Lecture 3
Semiconductor Physics (II)
Carrier Transport

Outline

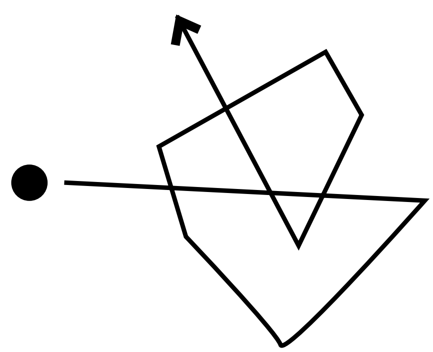
- Thermal Motion
- Carrier Drift
- Carrier Diffusion

Reading Assignment:
Howe and Sodini; Chapter 2, Sect. 2.4-2.6

1. Thermal Motion

In thermal equilibrium, carriers are not sitting still:

- Undergo collisions with vibrating Si atoms (***Brownian motion***)
- Electrostatically interact with each other and with ionized (charged) dopants



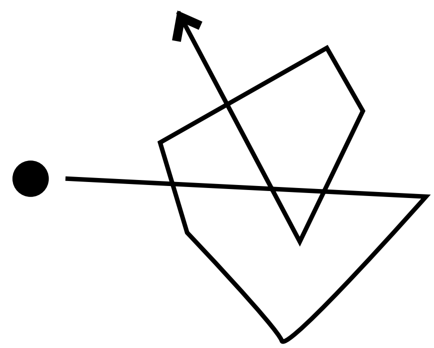
Characteristic time constant of thermal motion:
⇒ **mean free time between collisions**

$$\tau_c \equiv \textit{collison time}\ [s]$$

In between collisions, carriers acquire high velocity:

$$\mathbf{v_{th}} \equiv \textbf{thermal velocity}\ [\mathbf{cms}^{-1}]$$

…. but get nowhere!



Characteristic length of thermal motion:

$\lambda \equiv$ ***mean free path*** *[cm]*

$$\lambda = \mathbf{v_{th}} \tau_{\mathbf{c}}$$

Put numbers for Si at room temperature:

$$\tau_c \approx 10^{-13} s$$

$$v_{th} \approx 10^{7} cms^{-1}$$

$$\Rightarrow \lambda \approx 0.01\ \mu m$$

For reference, state-of-the-art production MOSFET:

$L_g \approx 0.1\ \mu m$

⇒ **Carriers undergo many collisions as they travel through devices**

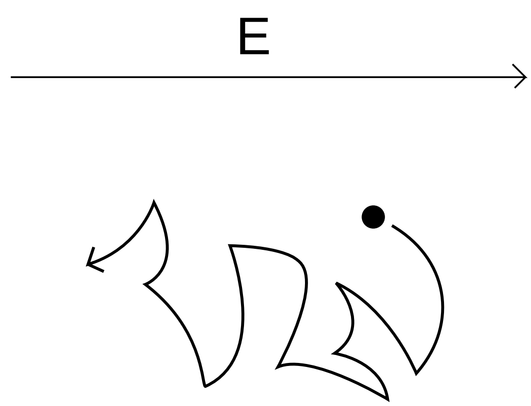
2. Carrier Drift

Apply electric field to semiconductor:

$$\mathbf{E} \equiv \textbf{electric field}\ [\mathrm{V\ cm^{-1}}]$$

$\Rightarrow$ net force on carrier

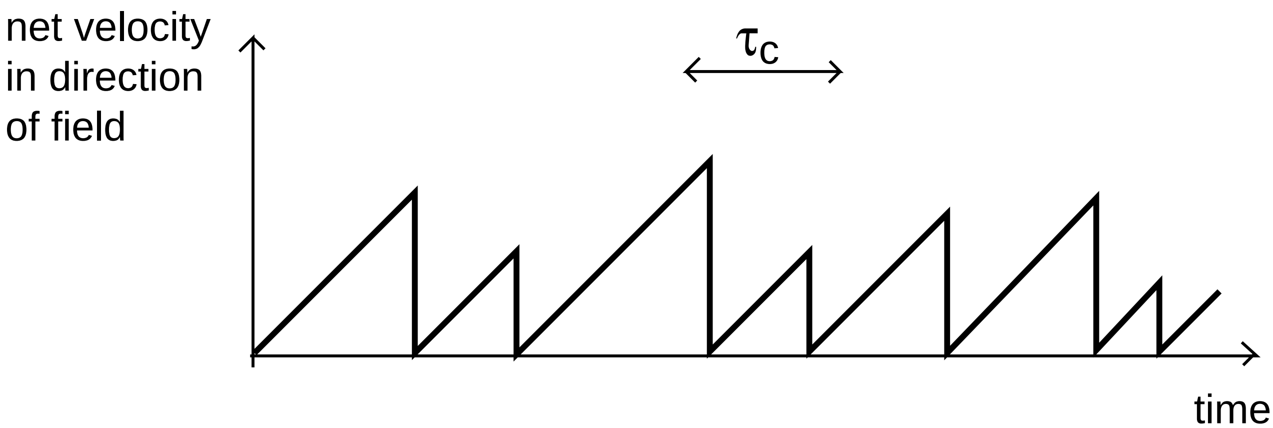
$$F = \pm qE$$



Between collisions, carriers accelerate in the direction of the electrostatic field:

$$\mathbf{v(t) = a \bullet t = \pm \frac{qE}{m_{n,p}} t}$$

But there is (on the average) a collision every τ_c and the velocity is randomized:



The average net velocity in direction of the field:

$$\bar{\mathbf{v}} = \mathbf{v_d} = \pm \frac{\mathbf{qE}}{2\mathbf{m_{n,p}}} \tau_\mathbf{c} = \pm \frac{\mathbf{q}\tau_\mathbf{c}}{2\mathbf{m_{n,p}}} \mathbf{E}$$

This is called **drift velocity** [cm s^{-1}]

Define:

$$\mu_{\mathbf{n,p}} = \frac{\mathbf{q}\tau_\mathbf{c}}{2\mathbf{m_{n,p}}} \equiv \mathbf{mobility}\,[\mathbf{cm}^2\mathbf{V}^{-1}\mathbf{s}^{-1}]$$

Then, for electrons:

$$\mathbf{v_{dn}} = -\mu_\mathbf{n}\mathbf{E}$$

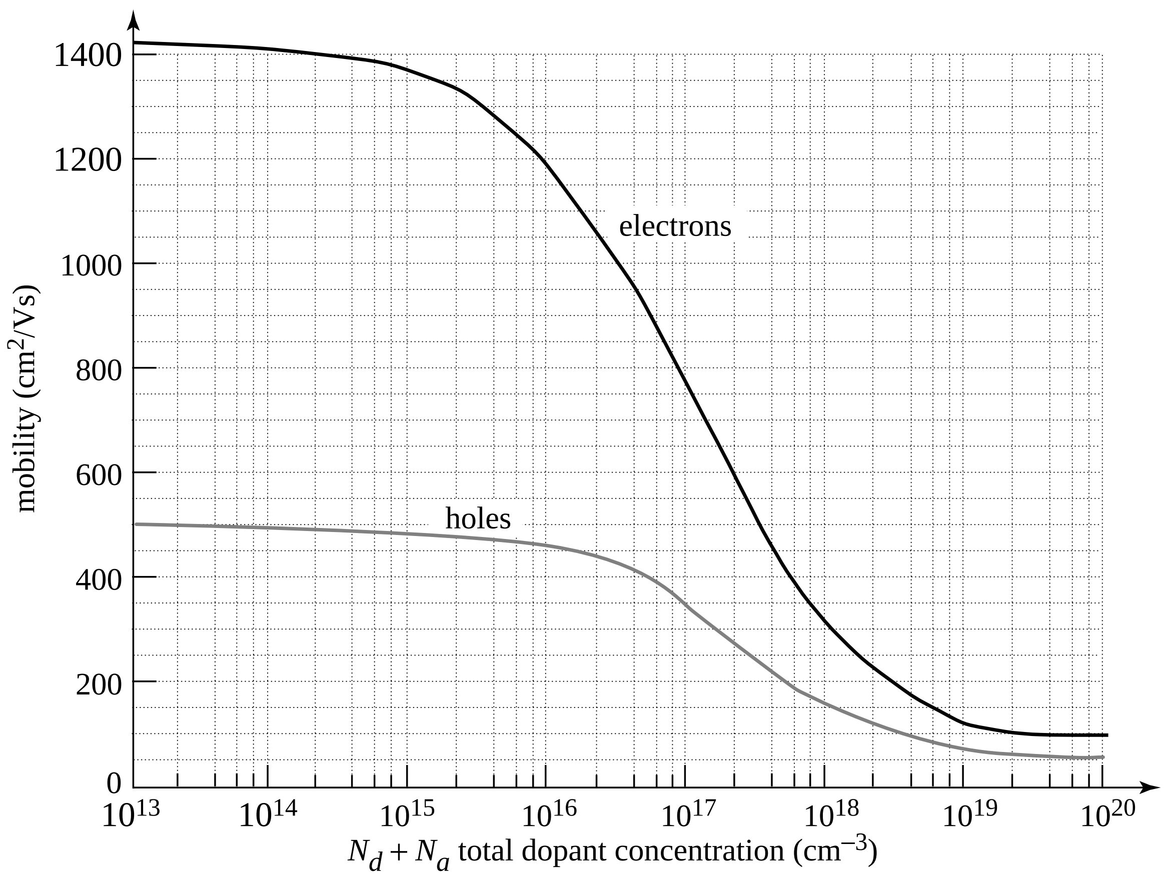
and for holes:

