VE320 – Summer 2024

Introduction to Semiconductor Devices

Instructor: Yaping Dan （但亚平）
yaping.dan@sjtu.edu.cn

Chapter 5 Carrier Transport Phenomena

Outline

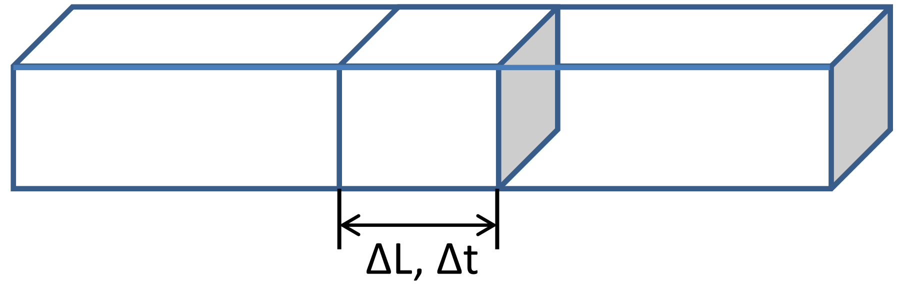
5.1 Carrier drift

5.2 Carrier diffusion

5.3 Graded impurity distribution

5.1 Carrier drift

Drift current density



$$for\ p\ type\ semiconductor, p_0 \gg n_0$$

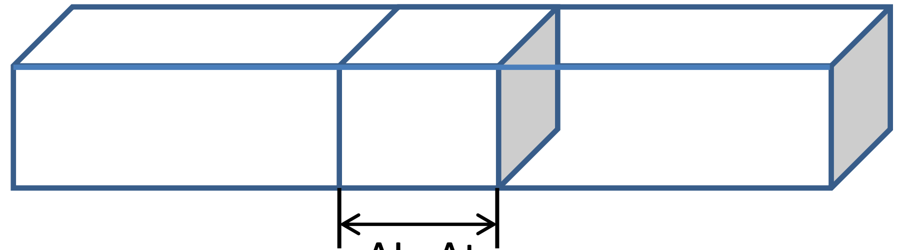
Drift current

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0A_c\Delta L}{\Delta t} = qp_0A_cv_d$$

ρ: *charge density*

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0\Delta LA_c}{\Delta t} = p_0qv_dA_c$$

5.1 Carrier drift (current in an ideal case)



Drift current density

Drift current

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0A_c\Delta L}{\Delta t} = qp_0A_cv_d$$

$for\ p\ type\ semiconductor, p_0 \gg n_0$

$\rho: charge\ density$

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0\Delta LA_c}{\Delta t} = p_0qv_dA_c$$

