EECS130
Integrated Circuit Devices

Professor Ali Javey

9/06/2007

<u>Semiconductor Fundamentals</u>

<u>Lecture 4</u>

Reading: Chapter 3

Announcements

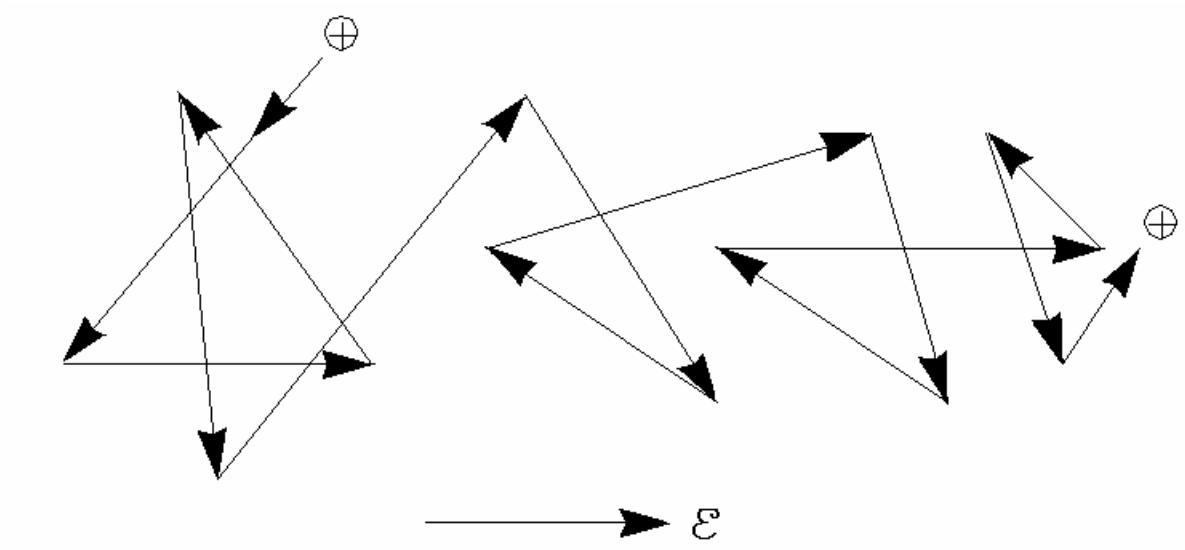
- 1st HW due Tuesday.
- New lecture room: 3106 Etcheverry, starting next Thursday (9/13)
- TA OHs will be held in Cory 353

What to memorize?

- Learn the concepts
- Understand the equations
- Only memorize the most important and fundamental equations

Drift

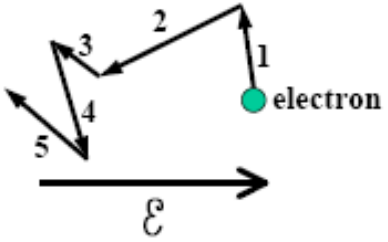
Electron and Hole Mobilities



- ***Drift*** is the motion caused by an electric field.

Carrier Drift

- **When an electric field** (*e.g.* due to an externally applied voltage) **is applied to a semiconductor, mobile charge-carriers will be accelerated by the electrostatic force. This force superimposes on the random motion of electrons:**



- **Electrons *drift* in the direction opposite to the electric field**
  → current flows

❖ **Because of scattering, electrons in a semiconductor do not achieve constant acceleration. However, they can be viewed as quasi-classical particles moving at a constant average *drift velocity* v_d**

Effective Mass

In an electric field, $\mathcal{E}$, an electron or a hole accelerates.

Remember :
F=ma=-qE

$$a = \frac{-q\mathcal{E}}{m_n} \qquad \text{electrons}$$

$$a = \frac{q\mathcal{E}}{m_p} \qquad \text{holes}$$

Electron and hole effective masses

	Si	**Ge**	**GaAs**	**GaP**
m_n/m_0	0.26	0.12	0.068	0.82
m_p/m_0	0.39	0.30	0.50	0.60

Electron Momentum

- With every collision, the electron loses momentum

$$m_n{}^* v_{\mathrm{d}}$$

- Between collisions, the electron gains momentum

$$(-q)\mathcal{E}\tau_{\mathrm{mn}}$$

Remember :
F=ma=mV/t = -qE

where τ_{mn} **= average time between scattering events**

Electron and Hole Mobilities

$$m_p v = q\mathcal{E}\tau_{mp}$$

$$v = \frac{q\mathcal{E}\tau_{mp}}{m_p}$$

$$v = \mu_p \mathcal{E}$$

$$\mu_p = \frac{q\tau_{mp}}{m_p}$$

$$v = -\mu_n \mathcal{E}$$

$$\mu_n = \frac{q\tau_{mn}}{m_n}$$

- μ_p is the hole mobility and μ_n is the electron mobility

Electron and Hole Mobilities

$v = \mu \mathcal{E}$; μ has the dimensions of $v/\mathcal{E}$ $\left[\frac{\text{cm/s}}{\text{V/cm}} = \frac{\text{cm}^2}{\text{V}\cdot\text{s}}\right]$.

