Lecture 7 - Carrier Drift and Diffusion *(cont.)*

September 19, 2001

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Reading assignment:

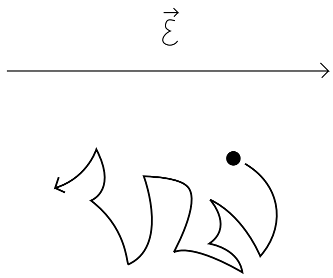
del Alamo, Ch. 4, §4.2-4.4

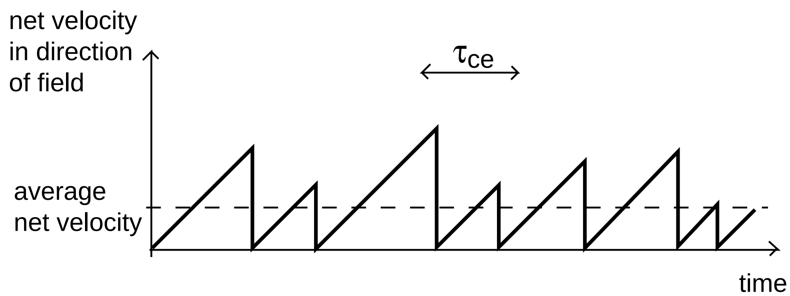
Key questions

- How do carriers move in an electric field? What are the key dependencies of the drift velocity?
- How do the energy band diagrams represent the presence of an electric field?
- How does a concentration gradient affect carriers?
- How much time does it take for a carrier, on average, to travel from one region of a semiconductor to another by drift or diffusion?

1. Drift

Carrier movement in presence of electric field:





□ Drift velocity

-electric field: $\mathcal{E}$
-electrostatic force on electron: $-q\mathcal{E}$
-acceleration between collisions: $\frac{-q\mathcal{E}}{m^*_{ce}}$
-velocity acquired during time τ_{ce}:

$$v_e^{drift} = -\frac{q\mathcal{E}\tau_{ce}}{m^*_{ce}}$$

or

$$v_e^{drift} = -\mu_e\mathcal{E}$$

$$\mu_e \equiv \text{electron mobility } [cm^2/V \cdot s]$$

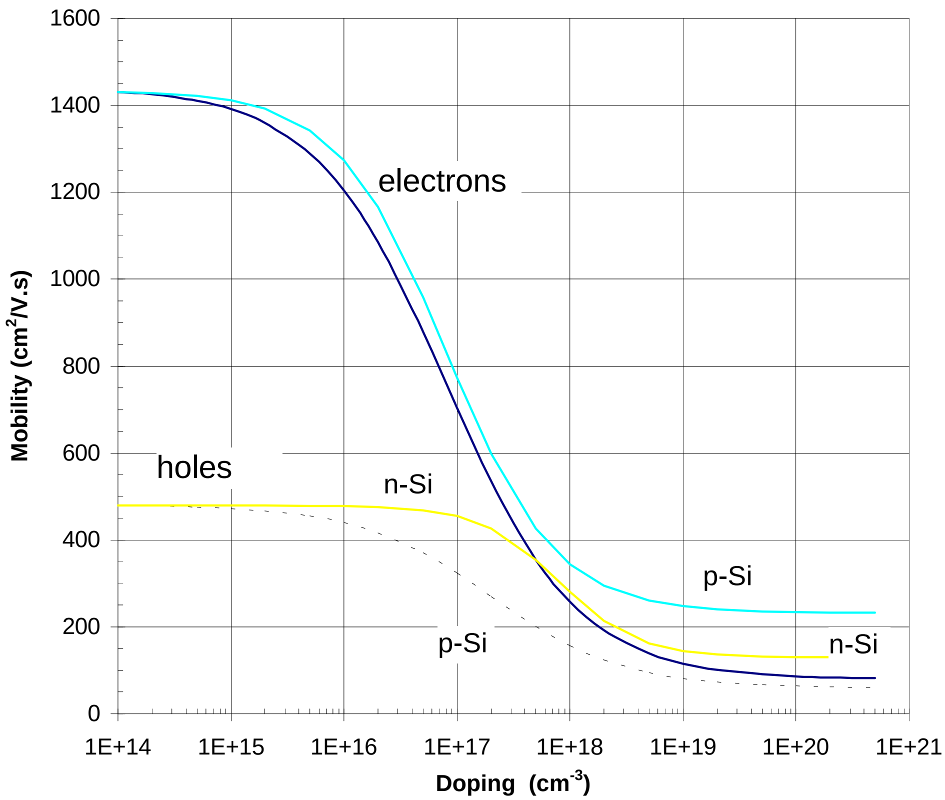
Mobility indicates ease of carrier motion in response to $\mathcal{E}$.