$$\mathrm{L} = \frac{1}{2}at^2 \quad \rightarrow t = \sqrt{2L/a}$$

$$\rightarrow \quad vd = at = \sqrt{2La} = \sqrt{2LqE/m_{cp}^*}$$

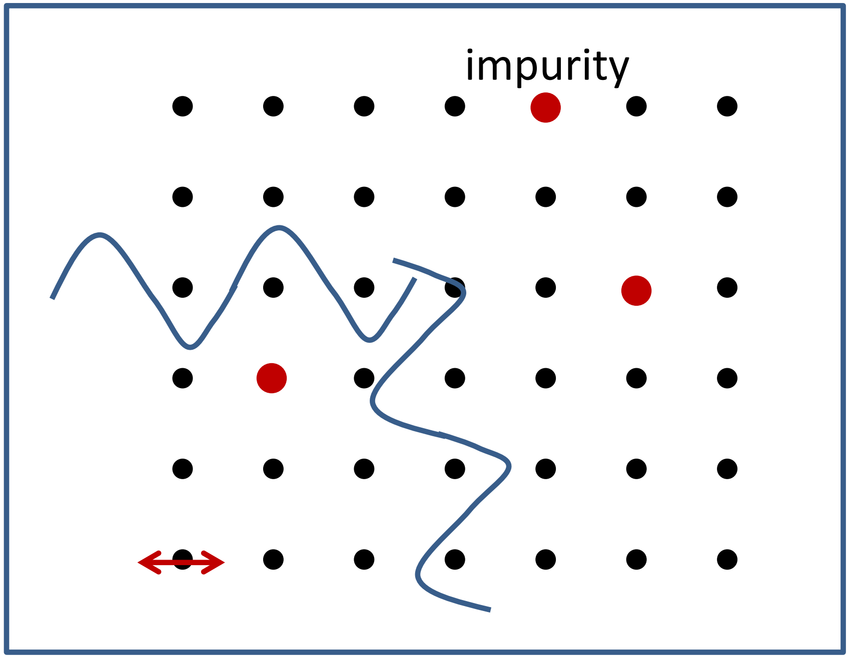
$$E = V/L$$

$$\rightarrow vd = \sqrt{2qV/m_{cp}^*}$$

$$\therefore I_{drf} = qp_0\sqrt{2qV/m_{cp}^*}A_c$$

$\boxed{However, Ohm's\ Law\ tells\ us: I = \sigma \cdot V}$

5.1 Carrier drift (phonons and scatterings)



Thermal vibrations of lattice are phonons

Scatterings include:

- Electrons scatter with phonons
- Electrons scatter with Impurities

5.1 Carrier drift

Drift current density

$$\boxed{scatterings}$$

$$\downarrow$$

$$\boxed{v \sim E}$$

$$\downarrow$$

$$\boxed{v = \mu E}$$

$$\swarrow \qquad \searrow$$

$$\boxed{v_n = \mu_n E} \qquad \boxed{v_p = \mu_p E}$$

Electrons　　Holes

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0 A_c \Delta L}{\Delta t} = qp_0 A_c v = qp_0 A_c \mu_p E = qp_0 A_c \mu_p \frac{V}{L} = \sigma \cdot V$$

5.1 Carrier drift

Drift current density

Hole drift current

$$J_{p|drf} = qp_0\mu_p E$$

Electron drift current

$$J_{n|drf} = qn_0\mu_n E$$

Both electrons and holes contribute to current:

$$J_{drf} = q(p_0\mu_p + n_0\mu_n)E$$

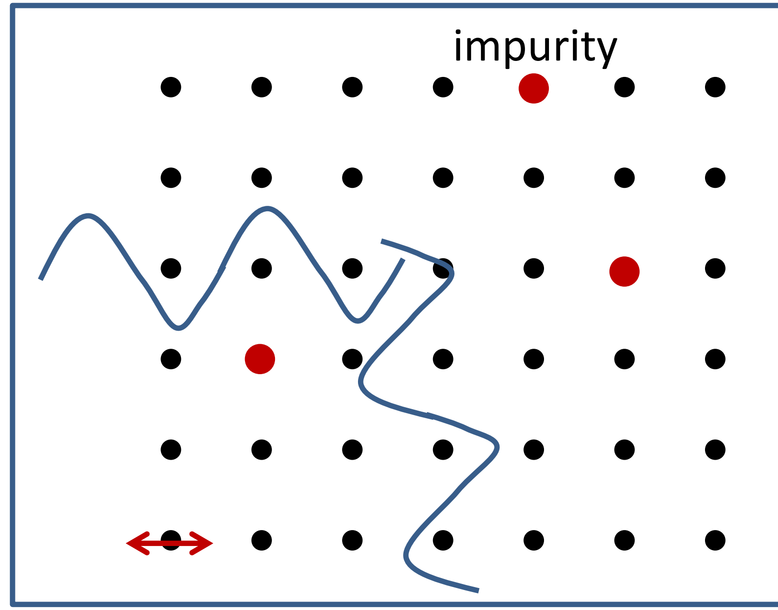
Table 5.1 | Typical mobility values at $T = 300$ K and low doping concentrations

	μ_n (cm²/V-s)	μ_p (cm²/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

5.1 Carrier drift

Mobility effect

Why are resistors heated up by current?



Power supply

Energy transfer — Electric field accelerates

High speed electrons (hot)

Energy transfer — Scatterings →

- Slow down electrons
- Reduce electron mobility

Lattice vibrations (hot)