$$\mathbf{v_{dp}} = \mu_\mathbf{p}\mathbf{E}$$

Mobility - is a measure of *ease* of carrier drift

- If $\tau_c \uparrow$, longer time between collisions $\Rightarrow \mu \uparrow$
- If m $\downarrow$, "lighter" particle $\Rightarrow \mu \uparrow$

At room temperature, mobility in Si depends on doping:



- For low doping level, μ is limited by collisions with lattice. As Temp ->**INCREASES;** μ-> **DECREASES**
- For medium doping and high doping level, μ limited by collisions with ionized impurities
- Holes " heavier" than electrons
  - For same doping level, $\mu_n > \mu_p$

Drift Current

Net velocity of charged particles ⇒ electric current:

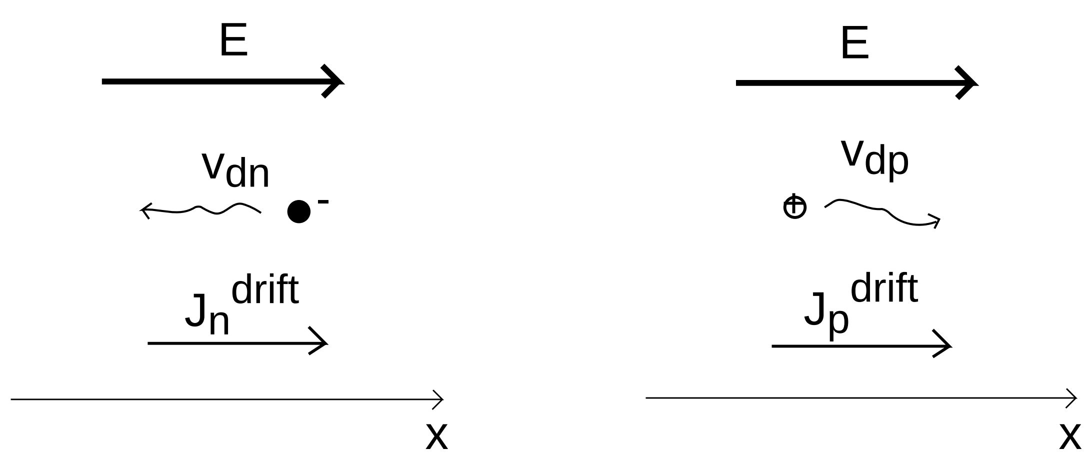
Drift current density	***∝ carrier drift velocity***
	∝ carrier concentration
	∝ carrier charge

Drift current densities:

$$J_n^{drift} = -qnv_{dn} = qn\mu_n E$$

$$J_p^{drift} = qpv_{dp} = qp\mu_p E$$

Check signs:



Total Drift Current Density :

$$\mathbf{J}^{\mathbf{drift}} = \mathbf{J}_{\mathbf{n}}^{\mathbf{drift}} + \mathbf{J}_{\mathbf{p}}^{\mathbf{drift}} = \mathbf{q}(\mathbf{n}\mu_{\mathbf{n}} + \mathbf{p}\mu_{\mathbf{p}})\mathbf{E}$$