$$v_e^{drift} = -\mu_e \mathcal{E}$$

$$v_h^{drift} = \mu_h \mathcal{E}$$

Mobility depends on doping level and whether carrier is majority or minority-type.

Si at 300 K:



- at low N: limited by phonon scattering
- at high N: limited by ionized impurity scattering

□ Velocity saturation

Implicit assumption: *quasi-equilibrium*, that is, scattering rates not much affected from equilibrium.

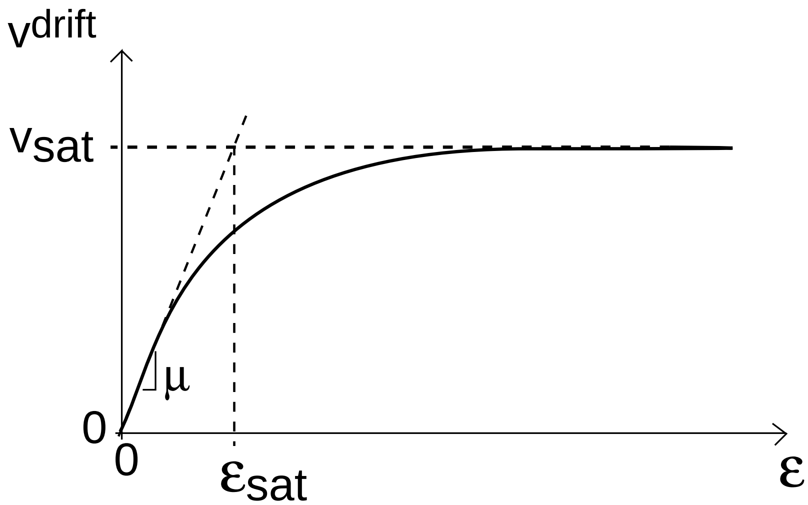
$$v^{drift} \sim \mathcal{E} \quad \text{only if} \quad v^{drift} \ll v_{th}$$

For high $\mathcal{E}$: carriers acquire substantial energy from $\mathcal{E}$

→ optical phonon emission strongly enhanced
→ scattering rate $\sim 1/\mathcal{E}$
→ **drift velocity saturates**

$$v_{sat} \simeq \sqrt{\frac{8}{3\pi}\frac{E_{opt}}{m_c^*}}$$

For Si at 300 K, $v_{sat} \simeq 10^7\ cm/s$



Drift velocity vs. electric field fairly well described by:

$$v^{drift} = \mp \frac{\mu \mathcal{E}}{1 + |\frac{\mu \mathcal{E}}{v_{sat}}|}$$

Field required to saturate velocity:

$$\mathcal{E}_{sat} = \frac{v_{sat}}{\mu}$$

Velocity saturation crucial in modern devices:

if $\mu = 500\ cm^2/V.s$, $\mathcal{E}_{sat} = 2 \times 10^4\ V/cm$ (2 V across 1 μm)

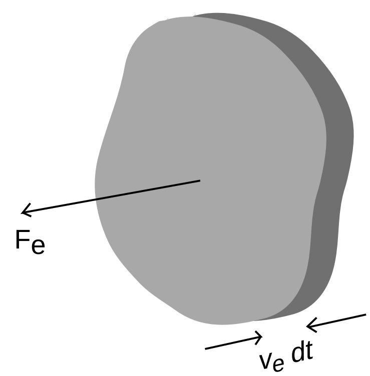
Since μ depends on doping, $\mathcal{E}_{sat}$ depends on doping too.