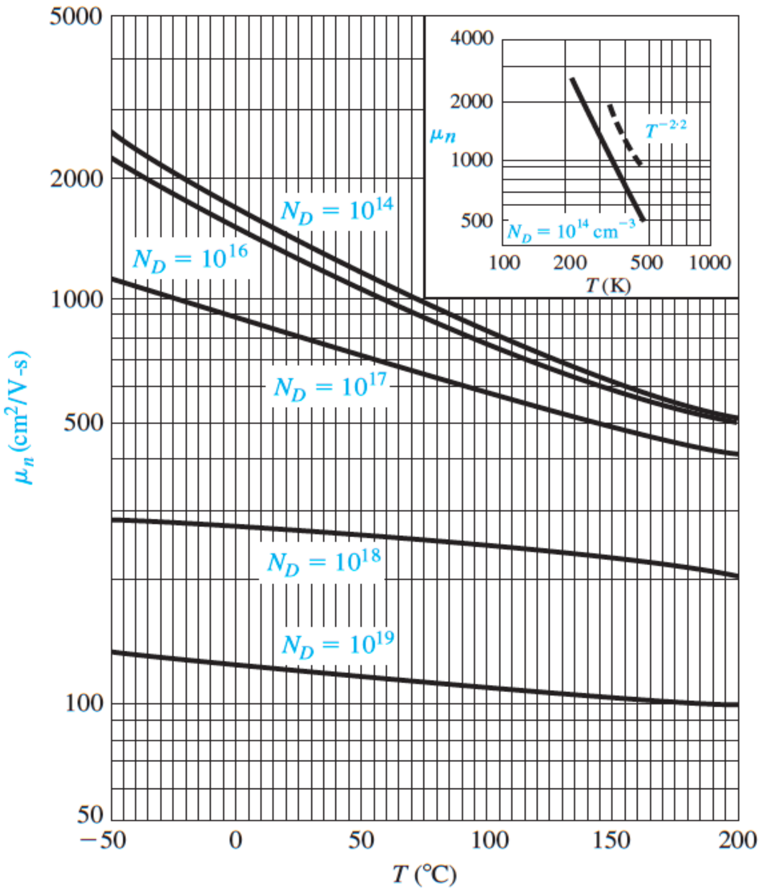
Conclusions:

- Higher doping concentration → lower mobility
- Higher Temperature → lower mobility

