EPFL

EE-557
Semiconductor devices I

Charge Transport

Génie Electrique et Electronique
Master Program
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Outline of the lecture

- Charge Transport
- thermal velocity
- Carrier transport: drift and diffusion

Read Chapter 4 of the reference book (on moodle)

References:

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)

Key questions

- Are carriers sitting still in thermal equilibrium?
- How do carriers move in an electric field?
- How do the energy band diagrams represent the presence of an electric field?
- How does a concentration gradient affect carriers?

Carrier flow in semiconductors

Any **motion of free carriers** in a semiconductor leads to a **current**.

Drift:

This motion can be caused by an **electric field** due to an externally applied voltage (electric field), since the carriers are charged particles. We will refer to this transport mechanism as **carrier drift**.

Ex: n-channel MOSFET

Diffusion:

In addition, carriers also move from regions where the **carrier density is high to regions where the carrier density is low**. This carrier transport mechanism is due to the thermal energy and the associated random motion of the carriers. We will refer to this transport mechanism as **carrier diffusion**.

Ex: npn bipolar transistors

The **total current** in a semiconductor equals the **sum** of the **drift and the diffusion** currents.

What happens with electrons at a given temperature without electric field?

Thermal motion and scattering

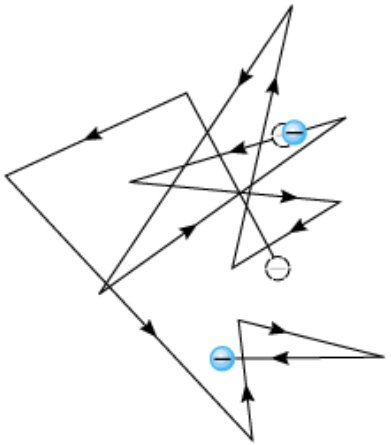
We can think of carriers as particles in **an ideal gas**.

At finite T, carriers have **finite thermal energy**. All this energy resides in the **kinetic energy** of the particles.

Carriers move in **random directions**: no net velocity, but average carrier velocity is thermal velocity:

$$v_{th} = \sqrt{\frac{8\,kT}{\pi\,m_c^*}}$$

Zero electric field



$m^*_{ce} \equiv$ **conductivity effective mass** [$eV \cdot s^2/cm^2$]

- This is the effective mass that connects the kinetic energy of an electrons with its velocity
- It accounts for all interactions between the carriers and the perfect periodic potential of the lattice.
- m^*_{ce} and m^*_{ch} are different from the effective mass from the density of states (you can find the values in appendix B on moodle)

For electrons in Si at 300 K (m_{ce} =0.28m_o) and v_{the} =2 × 10^7 cm/s

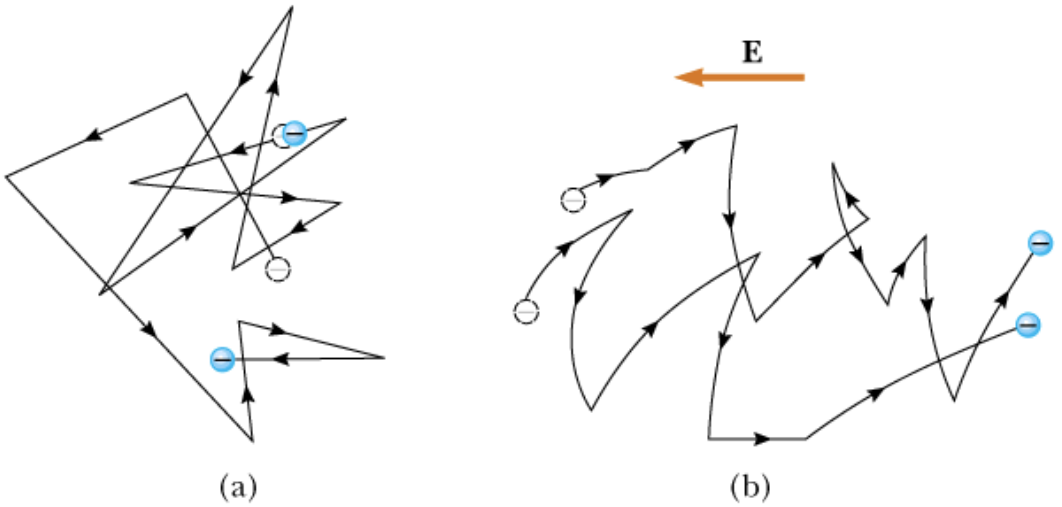
Thermal motion and scattering

But... **semiconductor crystal is not perfect**:

- Atoms themselves are vibrating around their equilibrium position in the lattice

- There are impurities and crystal imperfections.
  As carriers move around, they suffer frequent collisions: **scattering**

Zero electric field **Under electric field E**



- **Mean free path**, l_{ce}: average distance travelled between collisions [cm].

- **Scattering time**, τ_{ce}: average time between collisions [s].

$$l_{CE} = \frac{\pi}{4} v_{th} \tau_{CE}$$

Scattering mechanisms:

1. Lattice or **phonon scattering**: carriers collide with vibrating lattice atoms
   phonon absorption and emission
   ⇒ some energy exchanged (~ tens of meV)

2. **Ionized impurity scattering**: Coulombic interaction between charged impurities and carriers
   ⇒ no energy exchanged