Electron and hole mobilities of selected semiconductors

	Si	**Ge**	**GaAs**	**InAs**
μ_n ($\text{cm}^2/\text{V}\cdot\text{s}$)	1400	3900	8500	30000
μ_p ($\text{cm}^2/\text{V}\cdot\text{s}$)	470	1900	400	500

Based on the above table alone, which semiconductor and which carriers (electrons or holes) are attractive for applications in high-speed devices?

Drift Velocity, Mean Free Time, Mean Free Path

EXAMPLE: *Given μ_p = 470 cm^2/V·s, what is the hole drift velocity at $\mathcal{E}$ = 10^3 V/cm? What is τ_{mp} and what is the distance traveled between collisions (called the* ***mean free path****)? Hint: When in doubt, use the MKS system of units.*

Drift Velocity, Mean Free Time, Mean Free Path

EXAMPLE: *Given μ_p = 470 cm^2/V·s, what is the hole drift velocity at $\mathcal{E}$ = 10^3 V/cm? What is τ_{mp} and what is the distance traveled between collisions (called the* ***mean free path****)? Hint: When in doubt, use the MKS system of units.*

Solution: $v = \mu_p \mathcal{E} = 470\ \text{cm}^2/\text{V}\cdot\text{s} \times 10^3\ \text{V/cm} = 4.7\times 10^5\ \text{cm/s}$

$$\tau_{mp} = \mu_p m_p/q = 470\ \text{cm}^2/\text{V}\cdot\text{s} \times 0.39 \times 9.1\times10^{-31}\ \text{kg}/1.6\times10^{-19}\ \text{C}$$

$$= 0.047\ \text{m}^2/\text{V}\cdot\text{s} \times 2.2\times10^{-12}\ \text{kg/C} = 1\times10^{-13}\text{s} = 0.1\ \text{ps}$$

mean free path $= \tau_{mh} v_{th} \sim 1\times 10^{-13}\ \text{s} \times 2.2\times10^7\ \text{cm/s}$

$$= 2.2\times10^{-6}\ \text{cm} = 220\ \text{Å} = 22\ \text{nm}$$

This is smaller than the typical dimensions of devices, but getting close.

Mechanisms of Carrier Scattering

There are two main causes of carrier scattering:

1. Phonon Scattering
2. Impurity (Dopant) Ion Scattering

Phonon scattering mobility decreases when temperature rises*:*

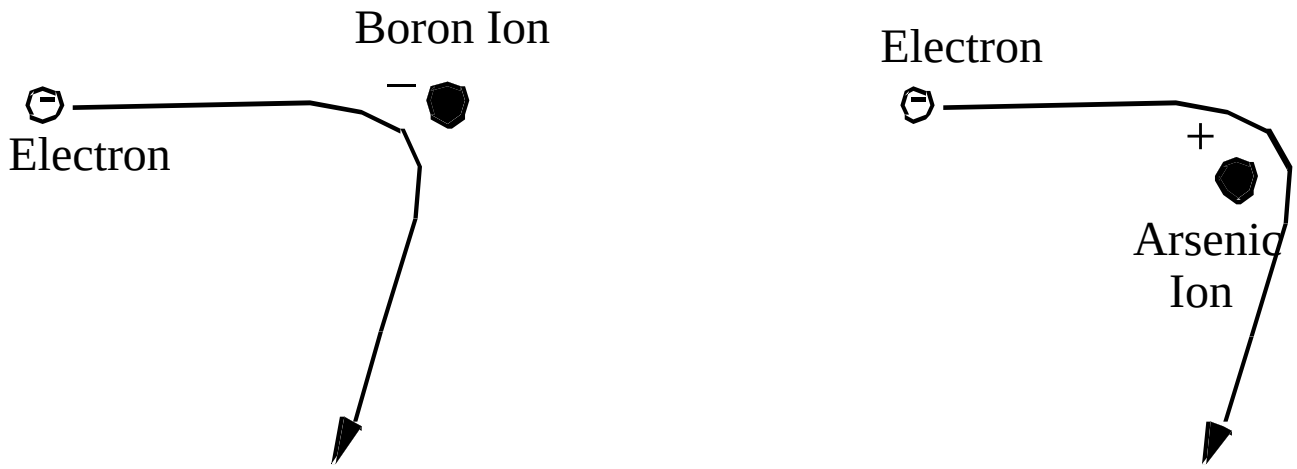
$$\mu_{phonon} \propto \tau_{phonon} \propto \frac{1}{phonon \quad density \times carrier \quad thermal \quad velocity} \propto \frac{1}{T \times T^{1/2}} \propto T^{-3/2}$$

