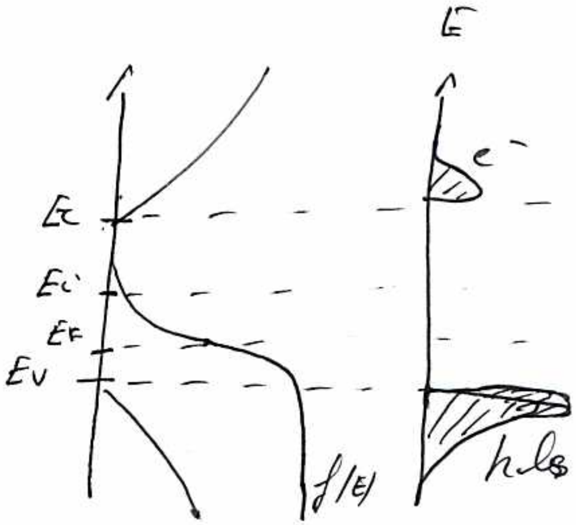
$$E_F - E_i = \frac{1}{\beta} \ln\left[\frac{N_d}{n_i}\right]$$

* if P-type $p \simeq N_a$.

$$E_F - E_i = -\frac{1}{\beta} \ln\left[\frac{N_a}{n_i}\right].$$



N-type



P-type

* if both Donor and acceptor impurities [compensated semiconduct

$$\boxed{n + N_A = p + N_D}$$ using $np = n_i^2$.

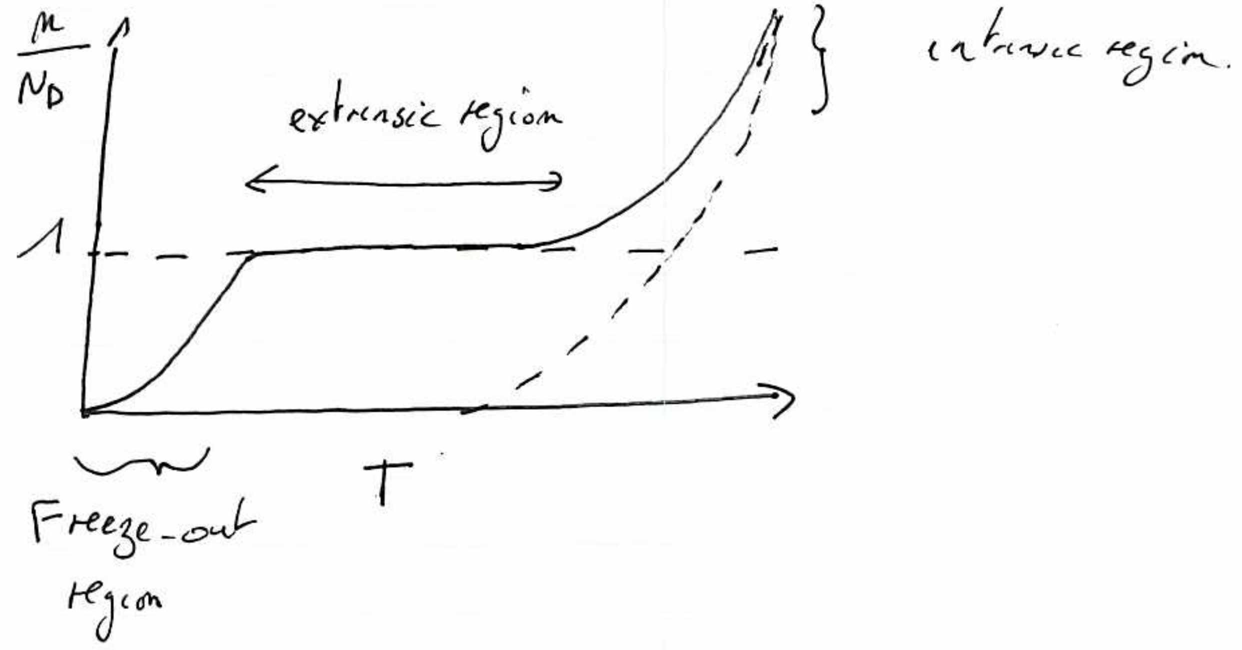
we get ⇒

$$\left[\begin{array}{l} n = \dfrac{N_D - N_A}{2} + \sqrt{\left(\dfrac{N_D - N_A}{2}\right)^2 + n_i^2} \\ p = \dfrac{N_A - N_D}{2} + \sqrt{\left(\dfrac{N_A - N_D}{2}\right)^2 + n_i^2} \end{array}\right.$$

Ⓒ Additional comments

(ii) Temperature variation of n.