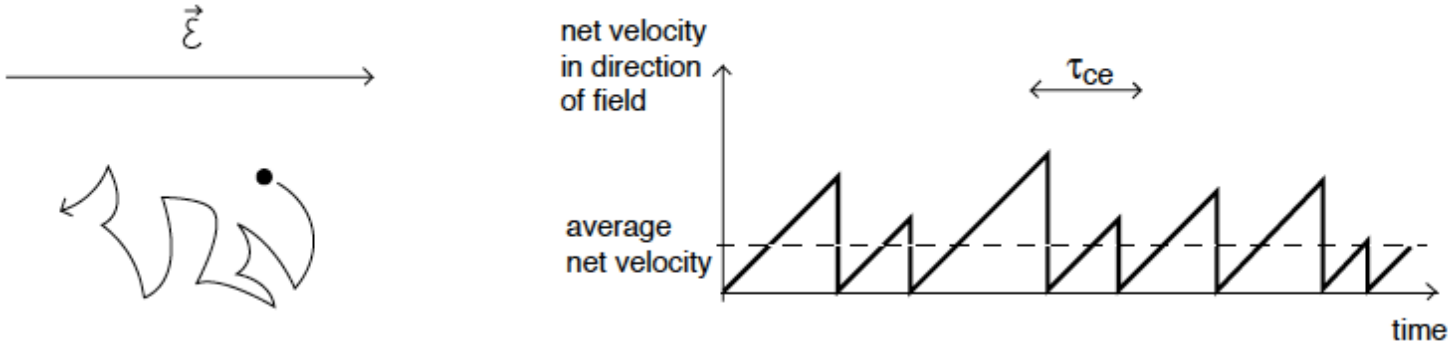
3. **Neutral impurity scattering** with neutral dopants, interstitials, vacancies, etc

4. **Surface scattering** in inversion layer (surface roughness)

5. **Carrier-carrier scattering (important when carrier concentration is high)**
   Order of magnitude of $\tau_c < 1$ ps
   Then, order of magnitude of $l_c < 50$ nm

Drift

In the presence of an electric field, electrons drift:



Drift velocity

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

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

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

Electron mobility: Corresponds to the **ease of carrier motion** in response to *E*.
It depends on the **strength of the scattering mechanisms**.

Drift

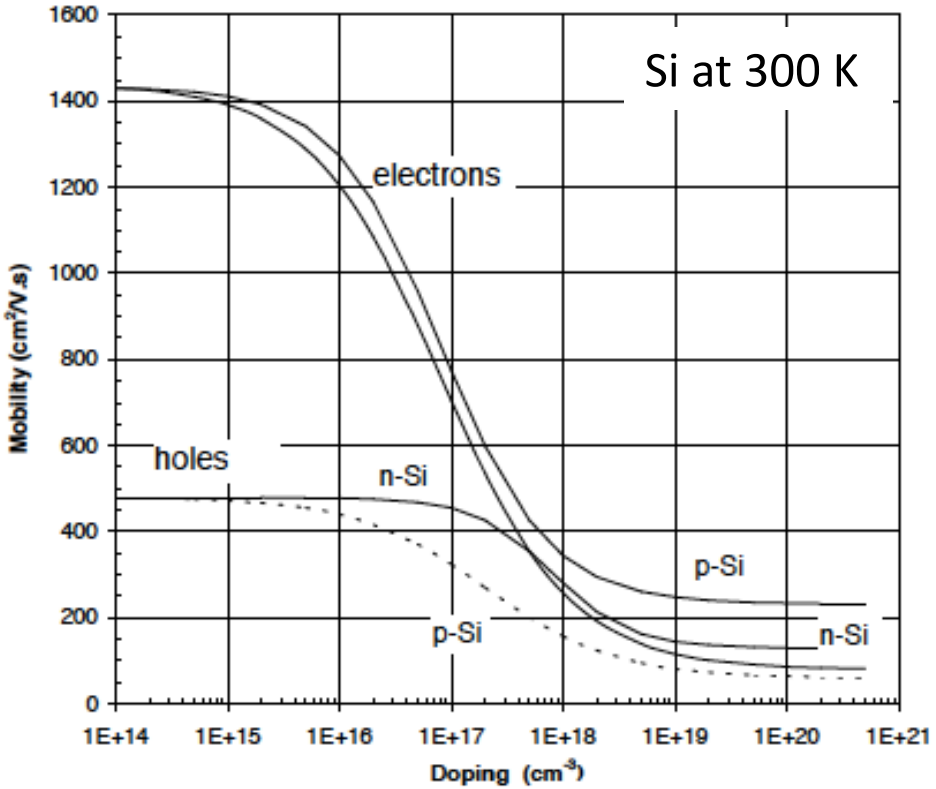
In the presence of an electric field, electrons drift:

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

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

Mobility depends on:

- **doping level**
- whether carrier is **majority** or **minority-type**.



at low *n*:

- Mobility is limited by phonon scattering
- thus independent of doping.

at high *n*:

- Mobility is limited by ionized impurity scattering;
- It is not a strong function of the type of dopant, but only on its concentration.
- Typically, attractive scattering is more pronounced then repulsive: majority carriers have lower mobility