$\mu = q\tau/m$

$\propto T$

$v_{th} \propto T^{1/2}$

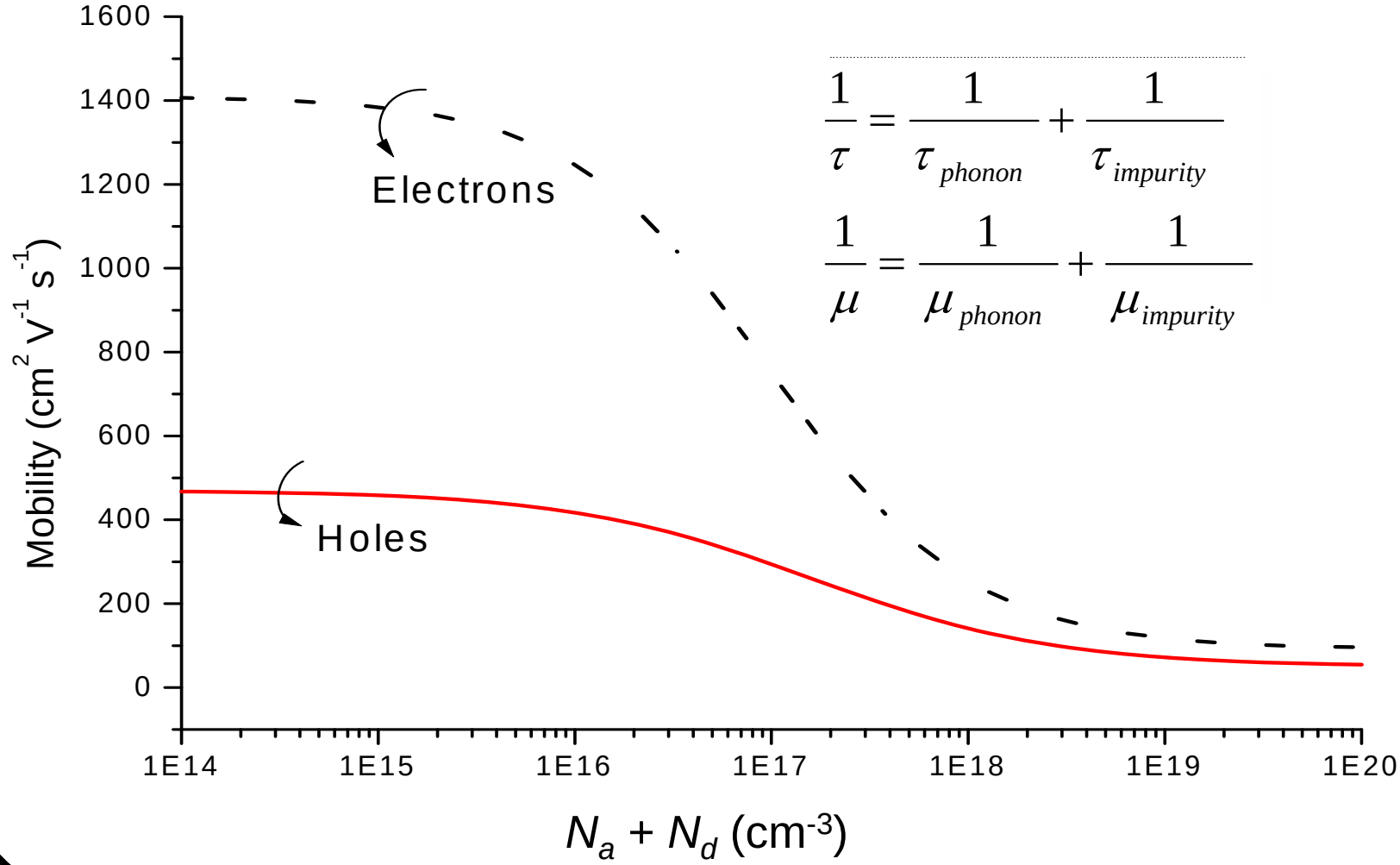
Impurity (Dopant)-Ion Scattering or Coulombic Scattering



There is less change in the direction of travel if the electron zips by the ion at a higher speed.

$$\mu_{impurity} \propto \frac{v_{th}^{3}}{N_a + N_d} \propto \frac{T^{3/2}}{N_a + N_d}$$