Type N ⇒ with N_D for donor concentration



* at low T, the thermal energy is not enough to ionize all the donor impurities present. Some e^- are frozen at the donor energy level.

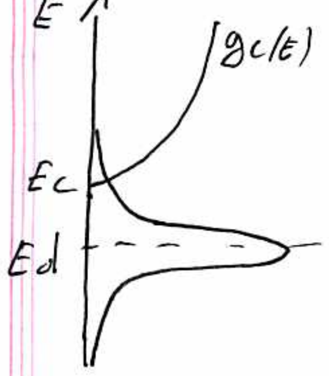
* if T increase, the condition of complete ionization is reached $[n = N_D]$.

* if T is very large, the intrinsic carrier concentration n_i, becomes comparable to the donor concentration. Beyond this point the semiconductor becomes intrinsic.

(ii) Impurity bands

usually doping concentration 10^{15} to 10^{18} atoms/cm^3
[Number of atoms 10^{22} cm^{-3}].

When doping increases, wavefunctions of the donors begin to overlap.



The discrete donor level ~~broadens~~ broadens into a band which overlaps with the CB.

⇒ reduction of the band-gap
⇒ band-gap narrowing effect.

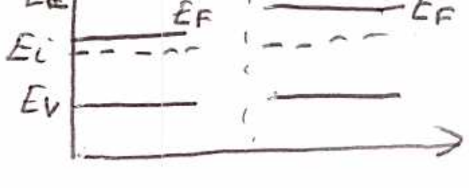
"degenerate semiconductor" or
"degenerately doped" semiconductor.

(iii) Fermi levels alignment

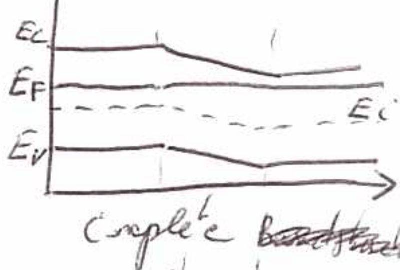
- At thermodynamic equilibrium, the Fermi-level in a structure is unique and constant.
- The energy gap between VB and CB is also cte.

What happen if the doping concentration in a semiconductor varies.

ex



Alignment



Complete ~~band~~ structure

IV Theory of Electrical Conduction

(1) Hierarchy of transport models

decreasing level of sophistication

Quantum model ⇒

- e^- as a wave
- From atomistic to effective mass description of the electr structure
- Scattering phenomena and many body effects [difficult to account for]
- necessary model to describe transport in small size semicon
  ⇒ nanoelectronics

Semi-Classical. BTE (Boltzmann Transport Equation) ⇒

- e^- as a particle
- Quantum probabilistic scattering rates (Fermi-Golden rule)
- Application area: ~~From~~ Microelectronics to Nanoelectron

Drift-Diffusion ⇒

- Fluid-type model for e^-
- Long device = electronics to microelectronics.

② Carrier transport = basics

- Any motion of free carriers in a semiconductor leads to a current
- Since these carriers are charge particles, this motion can be caused by an electric field. We refer to this transport mechanism as carrier drift.
- Carriers also move from region where the carrier density is high to regions where it is low. We refer this phenomenon as carrier diffusion.

Total current need to account for drift and diffusion currents.

In the x direction

for e^- $\longrightarrow$ $J_n = q n \mu_n \mathcal{E} + q D_n \frac{dn}{dx}$

for holes $\longrightarrow$ $J_p = q p \mu_p \mathcal{E} - q D_p \frac{dp}{dx}$

$$\boxed{\begin{aligned} J_n &= q n \mu_n \mathcal{E} + q D_n \frac{dn}{dx} \\ J_p &= \underbrace{q p \mu_p \mathcal{E}}_{\text{Drift current}} - \underbrace{q D_p \frac{dp}{dx}}_{\text{Diffusion current}} \end{aligned}}$$

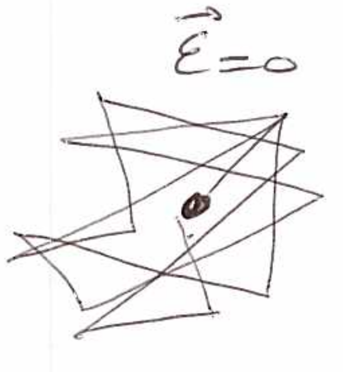
μ is the mobility

D is the diffusion coefficient.