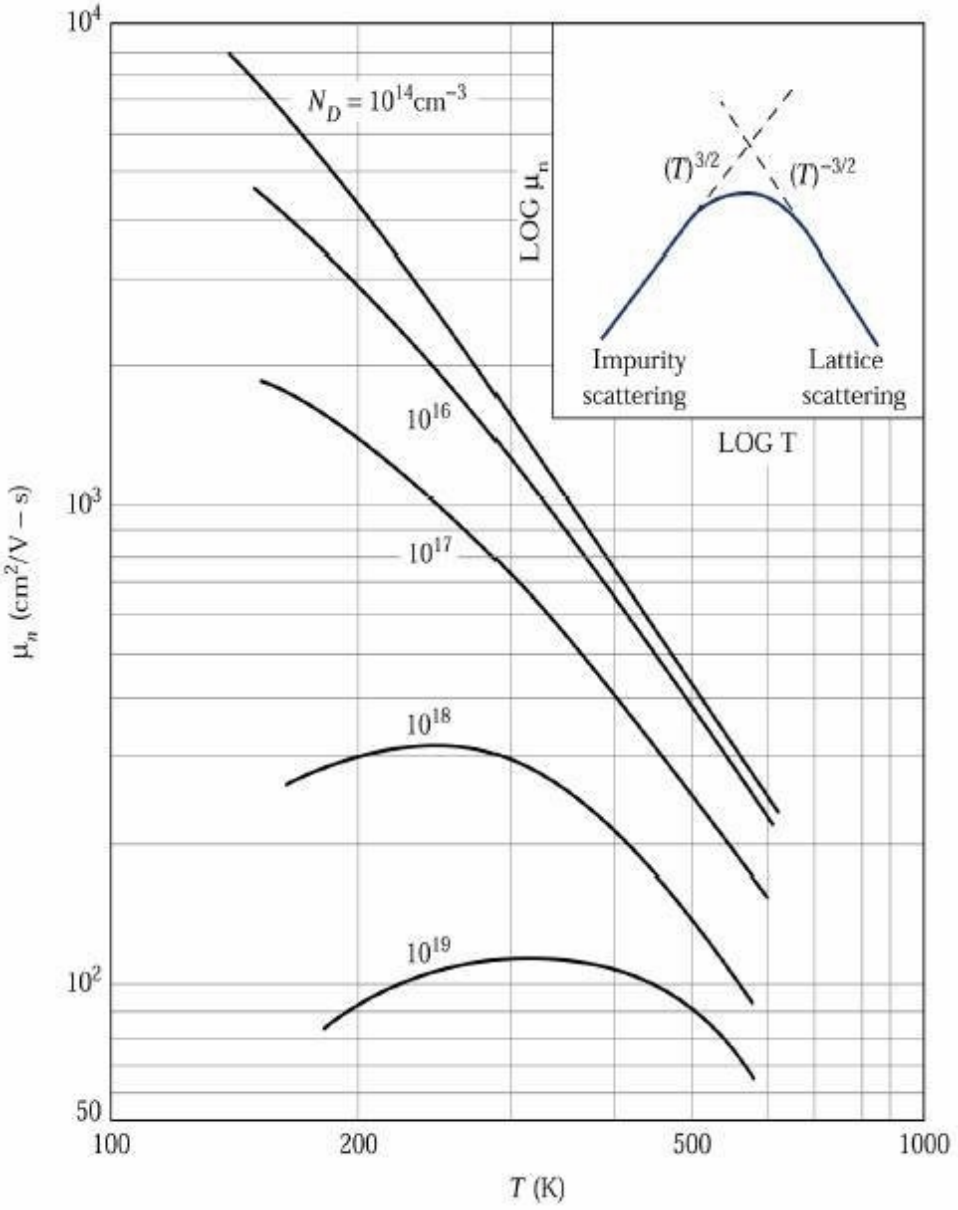
Increasing temperature and increasing doping results in reduction of mobility.

Increasing temperature: increases the number of phonons, which increases the probability that an electron will be scattered by a phonon.

Increasing doping: each dopant atom can scatter electrons.

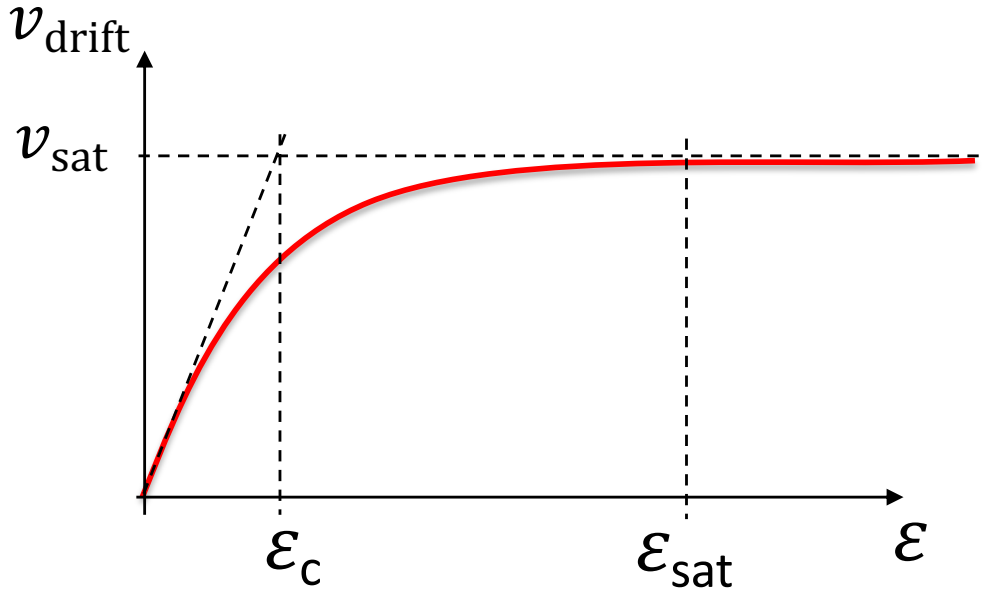
Thus:

higher doping level -> lower mobility
higher temperature -> lower mobility



Velocity saturation

The **linear relationship** between drift velocity and electric field **is no longer valid at high fields**



Drift velocity vs. electric field fairly well described by:

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

Field required to saturate velocity:

$$\mathcal{E}_c = \frac{v_{sat}}{\mu} \qquad \mathcal{E}_{\text{sat}} = 9\mathcal{E}_c$$

Velocity saturation crucial in modern devices:

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

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

Velocity saturation

The **linear relationship** between drift velocity and electric field **breaks at high fields**

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 *E***: carriers acquire substantial energy from *E*
→ optical phonon emission strongly enhanced

scattering time: $\sim 1/\mathcal{E}$

Drift velocity saturates at

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

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

For Si at 300 *K*:

- $v_{sat} \sim 10^7$ *cm/s* for electrons
- $v_{sat} \sim 6 \times 10^6$ *cm/s* for holes

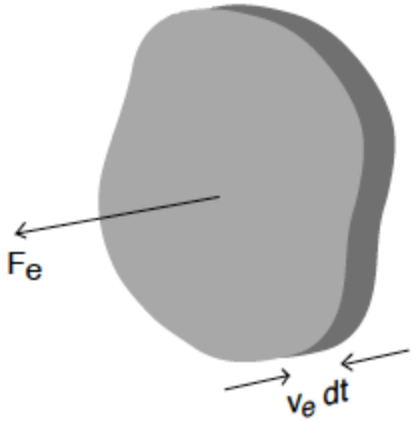
Particle flux and current density

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 [$C \cdot cm^{-2} \cdot s^{-1}$]

$$J_e = -qF_e$$

particle flux: $$F_e = \frac{nv_e dt}{dt} = nv_e$$



Electron and hole current density:

$$J_e = -qnv_e$$

$$J_h = qpv_h$$

Drift current

Drift current (low fields):