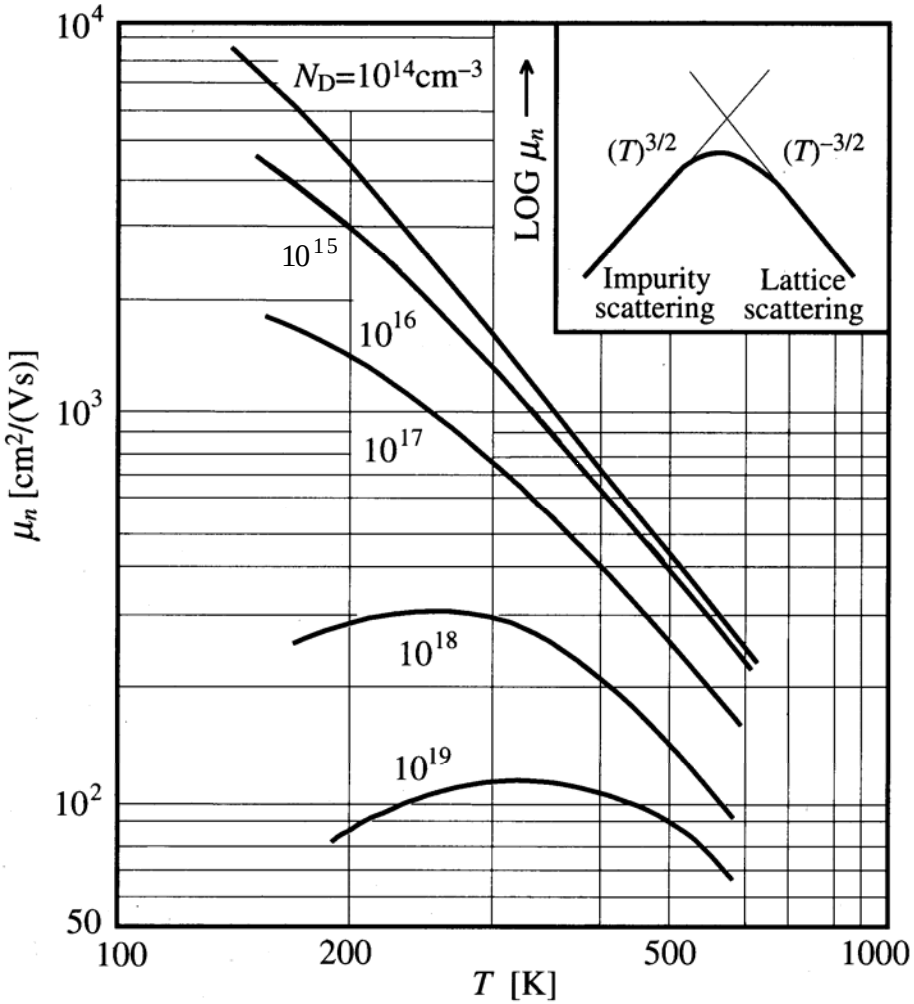
Total Mobility



$$\frac{1}{\tau} = \frac{1}{\tau_{phonon}} + \frac{1}{\tau_{impurity}}$$

$$\frac{1}{\mu} = \frac{1}{\mu_{phonon}} + \frac{1}{\mu_{impurity}}$$

Temperature Effect on Mobility



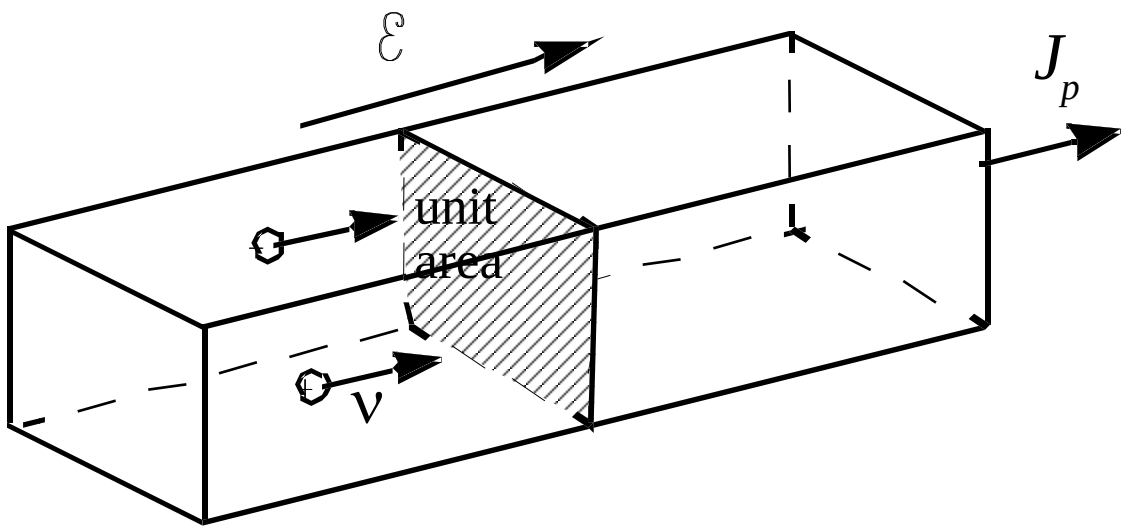
Question:
What N_d will make $d\mu_n/dT = 0$ at room temperature?