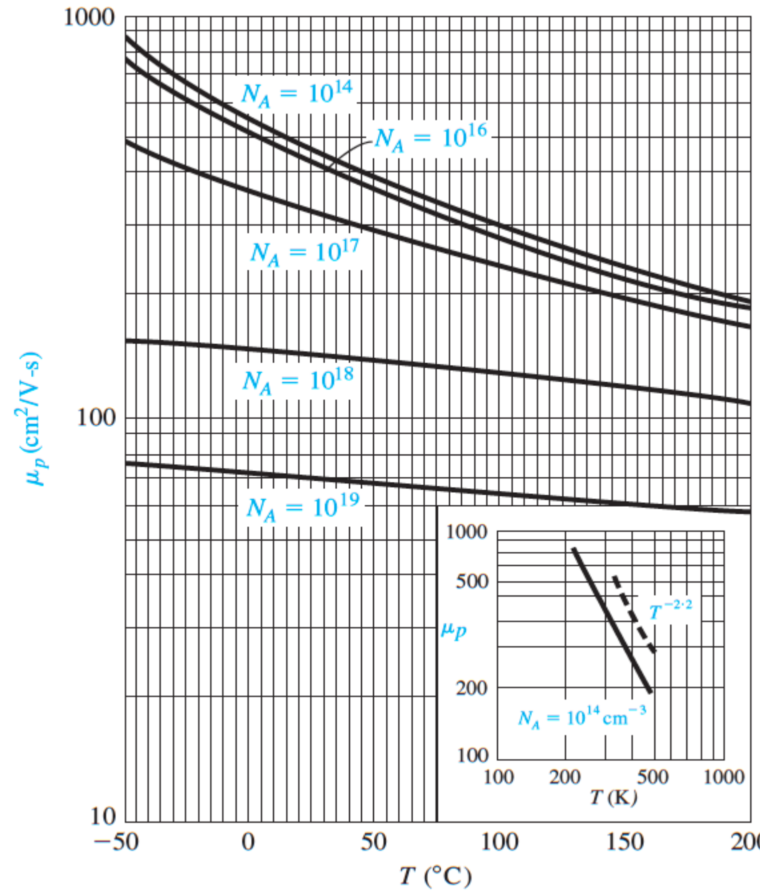
5.1 Carrier drift

<u>Mobility effect</u>: higher T and higher doping → lower mobility

Electron mobility in n-type doping



Hole mobility in p-type doping



5.1 Carrier drift

Conductivity

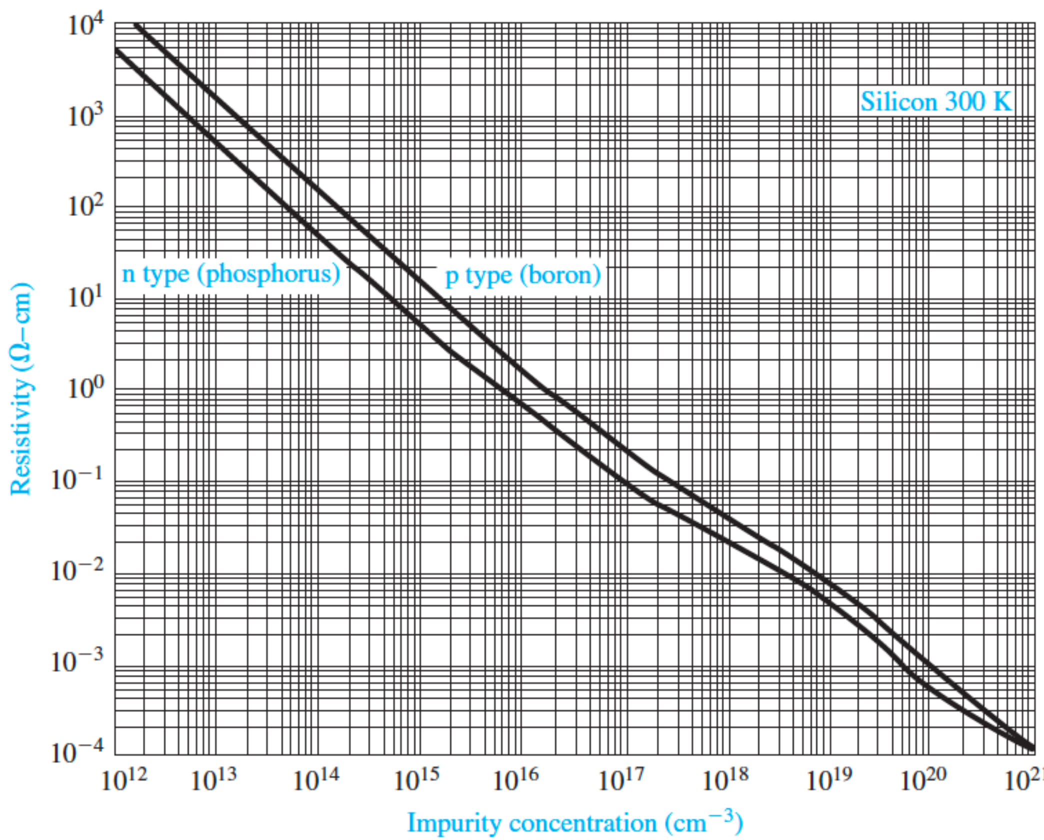
$$J_{drf} = q(p_0\mu_p + n_0\mu_n)E \;\Rightarrow\; \rho = \frac{1}{\sigma} = \frac{1}{q(\mu_n n + \mu_p p)}$$

For n-type doped semiconductor:

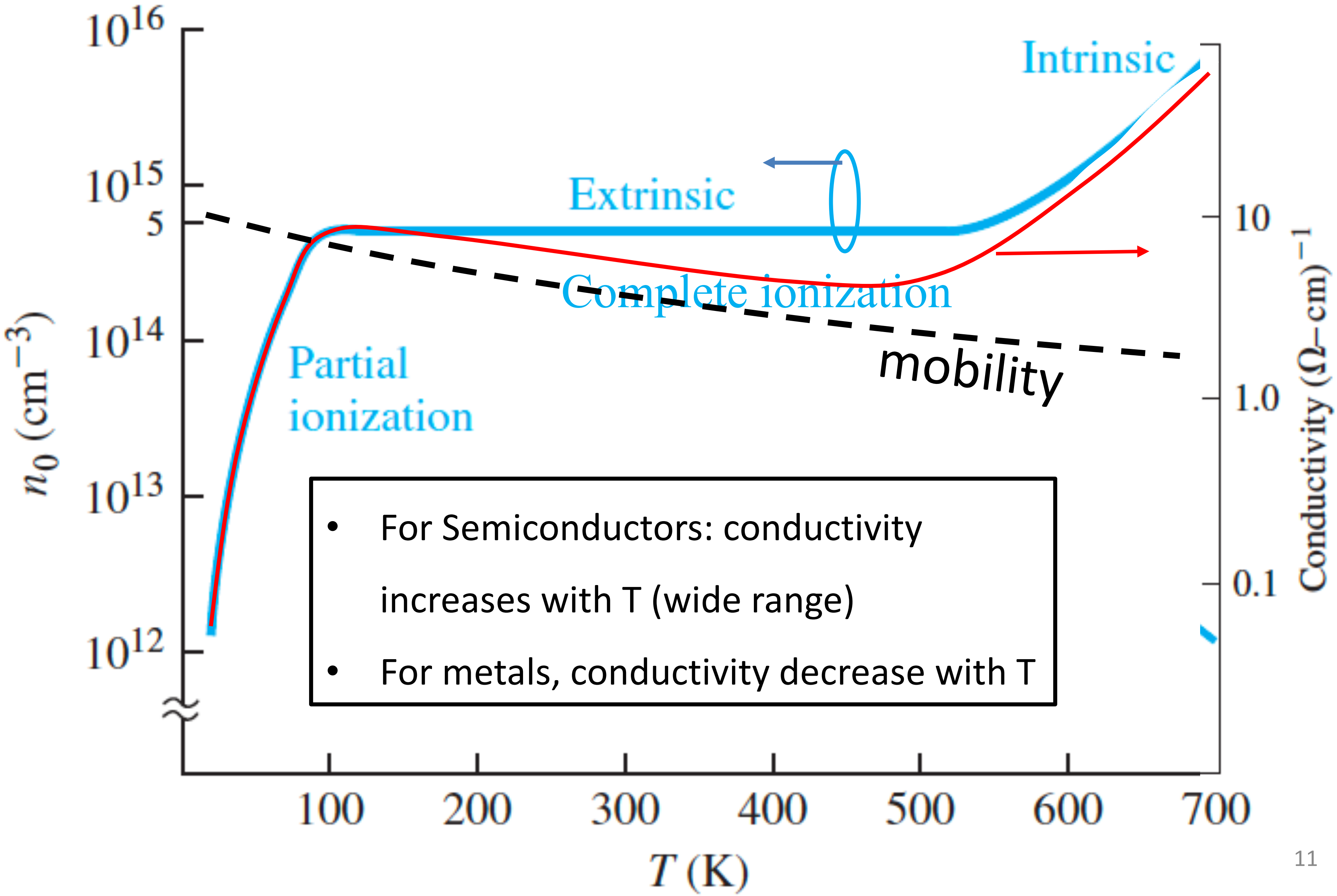
$$\rho = \frac{1}{\sigma} = \frac{1}{q\mu_n n} = \frac{1}{q\mu_n N_d}$$

For p-type doped semiconductor:

$$\rho = \frac{1}{\sigma} = \frac{1}{q\mu_n p} = \frac{1}{q\mu_n N_a}$$



5.1 Carrier drift (conductivity dependent on temperature)



- For Semiconductors: conductivity increases with T (wide range)
- For metals, conductivity decrease with T