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

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

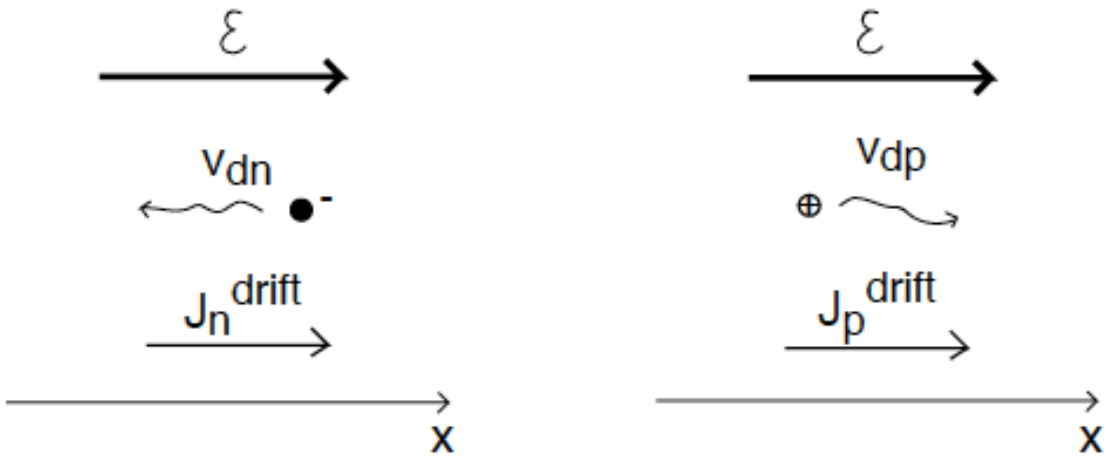
Total current:

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

Ohm's law for semiconductors

Electrical conductivity [$(\Omega \cdot cm)^{-1}$]: $\sigma = q(\mu_e n + \mu_h p)$

Electrical resistivity [$\Omega \cdot cm$]: $\rho = \dfrac{1}{q(\mu_e n + \mu_h p)}$



Drift current

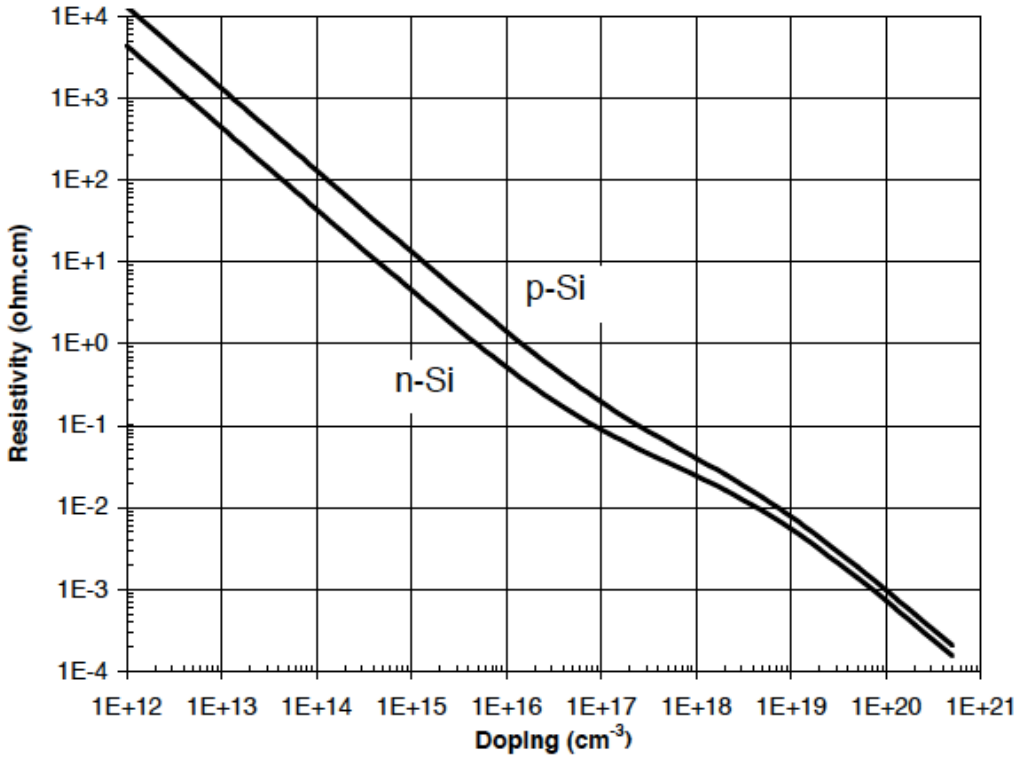
***ρ* strong function of doping ⇒**

frequently used by wafer vendors to specify doping level of substrates

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

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

Si at 300K:



Drift current

Drift current (**high fields**):