Velocity Saturation

When the kinetic energy of a carrier exceeds a critical value, it generates an optical phonon and loses the kinetic energy. Therefore, the kinetic energy is capped and the velocity does not rise above a saturation velocity, v_{sat}, no matter how large $\mathcal{E}$ is.

Velocity saturation has a deleterious effect on device speed as we will see in the later chapters.

Drift Current and Conductivity



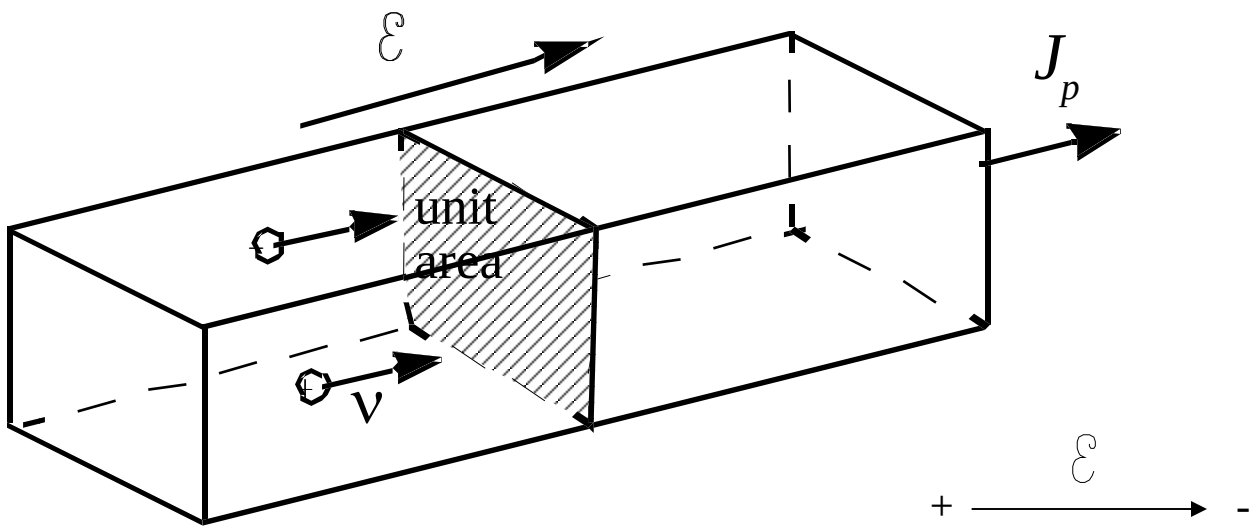
Current density $\boxed{J_p = qpv}$ A/cm^2 or C/cm^2·sec

EXAMPLE: If $p = 10^{15}$cm^{-3} and $v = 10^4$ cm/s, then

$$J_p = 1.6\times10^{-19}\text{C} \times 10^{15}\text{cm}^{-3} \times 10^4\text{cm/s}$$

$$= 1.6\ \text{C/s}\cdot\text{cm}^2 = 1.6\ \text{A/cm}^2$$

Drift Current and Conductivity



Remember:

- Holes travel in the direction of the Electric field
- Electrons travel in the direction opposite to that of the E-field

Drift Current and Conductivity

$$J_{p,drift} = qpv = qp\mu_p\mathcal{E}$$

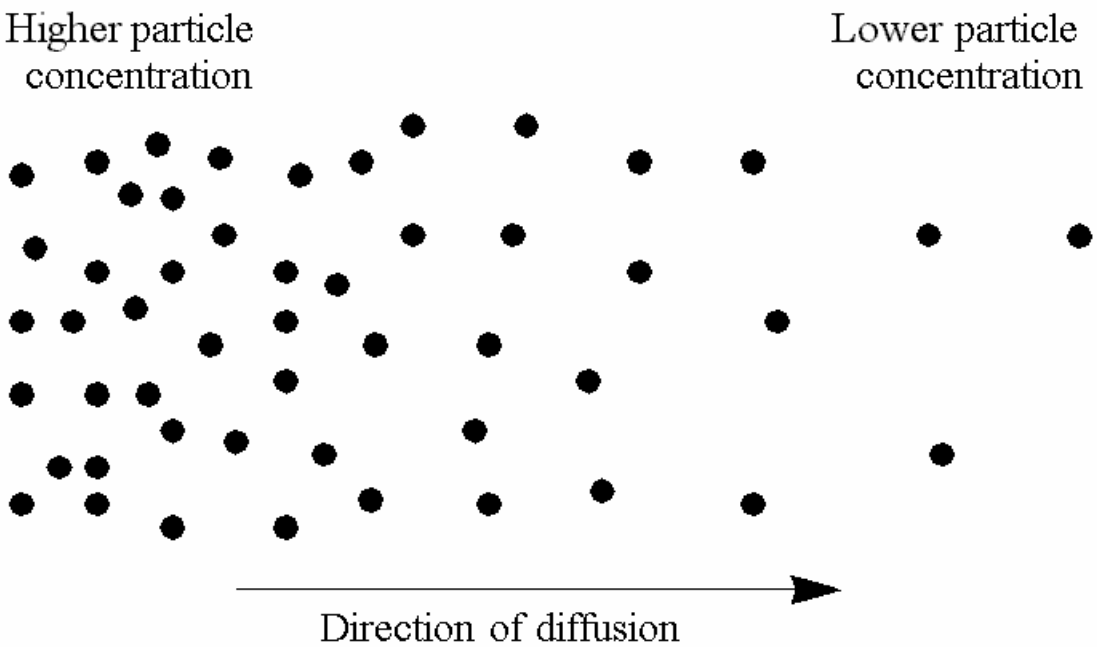
$$J_{n,drift} = -qnv = qn\mu_n\mathcal{E}$$

