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

What shall 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

$$J^{drift} \quad E \quad J^{drift} \quad \frac{d\phi}{dx}$$

- Diffusion current: produced by concentration gradient

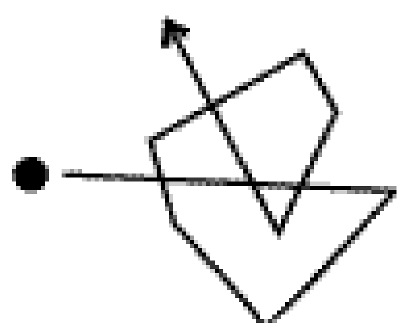
$$J^{diffusiont} \quad \frac{dn}{dx}, \frac{dp}{dx}$$

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

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 charged dopants



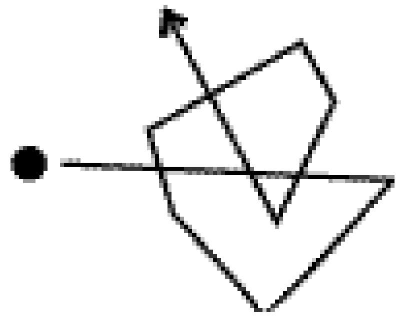
Characteristic time constant of thermal motion: mean free time between collisions

$$\tau_c \equiv \textbf{collison time}\ [\mathrm{s}]$$

In between collisions, carriers acquire high velocity:

$$v_{th} \equiv \textbf{thermal veleocity}\ [\mathrm{cm\ s^{-1}}]$$

…. 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:

$$\tau_{\mathbf{c}} \approx 10^{-13} \mathbf{s}$$

$$\mathbf{v_{th}} \approx 10^{7} \mathbf{cm\, s}^{-1}$$

$$\lambda \approx 0.01\, \mu\mathbf{m}$$

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

$L_g \approx 0.1\ \mu m$

Carriers undergo many collisions as they travel through devices

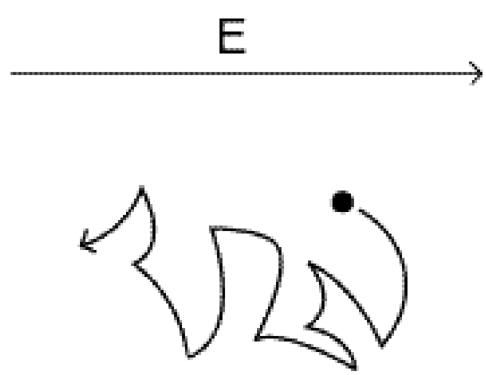
2. Carrier Drift

Apply electric field to semiconductor:

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

net force on carrier

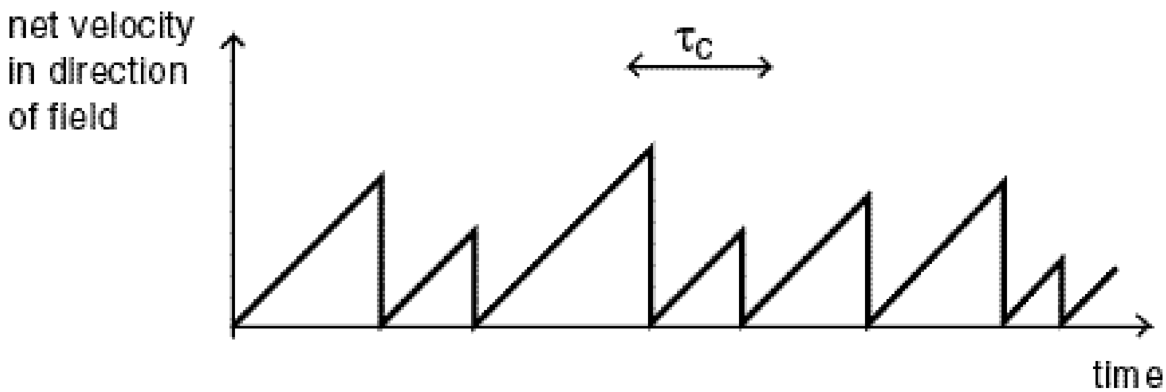
$$F = \pm qE$$



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

$$\mathbf{v(t)} = \int \frac{\mathbf{F}}{\mathbf{m}} \mathbf{dt} = \pm \frac{\mathbf{qE}}{\mathbf{m_{n,p}}} \mathbf{t}$$

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:

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

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

Define:

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

Then, for electrons:

$$v_{dn} = -\mu_n E$$

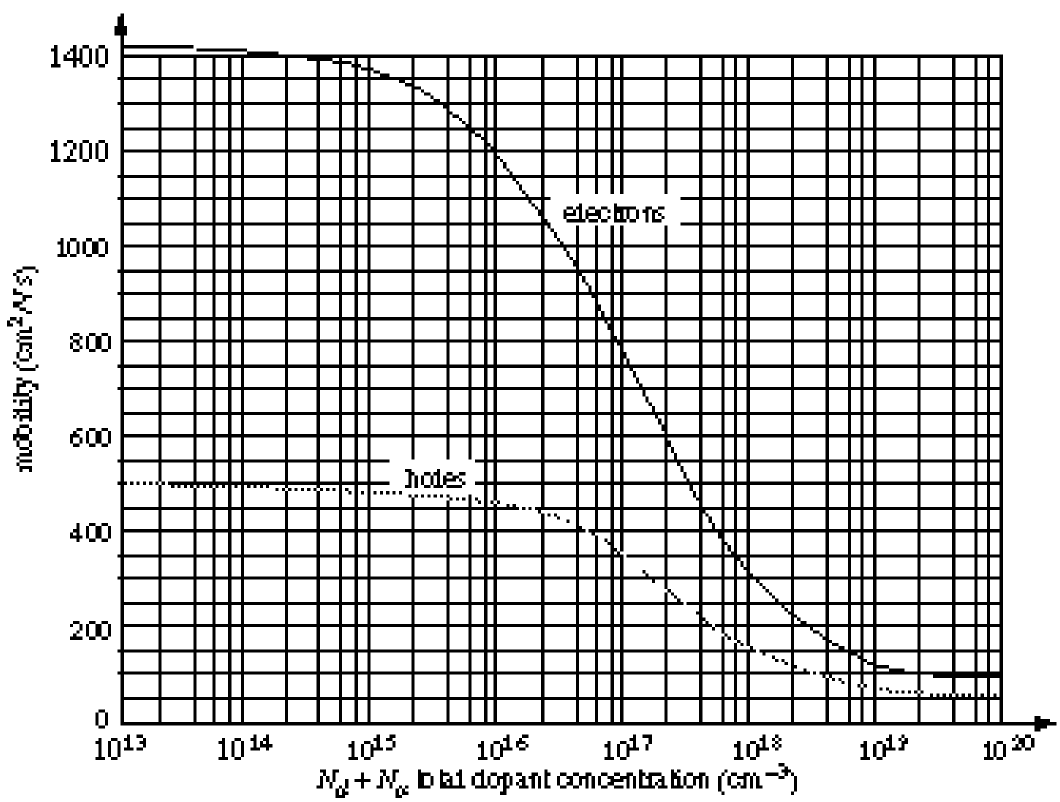
and for holes:

$$v_{dp} = \mu_p E$$

Mobility - is a measure of ease of carrier drift

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

At room temperature, mobility of Si depends on doping:



- For low doping level, μ is limited by collisions with lattice
- 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:

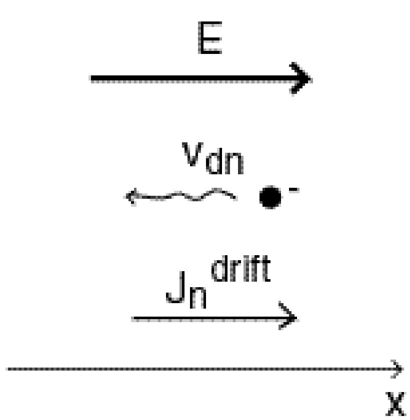
Drift current density   *carrier drift velocity*
carrier concentration
carrier charge

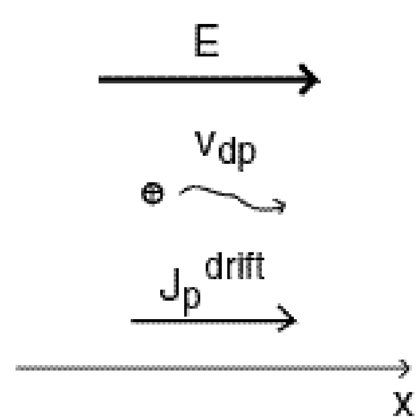
Drift currents:

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

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

Check signs:





Total drift current:

$$\mathbf{J^{drift} = J_n^{drift} + J_p^{drift} = q(n\mu_n + p\mu_p)E}$$

Has the form of *Ohm's Law*

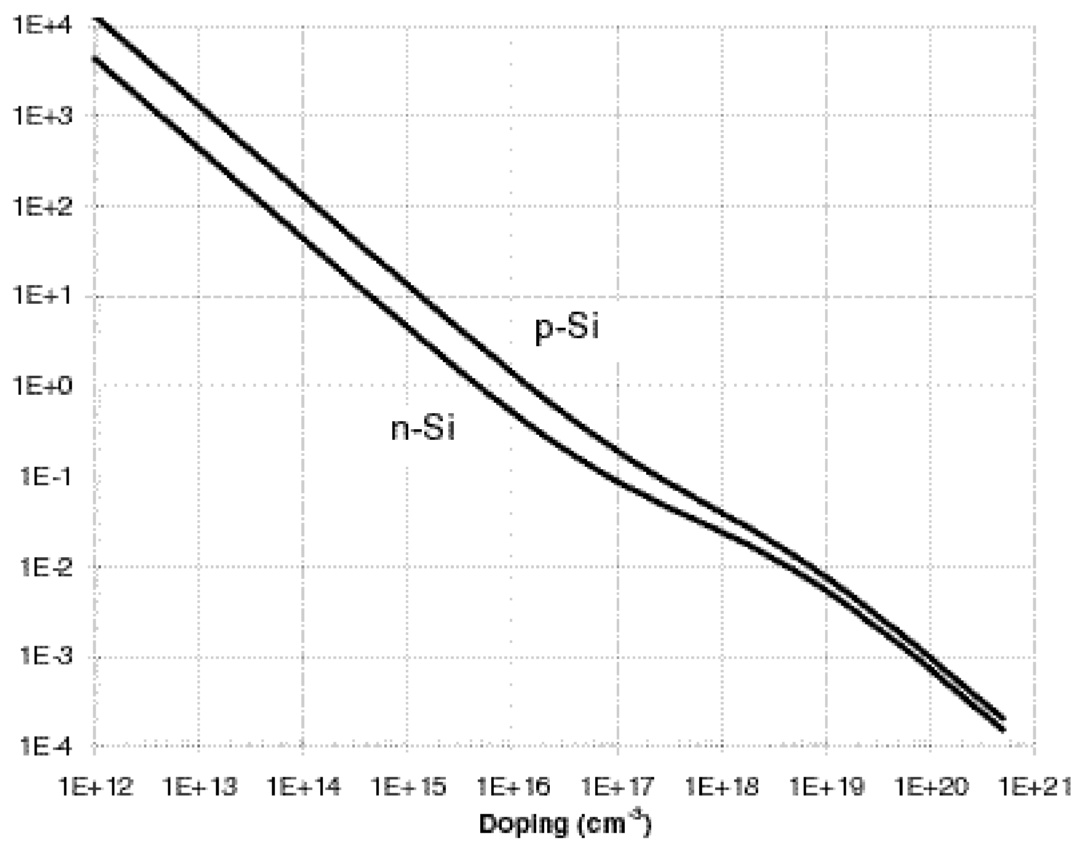
$$\mathbf{J} = \sigma\,\mathbf{E} = \frac{\mathbf{E}}{\rho}$$

Where:

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

Then:

$$\sigma = \frac{1}{\rho} = \mathbf{q}(\mathbf{n}\mu_\mathbf{n} + \mathbf{p}\mu_\mathbf{p})$$


1E+4
1E+3
1E+2
1E+1
1E+0
1E-1
1E-2
1E-3
1E-4
p-Si
n-Si
1E+12
1E+13
1E+14
1E+15
1E+16
1E+17
1E+18
1E+19
1E+20
1E+21
Doping (cm^{-3})

Numerical Example:

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

$$\mu_n \approx 1000\ \mathbf{cm}^2 / \mathbf{V} \cdot \mathbf{s}$$

$$\rho_n \approx 0.21\,\Omega \cdot \mathbf{cm}$$

Apply E = 1 kV/cm

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

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

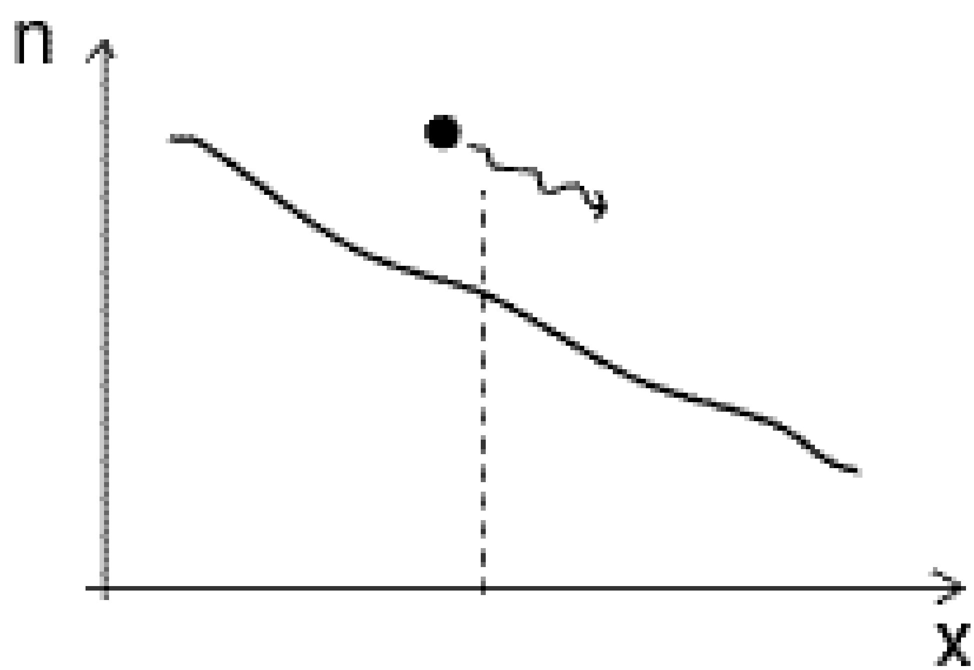
Time to drift through L = 0.1 μm

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

fast!

2. Carrier Diffusion

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



Elements of diffusion:

- A medium
- 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 - concentration gradient

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

For Electrons

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

For Holes

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

$\mathbf{D_n}$ **≡** electron diffusion current [$cm\ s^{-1}$]
$\mathbf{D_p}$ **≡** hole diffusion current [$cm\ s^{-1}$]

D measures the ease of carrier diffusion in response to a concentration gradient: D ↑ F^{diff} ↑

D limited by vibration of lattice atoms and ionized dopants.

Diffusion Current

Diffusion current density =charge × carrier flux

Check signs:

Einstein relation

At the core of drift and diffusion is same physics:
collisions among particles and medium atoms
there should be a relationship between D and μ

Einstein relation [would not derive in 6.012]

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

In semiconductors:

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

kT/q ≡ thermal voltage

At room temperature:

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

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

$$\mu_n \approx 1000\,\text{cm}^2/\text{V}\cdot\text{s} \qquad D_n \approx 25\,\text{cm}^2/\text{s}$$

$$\mu_p \approx 400\,\text{cm}^2/\text{V}\cdot\text{s} \qquad D_p \approx 10\,\text{cm}^2/\text{s}$$

Total Current

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

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

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

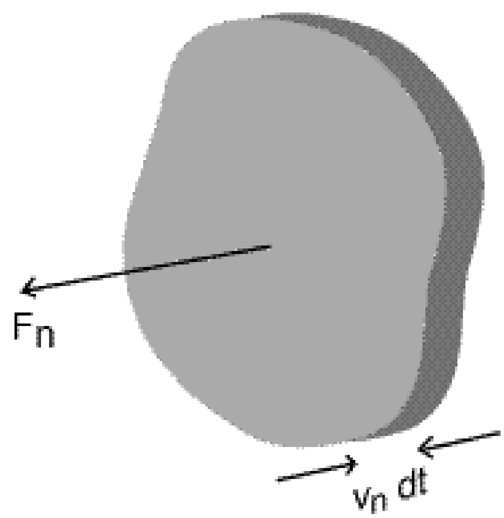
$$\mathbf{J_{total} = J_n + J_p}$$

Relationship between v, F and J

In semiconductors: charge particles move

particle flux   electrical current density

Particle flux: number of particles that cross surface of unit area placed normal to particle flow every unit time



Relationship between particle flux and velocity:

$$F_n = nv_n \qquad F_p = pv_p$$

Current density: amount of charge that crosses surface of unit area placed normal to particle flow every unit time

$$J_n = -qF_n = -qnv_n \qquad J_p = qF_p = qpv_p$$

Carriers could move by drift or diffusion

What did we learn today?

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