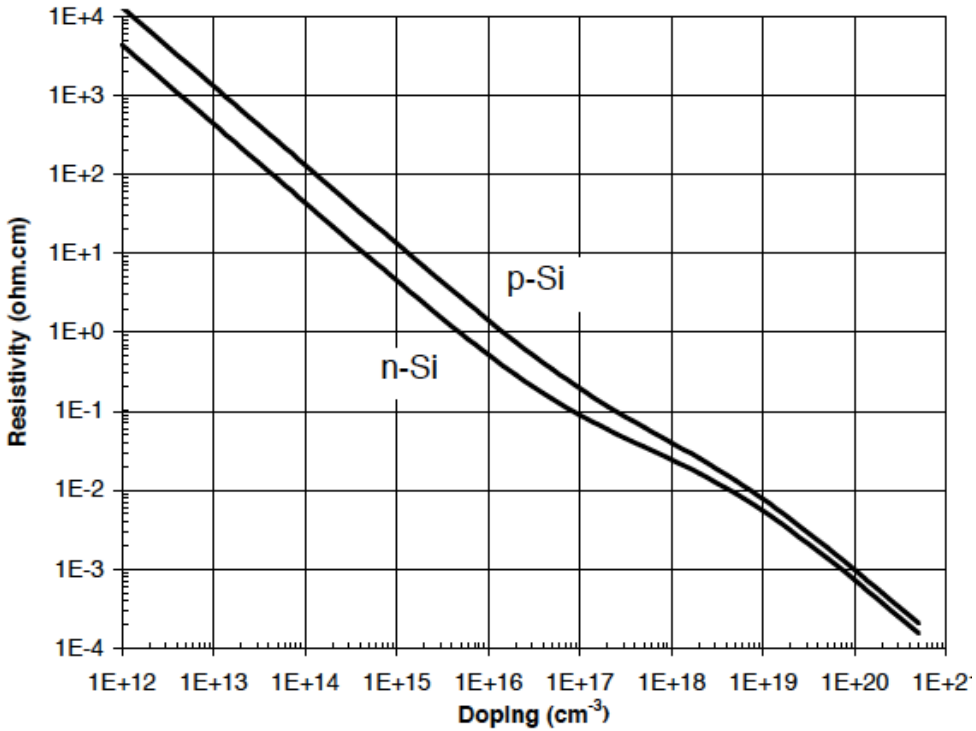
$$J_{esat} = qnv_{esat}$$

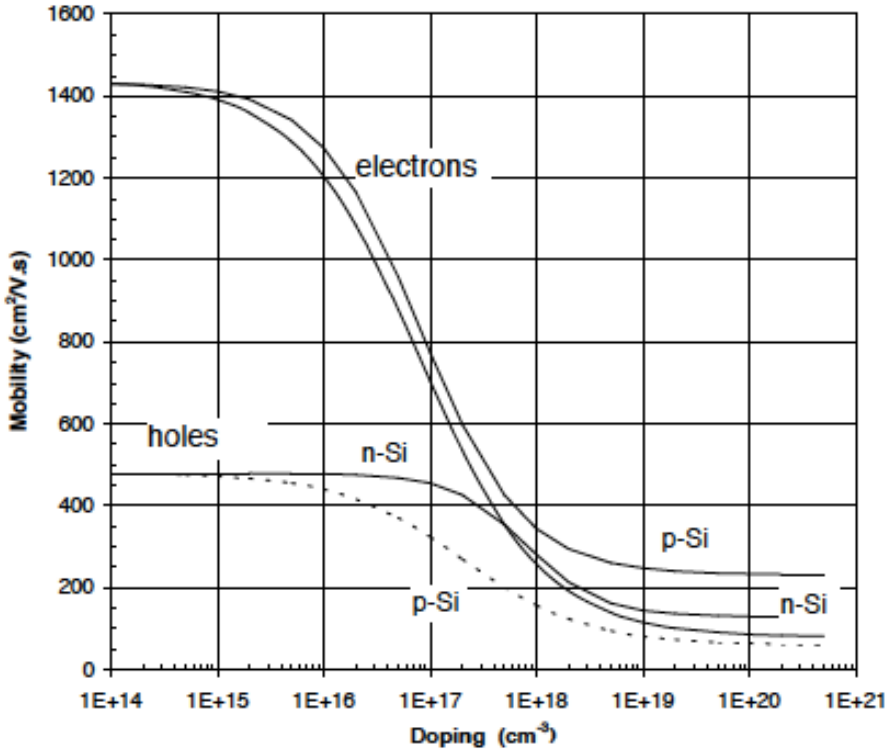
$$J_{hsat} = qpv_{hsat}$$

The only way to get **more current at high fields** is to **increase carrier concentration**.

Estimate the electrons and holes drift velocity, for a n-type Si with resistivity of 0.1 ohm cm and under an applied field of 1000 V/cm.

Si at 300K:





Sheet resistance

The sheet resistance concept is used to characterize both wafers and thin doped layers, since it is typically **easier to measure than the resistivity** of the material.

The sheet resistance of a uniformly doped layer with resistivity, ρ, and thickness, t, is given by their ratio:

$$Rs = \frac{\rho}{t}$$

While the unit of the sheet resistance is Ohms, one refers to it as **Ohms per square**.

This nomenclature comes in handy when the resistance of a rectangular piece of material with **length, L**, and **width W** must be obtained. It equals the product of the sheet resistance and the number of squares or:

$$R = Rs\frac{L}{W}$$

Transmission line method (TLM)

technique to determine the sheet resistance and contact resistance

The sheet resistance of a doped layer with resistivity, ρ, and thickness, t, is:

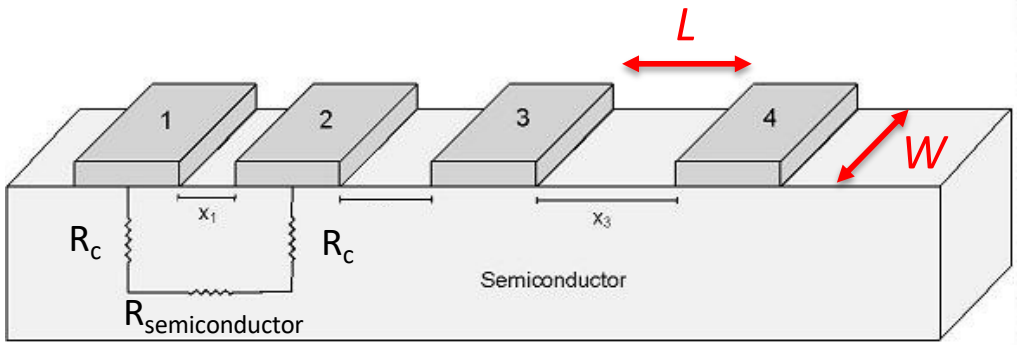
$$Rs = \frac{\rho}{t}$$

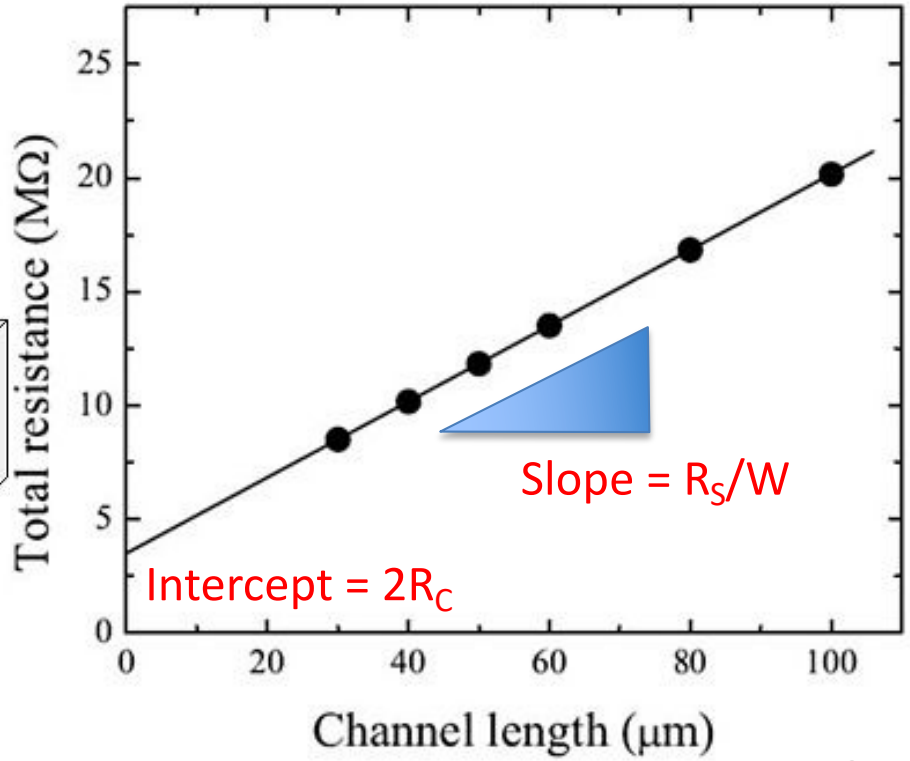
The resistance of a rectangular piece of material with length, L, and width W

$$R = Rs\frac{L}{W}$$

Taking into account the contact resistance (R_c):

$$R = 2R_c + R_s\frac{L}{W}$$

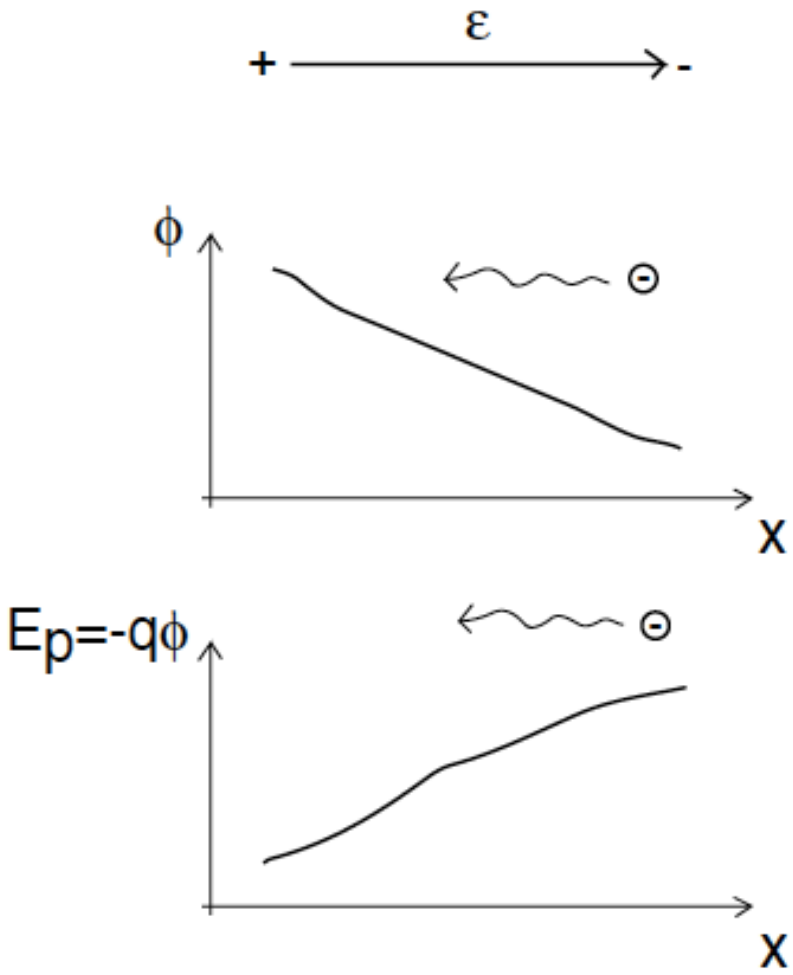




Energy band diagram under electric field

Energy band diagram under electric field:

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

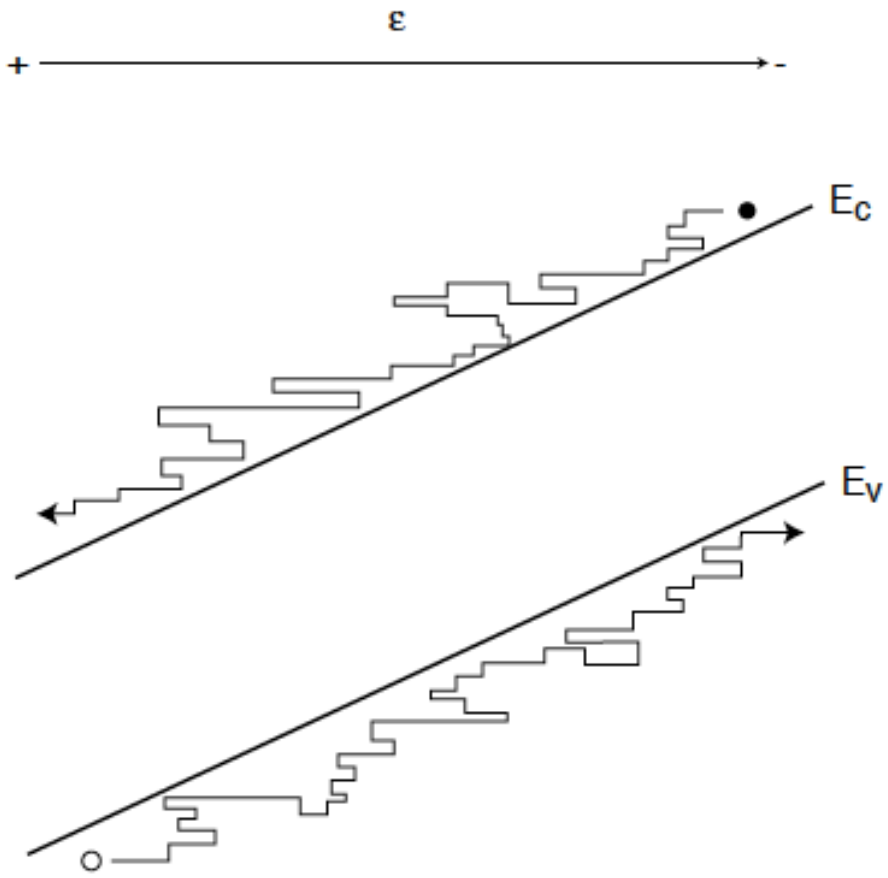


Electron trades potential energy by kinetic energy as it moves to the left

→ *total electron energy unchanged*

Energy band diagram under electric field

Energy band diagram is **picture of electron energy**
⇒ must add E_p to semiconductor energy band diagram ⇒ bands tilt: **Band bending**



Measuring from an arbitrary energy reference:

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

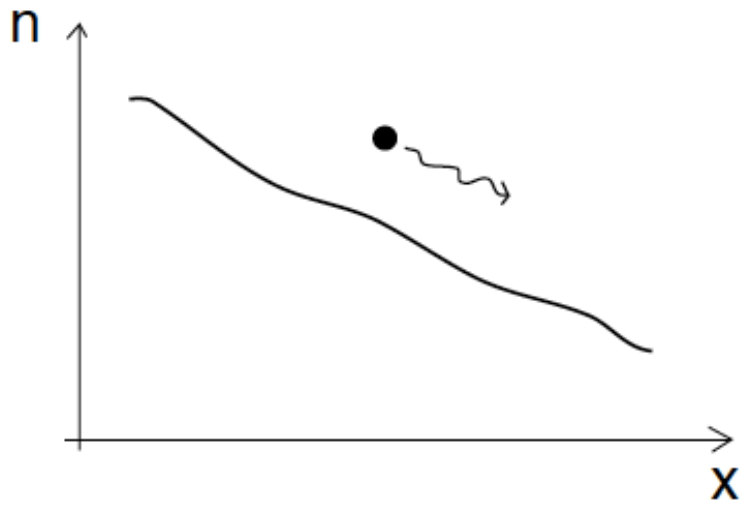
$$\mathcal{E} = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_c}{dx} = \frac{1}{q}\frac{dE_v}{dx}$$

Shape of energy bands = shape of φ with a minus sign.
Can easily compute E from energy band diagram.

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 is proportional to the gradient of concentration [Fick's first law]

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

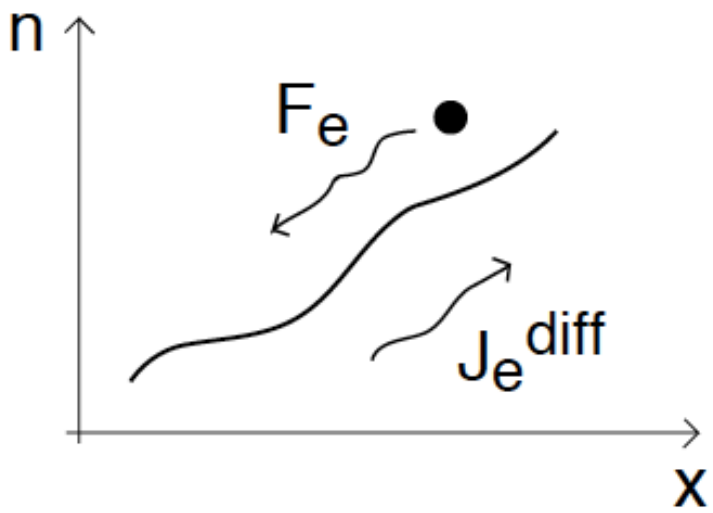
$$F_h = -D_h \frac{dp}{dx}$$

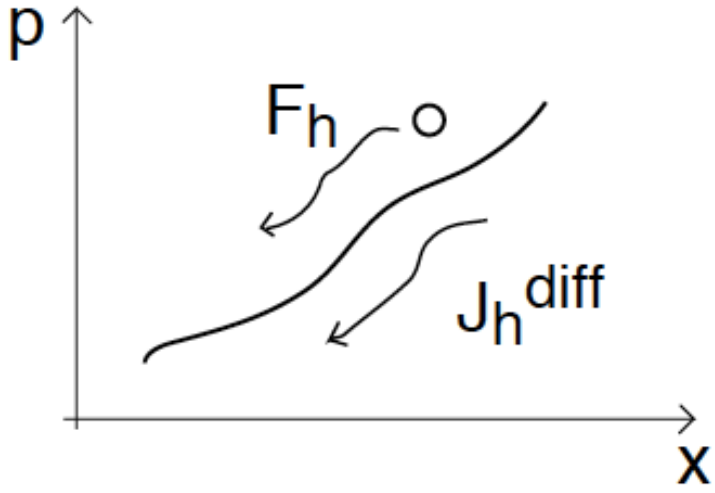
$$D \equiv \text{diffusion coefficient } [cm^2/s]$$

Diffusion current: Electrons and holes are charged particles and their diffusion creates current

$$F_e = -D_e \frac{dn}{dx} \qquad J_e = qD_e \frac{dn}{dx}$$

$$F_h = -D_h \frac{dp}{dx} \qquad J_h = -qD_h \frac{dp}{dx}$$





In summary:

μ relates to ”ease” of carrier drift in an electric field.