$$J_{drift} = J_{n,drift} + J_{p,drift} = (qn\mu_n + qp\mu_p)\mathcal{E} = \sigma\mathcal{E}$$

$\therefore$ *conductivity of a semiconductor is* $\sigma = qn\mu_n + qp\mu_p$

$\therefore$ *resistivity of a semiconductor is* $\rho = 1/\sigma$

Diffusion Current

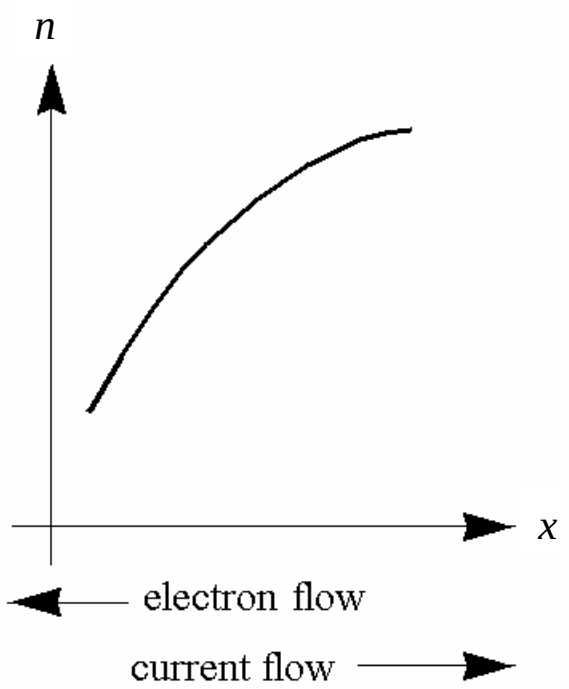


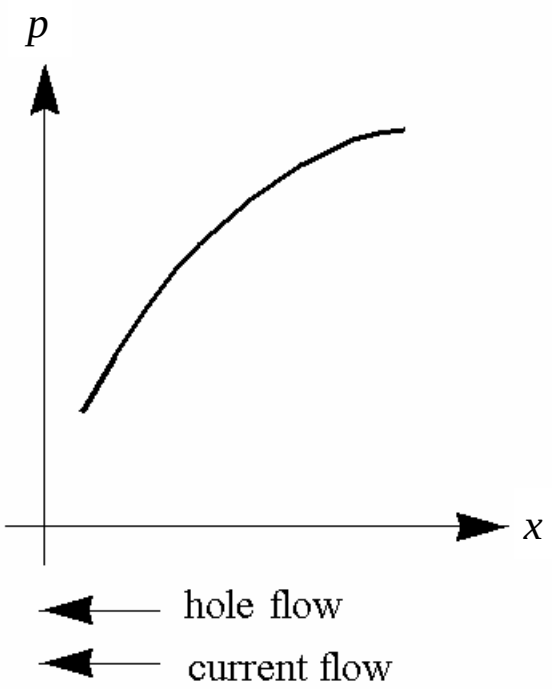
Particles diffuse from a higher-concentration location to a lower-concentration location.

Diffusion Current

$$J_{n,diffusion} = qD_n \frac{dn}{dx} \qquad J_{p,diffusion} = -qD_p \frac{dp}{dx}$$

D is called the diffusion constant. Signs explained:





Total Current – Review of Four Current Components

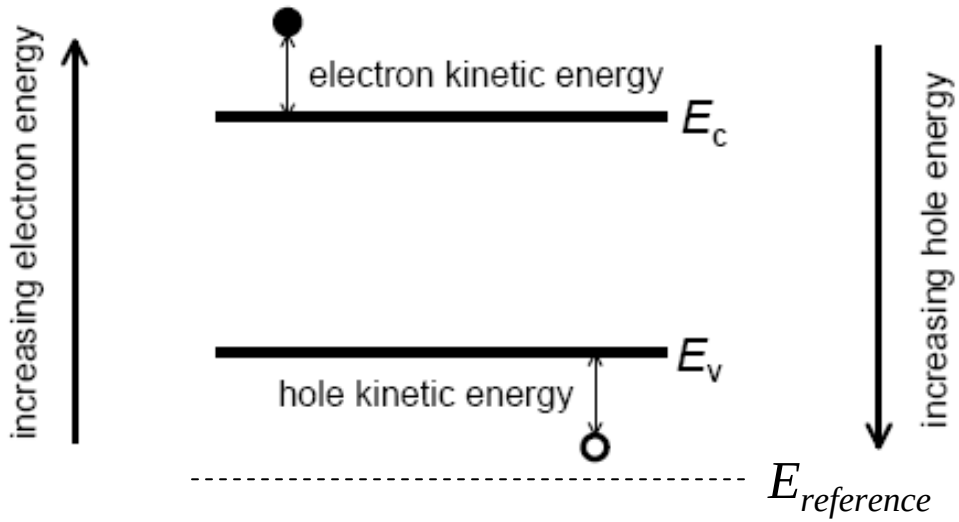
$$J_{TOTAL} = J_n + J_p$$

$$J_n = J_{n,drift} + J_{n,diff} = qn\mu_n\mathcal{E} + qD_n \frac{dn}{dx}$$

$$J_p = J_{p,drift} + J_{p,diff} = qp\mu_p\mathcal{E} - qD_p \frac{dp}{dx}$$

$$\boldsymbol{J_{TOTAL} = J_{n,drift} + J_{n,diff} + J_{p,drift} + J_{p,diff}}$$

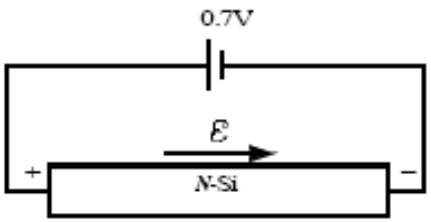
Band Diagram: Potential *vs.* Kinetic Energy

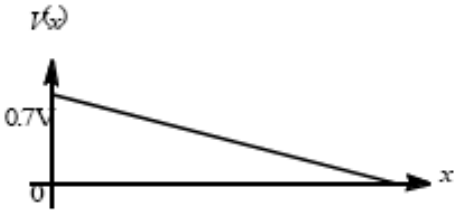


E_c represents the electron potential energy:

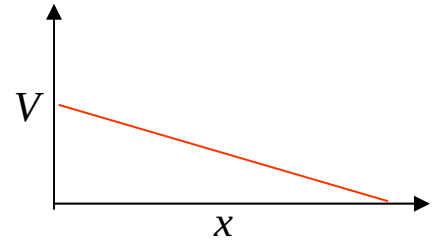
$$\text{P.E.} = E_c - E_{\text{reference}}$$

Electrostatic Potential *V*





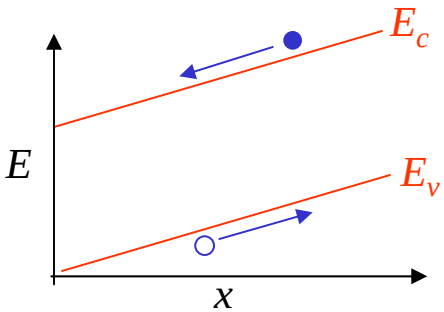
- Potential energy of a $-q$ charged particle is related to the electrostatic potential $V(x)$:



E_c and E_v vary in the opposite direction from the voltage. That is, E_c and E_v are higher where the voltage is lower.

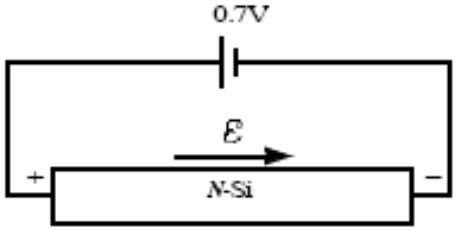
$$\text{P.E.} = -qV$$

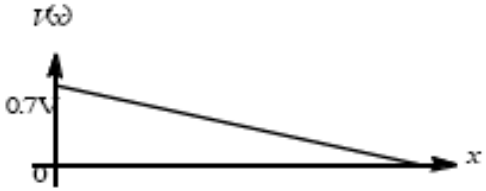
$$E_c - E_{reference} = -qV$$



Variation in E_c with position is called <u>band bending</u>

Electric Field $\mathcal{E}$

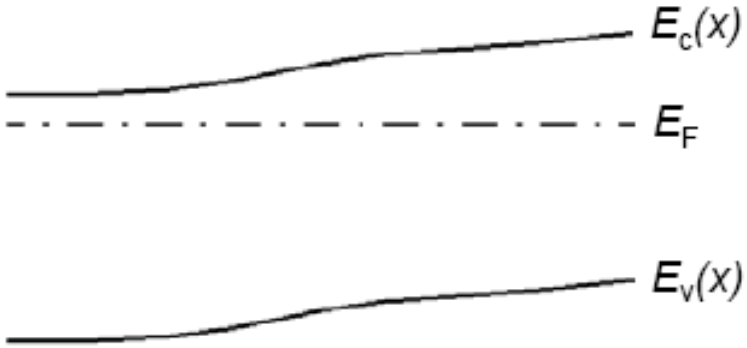




$$\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

Non-Uniformly-Doped Semiconductor

- The position of E_F relative to the band edges is determined by the carrier concentrations, which is determined by the dopant concentrations.
- **In equilibrium, E_F is constant**; therefore, the band energies vary with position:



- In equilibrium, there is no net flow of electrons or holes

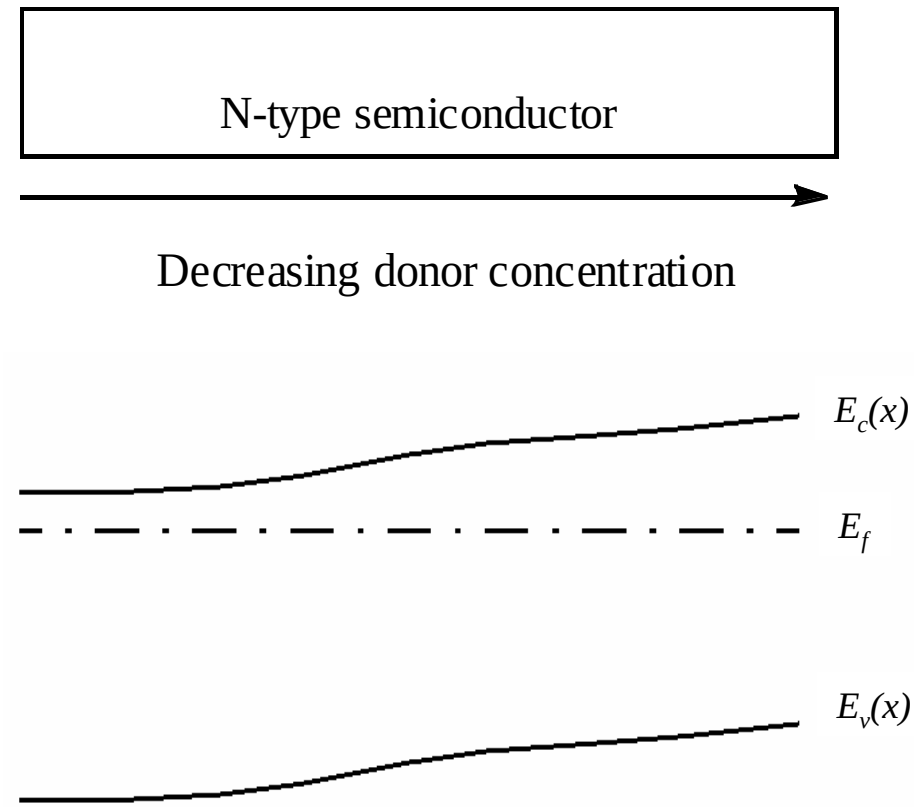
$$J_N = 0 \quad \text{and} \quad J_P = 0$$

➔ The drift and diffusion current components must balance each other exactly. (A built-in electric field exists, such that the drift current exactly cancels out the diffusion current due to the concentration gradient.)

$$J_N = qn\mu_n\mathcal{E} + qD_N\frac{dn}{dx} = 0$$

Einstein Relationship between D and μ

Consider a piece of non-uniformly doped semiconductor.



$$n = N_c e^{-(E_c - E_f)/kT}$$

$$\frac{dn}{dx} = -\frac{N_c}{kT} e^{-(E_c - E_f)/kT} \frac{dE_c}{dx}$$

$$= -\frac{n}{kT} \frac{dE_c}{dx}$$

$$= -\frac{n}{kT} q \mathcal{E}$$

Einstein Relationship between D and μ

$$\frac{dn}{dx} = -\frac{n}{kT} q\mathcal{E}$$

$$J_n = qn\mu_n\mathcal{E} + qD_n \frac{dn}{dx} = 0 \quad \text{at equilibrium.}$$

$$0 = qn\mu_n\mathcal{E} - qn\frac{qD_n}{kT}\mathcal{E}$$

$$\boxed{D_n = \frac{kT}{q}\mu_n} \quad \text{Similarly,} \quad \boxed{D_p = \frac{kT}{q}\mu_p}$$

These are known as the <u>Einstein relationship</u>.

EXAMPLE: Diffusion Constant

What is the hole diffusion constant in a piece of silicon with $\mu_p = 410\ cm^2\ V^{-1} s^{-1}$ *?*

Solution:

$$D_p = \left(\frac{kT}{q}\right)\mu_p = (26\,\mathrm{mV}) \cdot 410\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1} = 11\,\mathrm{cm}^2/\mathrm{s}$$

Remember: kT/q = 26 mV at room temperature.