Has the form of *Ohm's Law*

$$J = \sigma E = \frac{E}{\rho}$$

Where:

$\sigma \equiv$ conductivity $[\Omega^{-1} \bullet \text{cm}^{-1}]$
$\rho \equiv$ resistivity $[\Omega \bullet \text{cm}]$

Then:

$$\sigma = \frac{1}{\rho} = q(n\mu_n + p\mu_p)$$

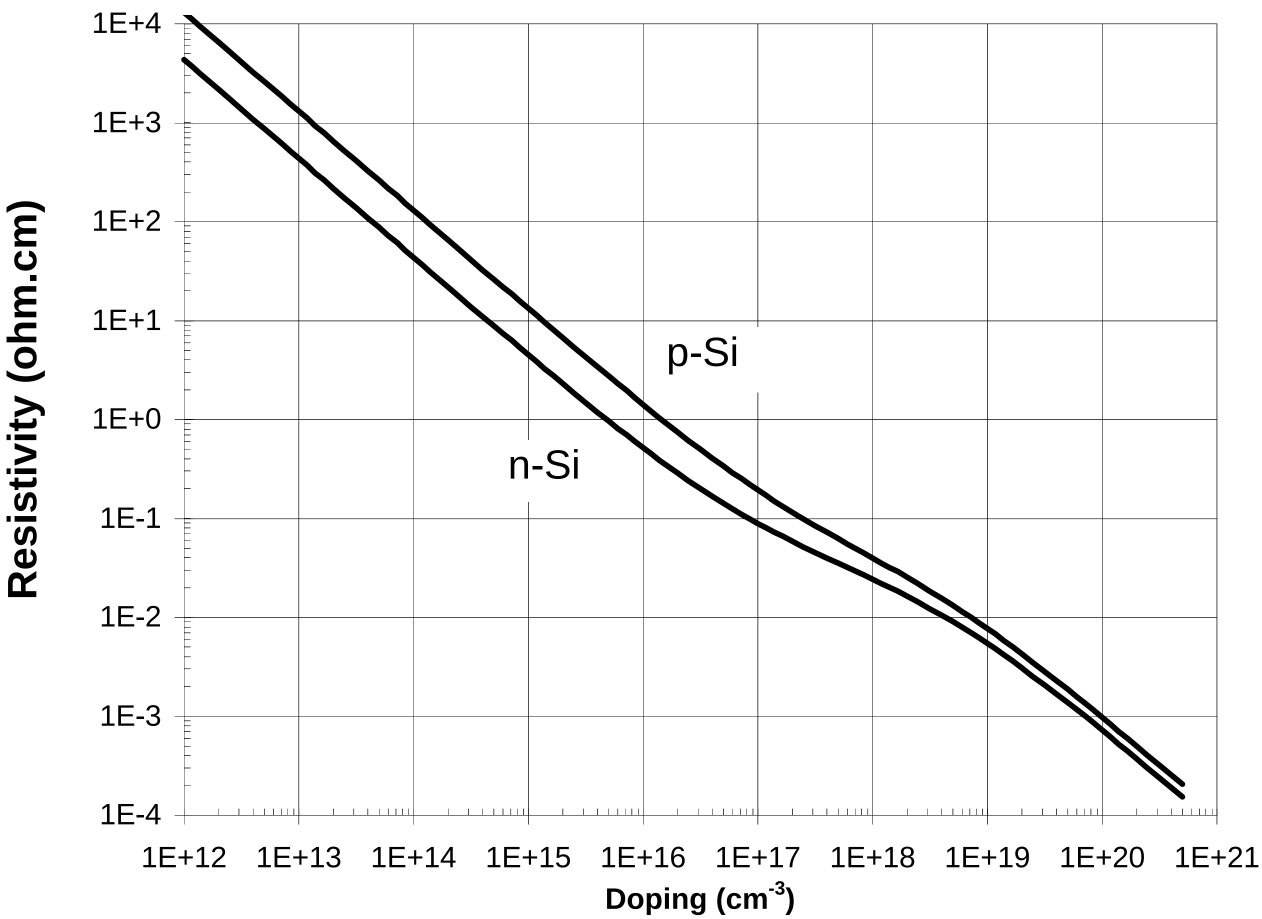
Resistivity is commonly used to specify the doping level