D relates to ”ease” of carrier diffusion as a result of a concentration gradient.

Is there a relationship between μ and D?

In summary:

μ relates to ”ease” of carrier drift in an electric field.

D relates to ”ease” of carrier diffusion as a result of a concentration gradient.

Is there a relationship between μ and D?

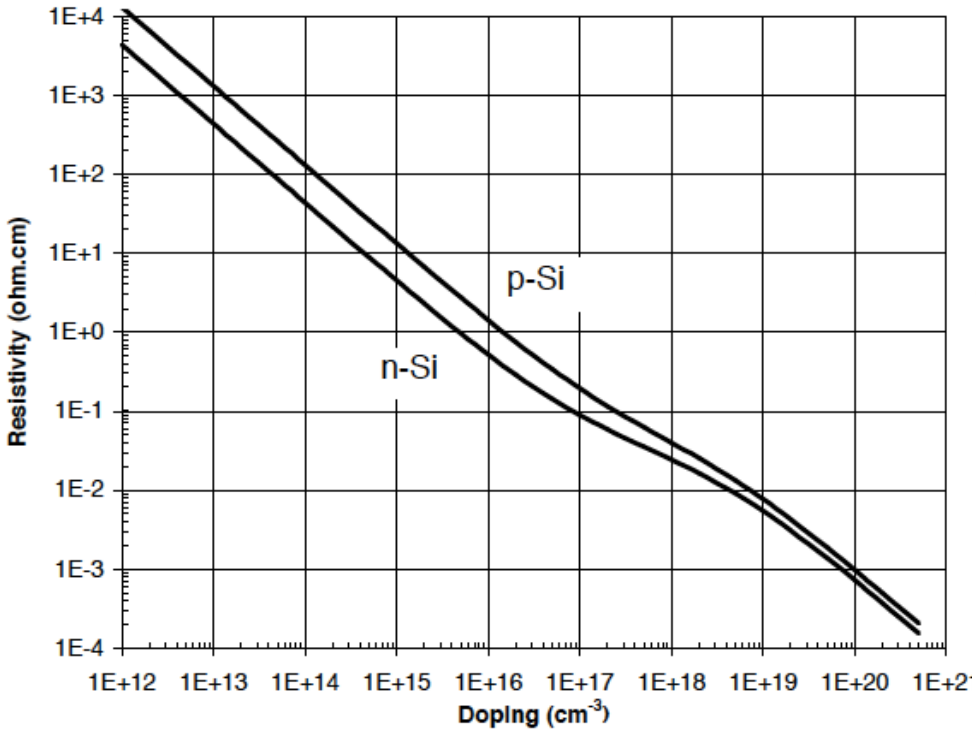
Yes, Einstein relation:

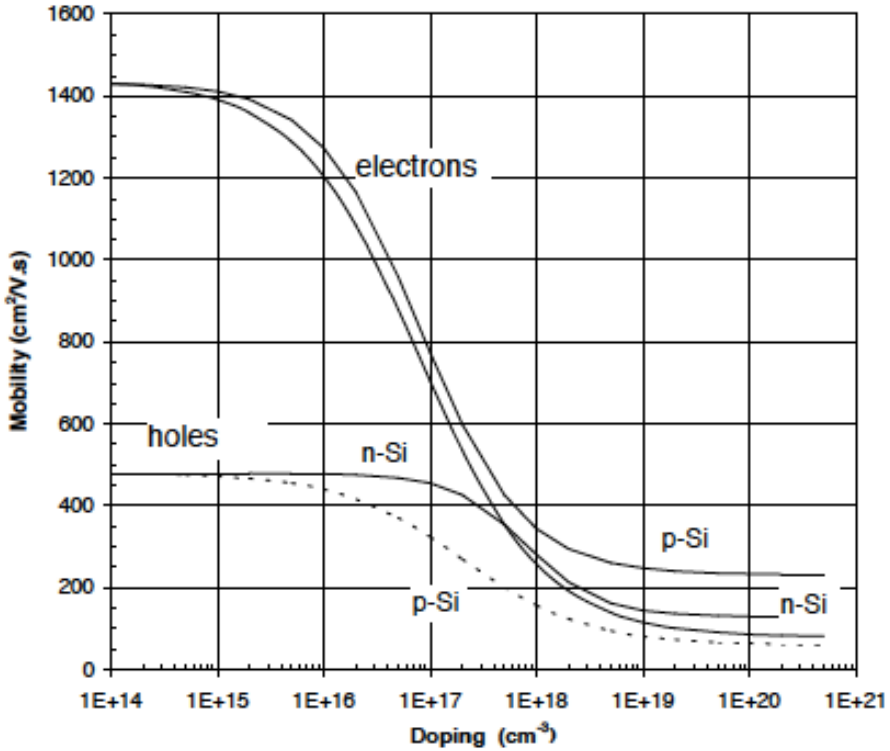
$$\frac{D_e}{\mu_e} = \frac{D_h}{\mu_h} = \frac{kT}{q}$$

Relationship between D and μ only depends on T.

Estimate the diffusion coefficients for electrons and holes, for a p-type Si with resistivity of 0.1 ohm cm

Si at 300K:





Key conclusions

At finite temperatures, carriers move around in a **random way** suffering many collisions: ***thermal motion***.

Dominant scattering mechanisms in bulk Si at 300K: **phonon scattering** and **ionized impurity scattering**.

Two processes for carrier flow in semiconductors: **drift and diffusion**.

General relationship between carrier net velocity (by drift or diffusion) and current density:

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

For low fields, $v_{drift} \sim E$
For high fields, $v_{drift} \sim v_{sat}$

Driving force for **diffusion**: **concentration gradient**.

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: $v_{sat} \sim 10^7\ cm/s$
- $v_{th} \sim 2 \times 10^7\ cm/s$
- $\tau_c < 1\ ps$
- $l_c < 50\ nm$