③ Carrier drift

ⓐ Mobility

* w/o Electric field

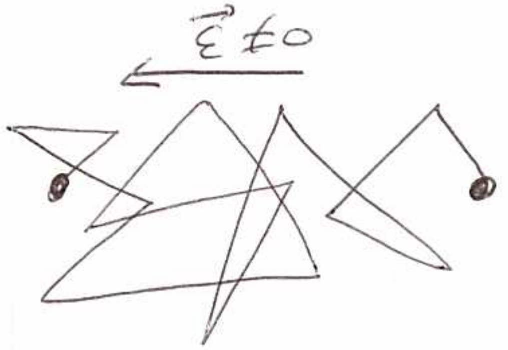


The change of direction is due to scattering

- The carrier exhibits random motion (can be compared to the Brownian motion of fine particles in a liquid)

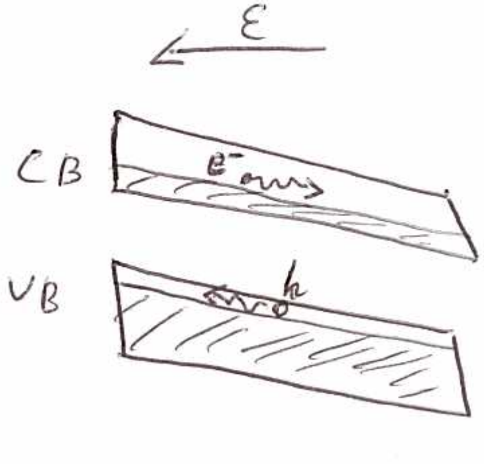
- all those small movements average out and the net displacement of the electron is zero.

* with Electric field



- random motion still occurs but in addition, there is on average a net motion along the direction of the field

- Due to their electric charge, e^- move on average in the opposite direction of $\vec{E}$.
  holes move in the same direction



we consider the average velocity $\langle\vec{v}\rangle$ of the carriers. Following Newton law:

$$\vec{F} = m\vec{a} = m\frac{d\langle\vec{v}\rangle}{dt}.$$

$\vec{F}$ consists of the difference between the electrostatic force and the scattering force (loss of momentum at the time of scattering) this force is then equal to the momentum divided by the average time between scattering events τ:

$$\boxed{\vec{F} = q\vec{\mathcal{E}} - \frac{m\langle\vec{v}\rangle}{\tau}} \qquad \underline{q = \text{charge of the particle}}$$

we get $\quad q\vec{\mathcal{E}} = m\frac{d\langle\vec{v}\rangle}{dt} + \frac{m\langle\vec{v}\rangle}{\tau}$

under steady state current (the particle has reached a constant average velocity)

$$q\vec{\mathcal{E}} = \frac{m\langle\vec{v}\rangle}{\tau}$$

we call μ mobility $\Rightarrow \boxed{\mu = \frac{q\tau}{m}}$ $q>0$

μ is expected to be large
- if m is small
- if τ (time between scattering events) is large.

For e^- $\quad \langle\vec{v}_n\rangle = -\mu_n\vec{\mathcal{E}} \qquad \mu_n = \frac{q\tau}{m_e^*}$

For holes $\quad \langle\vec{v}_p\rangle = \mu_p\vec{\mathcal{E}} \qquad \mu_p = \frac{\tau q}{m_h^*}$

- If effective mass of $\bar{e}$ / ~~and~~ holes is anisotropic, the effective mass is represented by a tensor (so the mobility). Because of the symmetry of Si, one can however use a scalar expression:

$$\frac{1}{m^*} = \frac{1}{3}\left(\frac{1}{m^*_p} + \frac{2}{m^*_t}\right)$$

in Si $m^*_e = 0.26 m_0$

$m^*_h = 0.37 m_0$

- mobility depends on ~~the interactions between $\bar{e}$ and phonons, and impurities~~. Scatterings including:

$\frac{1}{\mu} = \sum_x \frac{1}{\mu_x}$

(i) - impurity scattering = such as ionized atoms (donors and acceptors).

one can show that

$$\mu_{ii} \sim \frac{T^{3/2}}{N}$$ N = impurity concentration

(ii) Lattice scattering = interactions between e^- and phonons. density of phonons increases with T ⇒ scattering time. so mobility will decrease with T. We expect:

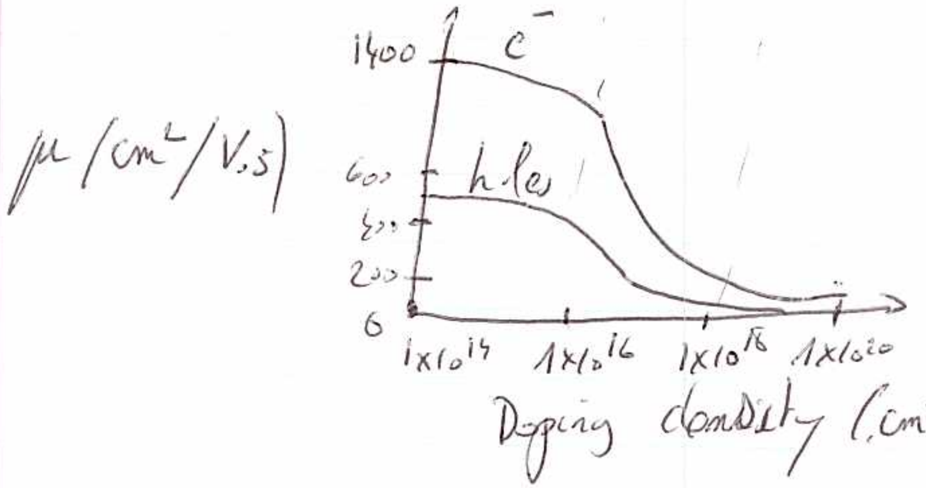
$$\mu_{ac} \sim T^{-3/2} \text{ (acoustic phonons)}$$

$$\mu_{op} \sim T^{-1/2} \text{ (optical phonons)}$$

(iii) Surface scattering =

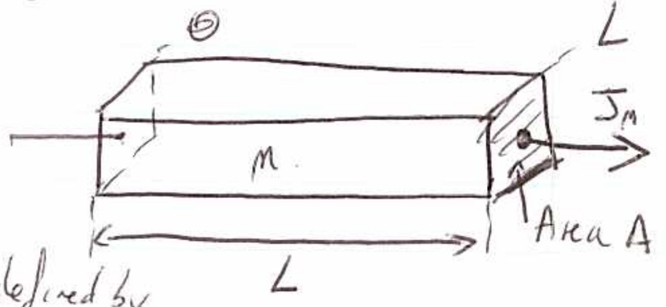
μ can be much lower ~~than~~ at the surface, than in the bulk.

Remark * Doping dependence. (room temperature)



For low doping concentration, the mobility is almost cte, and is primarily limited by phonon scattering - if the doping increases, μ ↘ due to ionized impurity scattering.

(b) Drift current



the current is defined by

$$I = \frac{Q}{t_r}$$ where Q is total charge in the semiconductor.

$Q = -q\underline{n}V$ for e⁻ $\underline{V = LA}$

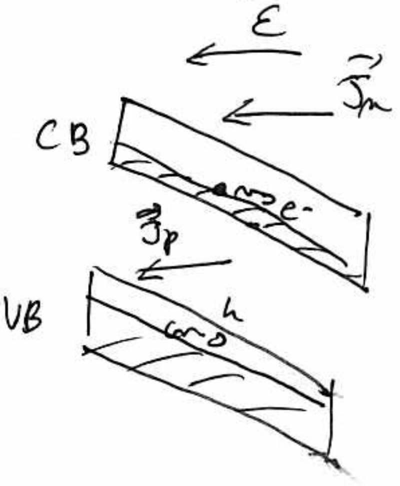
$Q = q\underline{p}V$ for holes

t_r is the transit time of the particle (time needed to go from 0 to L)

$$t_r = \frac{L}{v}$$

The current density can be written

$$\boxed{\vec{J_n} = \frac{I_n}{A} = \frac{-qn\cancel{V}\vec{v_n}}{\cancel{L}A} = -qn\vec{v_n}}$$



similarly $\boxed{\vec{J_p} = qp\vec{v_p}}$

using the relations $\vec{v_n} = -\mu_n \vec{\mathcal{E}}$

$\vec{v_p} = \mu_p \vec{\mathcal{E}}$

the total current density becomes

$$\boxed{\vec{J} = \vec{J_n} + \vec{J_p} = (qn\mu_n\vec{\mathcal{E}} + qp\mu_p\vec{\mathcal{E}}}$$

* $\vec{J} = q(n\mu_n + p\mu_p)\vec{\mathcal{E}}$

we set $q(n\mu_n + p\mu_p) = \sigma$ conductivity

$\Rightarrow \boxed{\vec{J} = \sigma\vec{\mathcal{E}}}$

the resistivity is given by $\rho = \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\mu_p)}$

For N-type device ⇒ $\rho \simeq \frac{1}{qn\mu_n}$.

For P-type device ⇒ $\rho \simeq \frac{1}{qp\mu_p}$