□ Particle flux and current density

particle flux ≡ # particles crossing unity surface (normal to flow) per unit time $[cm^{-2} \cdot s^{-1}]$

current density ≡ electrical charge crossing unity surface (normal to flow) per unit time $[cm^{-2} \cdot s^{-1}]$

$$J_e = -qF_e$$



$$F_e = \frac{nv_e dt}{dt} = nv_e$$

Then

$$J_e = -qnv_e$$

$$J_h = qpv_h$$

• Drift current (low fields):

$$J_e = q\mu_e n\mathcal{E}$$

$$J_h = q\mu_h p\mathcal{E}$$

total:

$$J = q(\mu_e n + \mu_h p)\mathcal{E}$$

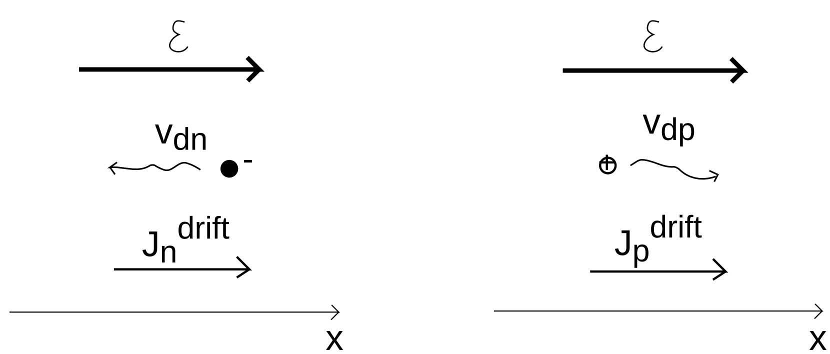
Electrical conductivity $[(\Omega \cdot cm)^{-1}]$:

$$\sigma = q(\mu_e n + \mu_h p)$$

Electrical resistivity $[\Omega \cdot cm]$:

$$\rho = \frac{1}{q(\mu_e n + \mu_h p)}$$

Check signs:



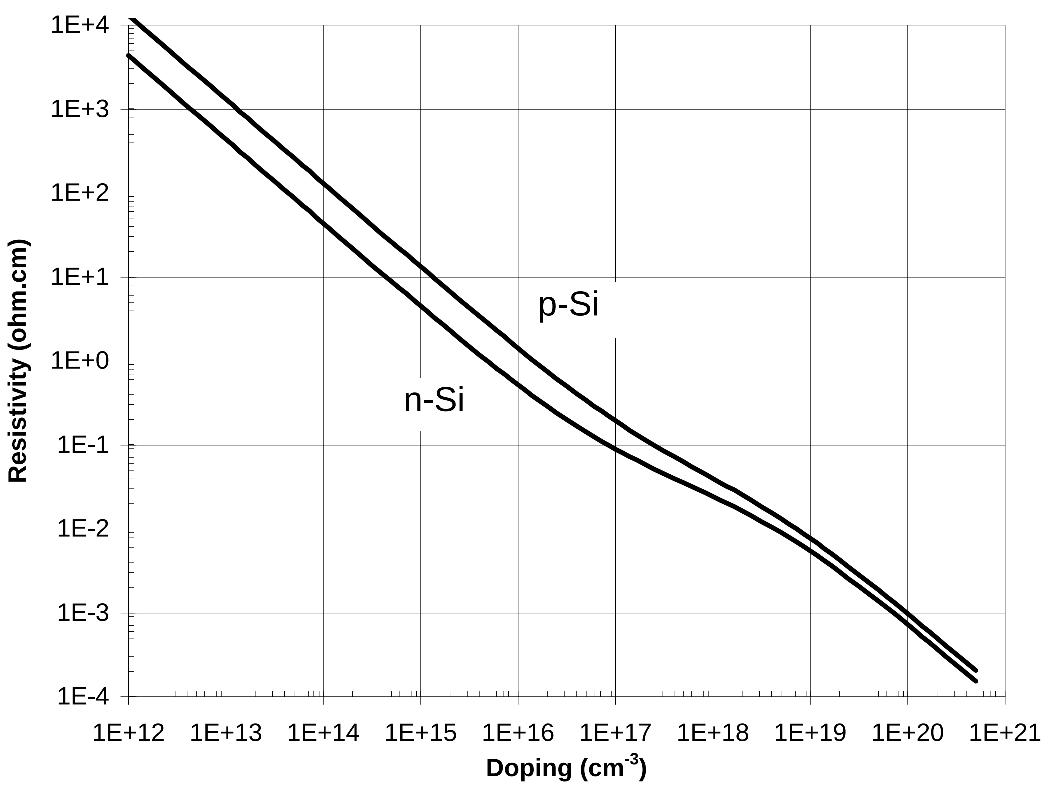
$$\rho = \frac{1}{q(\mu_e n + \mu_h p)}$$