- In n-type semiconductor:

$$\rho_n \approx \frac{1}{q N_d \mu_n}$$

- In p-type semiconductor:

$$\rho_p \approx \frac{1}{q N_a \mu_p}$$



Numerical Example:

Si with $N_d = 3 \times 10^{16}$ cm^{-3} at room temperature

$$\mu_n \approx 1000\ cm^2 / V \bullet s$$

$$\rho_n \approx 0.21 \Omega \bullet cm$$

$$n \approx 3X10^{16}\ cm^{-3}$$

Apply E = 1 kV/cm

$$|v_{dn}| \approx 10^6 cm/s << v_{th}$$

$$J_n^{drift} \approx qnv_{dn} = qn\mu_n E = \sigma E = \frac{E}{\rho}$$

$$J_n^{drift} \approx 4.8 \times 10^3 A/cm^2$$

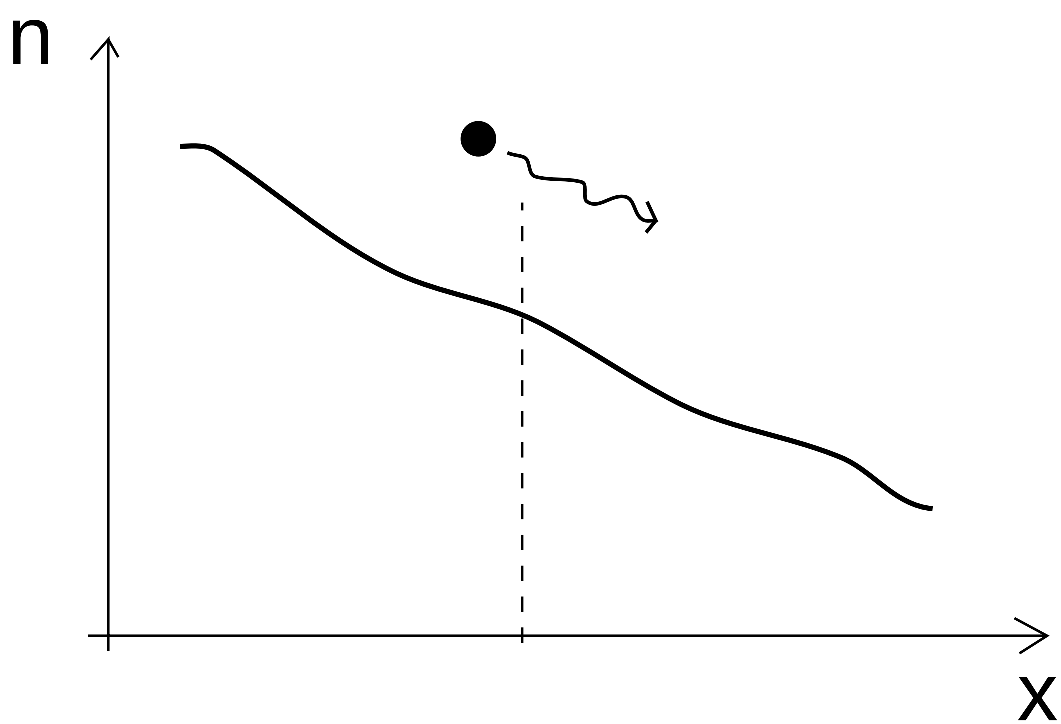
Time to drift through L = 0.1 μm

$$t_d = \frac{L}{v_{dn}} = 10\ ps$$

fast!

3. Carrier Diffusion

<u>Diffusion</u> = particle movement (flux) in response to concentration gradient



Elements of diffusion:

- A medium (***Si Crystal***)
- A gradient of particles (***electrons and holes***) inside the medium
- Collisions between particles and medium send particles off in random directions
  - Overall result is to erase gradient

Fick's first law-

Key diffusion relationship

Diffusion flux $\propto$ - concentration gradient

Flux $\equiv$ number of particles crossing a unit area per unit time [$cm^{-2} \bullet s^{-1}$]

For Electrons:

$$F_n = -D_n \frac{dn}{dx}$$

For Holes:

$$F_p = -D_p \frac{dp}{dx}$$

$D_n \equiv$ electron diffusion coefficient [$cm^2\ s^{-1}$]
$D_p \equiv$ hole diffusion coefficient [$cm^2\ s^{-1}$]

D measures the ***ease*** of carrier diffusion in response to a concentration gradient: $D \uparrow \Rightarrow F^{diff} \uparrow$

D limited by vibration of lattice atoms and ionized dopants.