5.1 Carrier drift

Velocity saturation

$$\frac{1}{2}mv_{th}^2 = \frac{3}{2}kT = 0.03885eV\ (300K)$$

$$\Rightarrow thermal\ velocity\ v_{th} \approx 10^7\ cm/s$$

$$Drift\ velocity\ v_d = \mu_n E$$

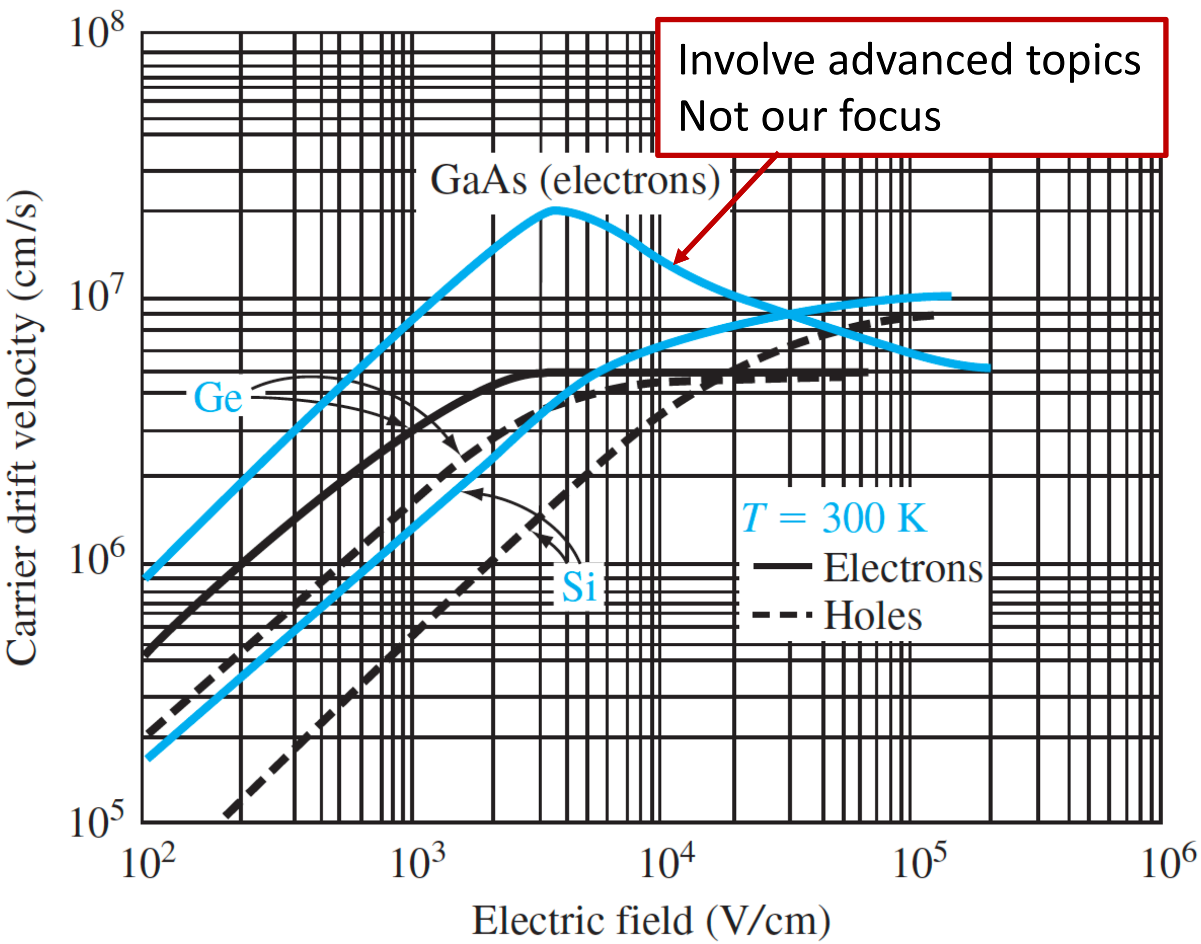
$$\Rightarrow E = \frac{v_d}{\mu_n} = \frac{10^7 cm/s}{1350cm^2/(Vs)} = 7\times 10^3\ V/cm$$

5.1 Carrier drift

Velocity saturation

$$\boxed{v_d \rightarrow v_{th}}$$

- Electric field is heating up electrons
- Electrons transfer energy to lattice to reach thermal equilibrium