ρ strong function of doping $\Rightarrow$ frequently used by wafer vendors to specify doping level of substrates

-for n-type: $\rho_n \simeq \frac{1}{q\mu_e N_D}$

-for p-type: $\rho_p \simeq \frac{1}{q\mu_h N_A}$

Si at 300K:



- Drift current (high fields):

$$J_{esat} = qnv_{esat}$$

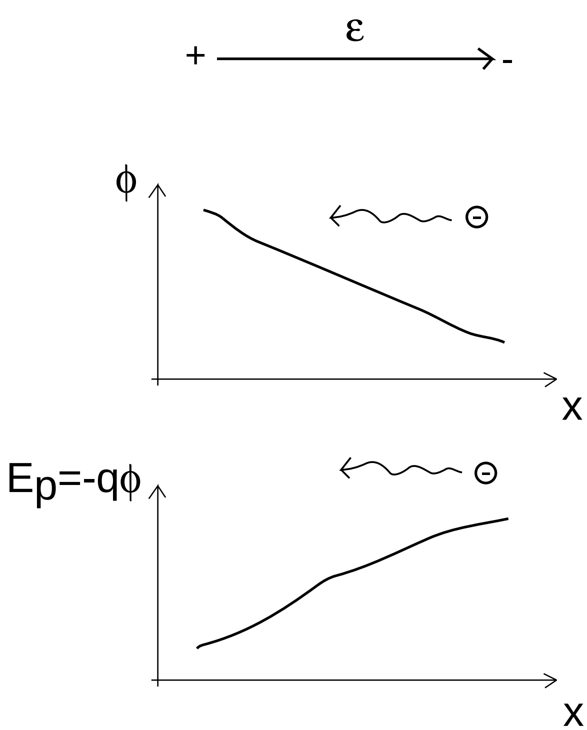
$$J_{hsat} = qpv_{hsat}$$

The only way to get more current is to increase carrier concentration.

□ Energy band diagram under electric field

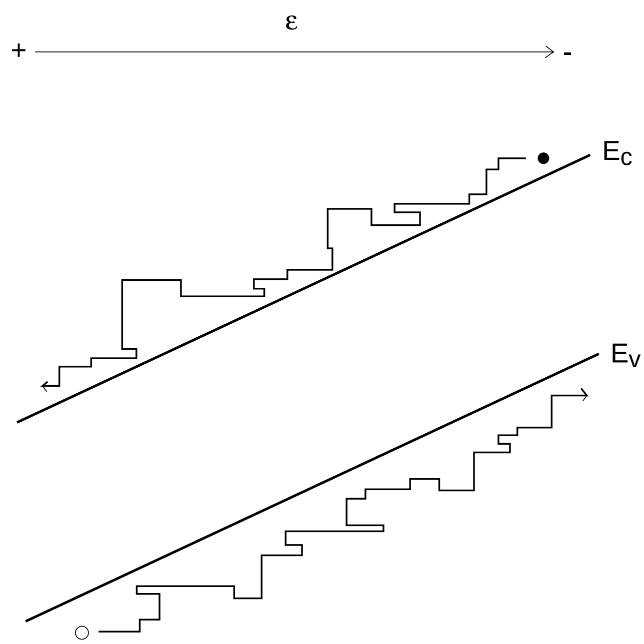
Energy band diagram needs to account for potential energy of electric field