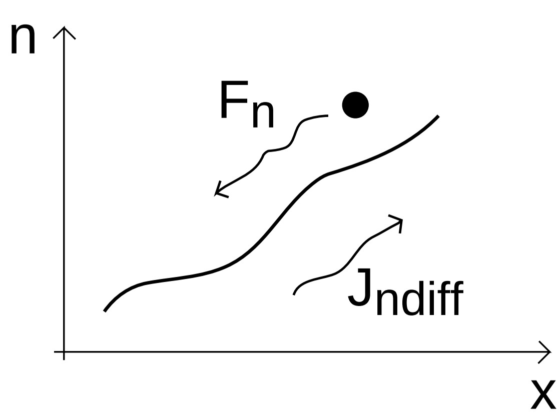
Diffusion Current

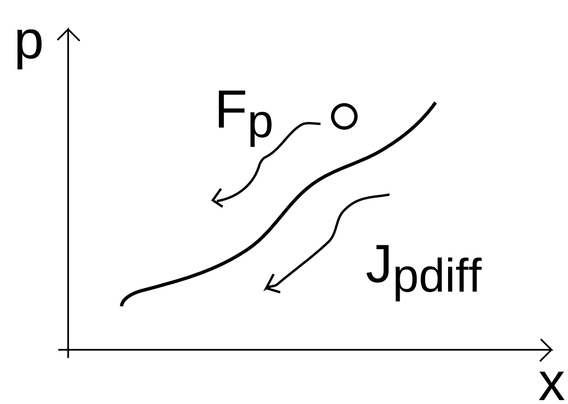
Diffusion current density =charge × carrier flux

$$J_n^{diff} = qD_n \frac{dn}{dx}$$

$$J_p^{diff} = -qD_p \frac{dp}{dx}$$

Check signs:





Einstein relation

At the core of drift and diffusion is same physics: collisions among particles and medium atoms

$\Rightarrow$ **there should be a relationship between D and μ**

Einstein relation [will not derive in 6.012]

$$\frac{D}{\mu} = \frac{kT}{q}$$

In semiconductors:

$$\frac{D_n}{\mu_n} = \frac{kT}{q} = \frac{D_p}{\mu_p}$$

$kT/q \equiv$ thermal voltage

At room temperature:

$$\frac{kT}{q} \approx 25\,mV$$

For example: for $N_d = 3 \times 10^{16}$ cm^{-3}

$$\mu_n \approx 1000\,cm^2 / V \bullet s \quad \Rightarrow D_n \approx 25\,cm^2 / s$$

$$\mu_p \approx 400\,cm^2 / V \bullet s \quad \Rightarrow D_p \approx 10\,cm^2 / s$$

Total Current Density

In general, total current can flow by drift and diffusion separately. **Total current density:**

$$\mathbf{J_n = J_n^{drift} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}}$$

$$\mathbf{J_p = J_p^{drift} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}}$$

$$\mathbf{J_{total} = J_n + J_p}$$

What did we learn today?

Summary of Key Concepts

- Electrons and holes in semiconductors are mobile and charged
  - ⇒ **Carriers of electrical current!**
- ***Drift current***: produced by electric field

$$\mathbf{J}^{\mathbf{drift}} \propto \mathbf{E} \qquad \mathbf{J}^{\mathbf{drift}} \propto \frac{\mathbf{d}\phi}{\mathbf{dx}}$$

- ***Diffusion current***: produced by concentration gradient

$$\mathbf{J}^{\mathbf{diffusion}} \propto \frac{\mathbf{dn}}{\mathbf{dx}}, \frac{\mathbf{dp}}{\mathbf{dx}}$$

- Diffusion and drift currents are sizeable in modern devices
- Carriers move fast in response to fields and gradients