- Vacuum:



Electron trades potential energy by kinetic energy as it moves to the left → *total electron energy unchanged*

- Must add E_p to semiconductor energy band diagram $\Rightarrow$ bands tilt



Meauring from an arbitrary energy reference, E_{ref}:

$$E_c + E_{ref} = E_p = -q\phi$$

Then:

$$\mathcal{E} = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_c}{dx} = \frac{1}{q}\frac{dE_v}{dx}$$

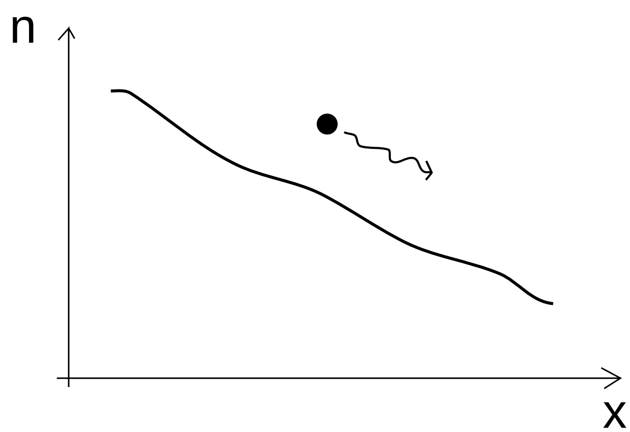
Shape of energy bands = shape of ϕ with a minus sign.

Can easily compute $\mathcal{E}$ from energy band diagram.

2. Diffusion

Movement of particles from regions of high concentration to regions of low concentration.

Diffusion produced by collisions with background medium (*i.e.*, vibrating Si lattice).



- Diffusion flux $\propto$ concentration *gradient* [Fick's first law]

$$F_e = -D_e \frac{dn}{dx}$$

$$F_h = -D_h \frac{dp}{dx}$$

$$D \equiv \text{diffusion coefficient } [cm^2/s]$$

$$F_e = -D_e \frac{dn}{dx}$$

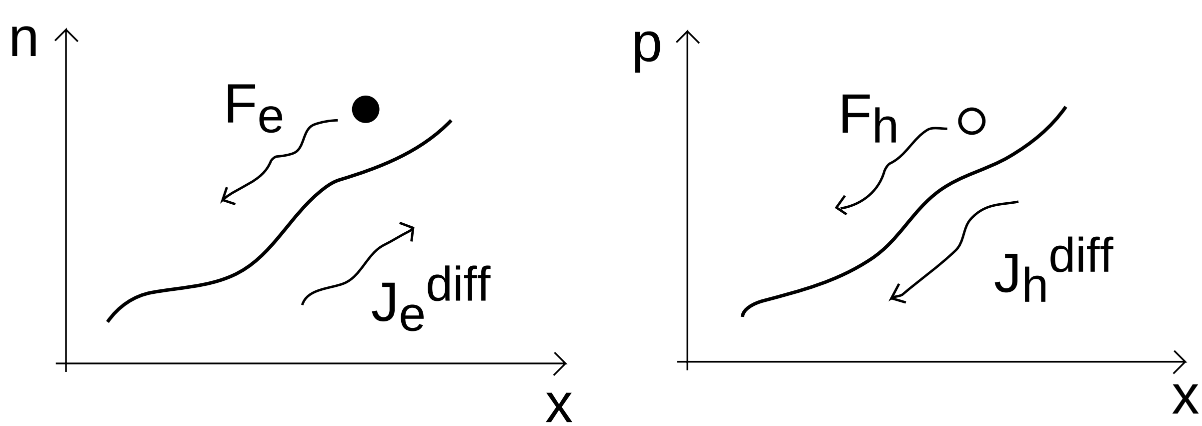
$$F_h = -D_h \frac{dp}{dx}$$

- Diffusion current:

$$J_e = qD_e \frac{dn}{dx}$$

$$J_h = -qD_h \frac{dp}{dx}$$

Check signs:



3. Transit time

Transit time ≡ average time for a carrier to travel through a certain region.

$$\tau_t = \int_0^{\tau_t} dt = \int_0^L \frac{dx}{v(x)}$$

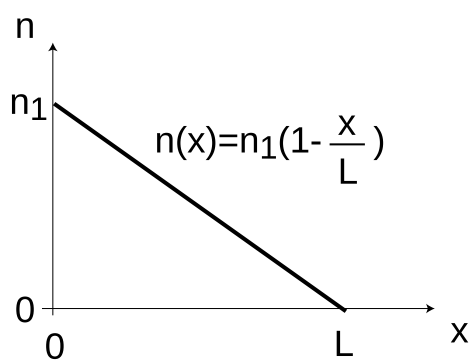
- Diffusion transit time:

$$J_e = qD_e \frac{dn}{dx} = -qnv_e^{diff} \;\Rightarrow\; v_e^{diff} = -D_e \frac{1}{n}\frac{dn}{dx}$$

Then:

$$\tau_t = -\frac{1}{D_e}\int_0^L \frac{n}{\frac{dn}{dx}} dx$$

Example: linear profile (as in base of BJT):

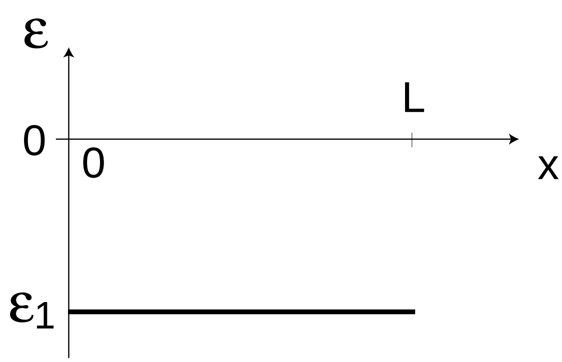


pure diffusion: $\tau_t = \frac{L^2}{2D_e}$

- Drift transit time (low field):

$$v_e^{drift} = -\mu_e \mathcal{E}$$

Example: uniform field:



pure drift: $\tau_t = \frac{L}{\mu_e \mathcal{E}_1}$

Key conclusions

- Two processes for carrier flow in semiconductors: drift and diffusion.
- General relationship between carrier net velocity (by drift or diffusion) and current density:

$$J_e = -qnv_e \qquad\qquad J_h = qpv_h$$

- For low fields, $v^{drift} \sim \mathcal{E}$.
- For high fields, $v^{drift} \sim v_{sat}$.
- Driving force for diffusion: concentration gradient.
- *Transit time*: mean time for carriers to travel from one region to another by drift or diffusion.
  - by diffusion:
$$\tau_t \sim \frac{L^2}{D}$$
  - by drift:
$$\tau_t \sim \frac{L}{\mu\mathcal{E}}$$
- Order of magnitude of key parameters for Si at 300K:
  - electron mobility: $\mu_e \sim 100 - 1400\ cm^2/V \cdot s$
  - hole mobility: $\mu_h \sim 50 - 500\ cm^2/V \cdot s$
  - saturation velocity: $v_{sat} \sim 10^7\ cm/s$

Self study

- Study doping dependence of $\mathcal{E}_{sat}$.
- Study phenomenological diffusion model in §4.3.
- Perform calculations of transit time of both lecture examples.
- Study transit time calculation if drift and diffusion are present simultaneously.