$$v_n = \frac{v_s}{\left[1 + \left(\frac{E_{on}}{E}\right)^2\right]^{1/2}}$$

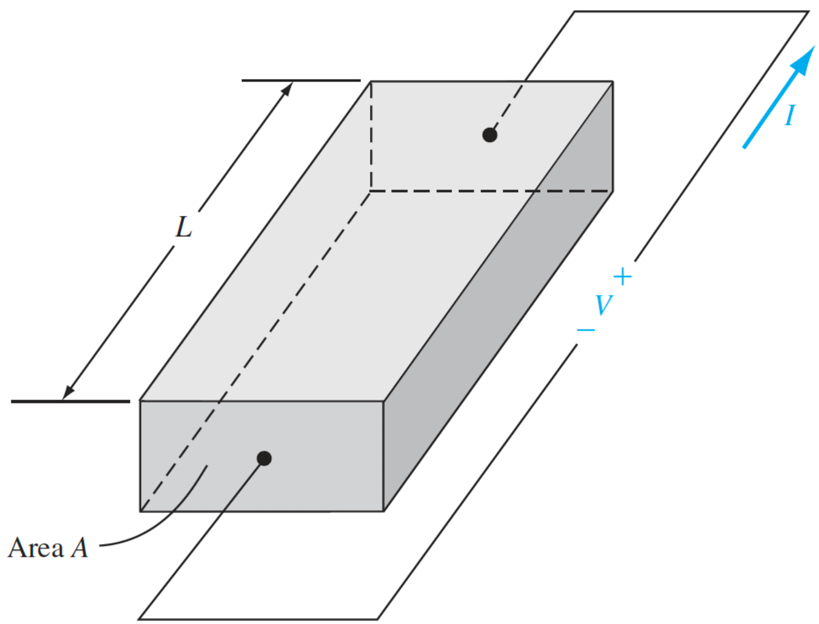
$$v_p = \frac{v_s}{\left[1 + \left(\frac{E_{op}}{E}\right)^{2}\right]^{1/2}}$$

Probably a typo in textbook

Check your understanding

Problem Example #1

A bar of p-type silicon at 300K in the figure below has a cross-sectional area $A = 10^{-6}$ cm^2 and a length $L = 1.2 \times 10^{-3}$ cm. For an applied voltage of 5V, a current of 2mA is required. What is the required (a) resistance, (b) resistivity, and (c) impurity doping concentration? (d) What is the resulting hole mobility?



Outline

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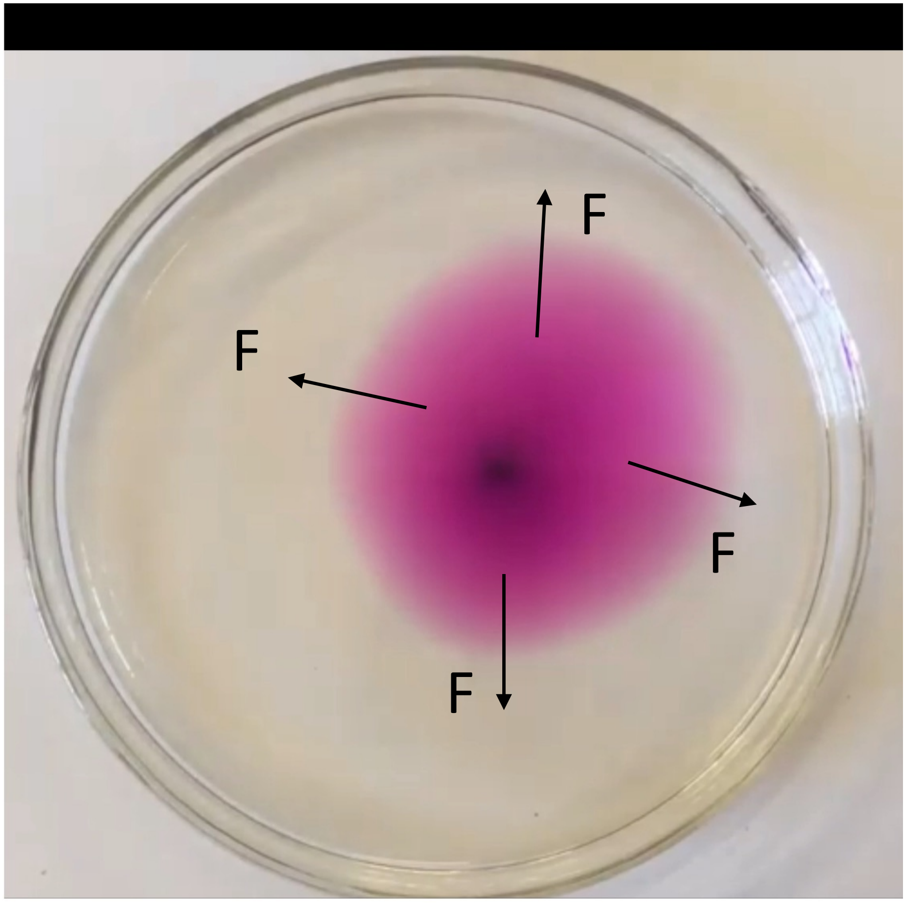
5.2 Carrier diffusion

5.3 Graded impurity distribution

5.2 Carrier diffusion

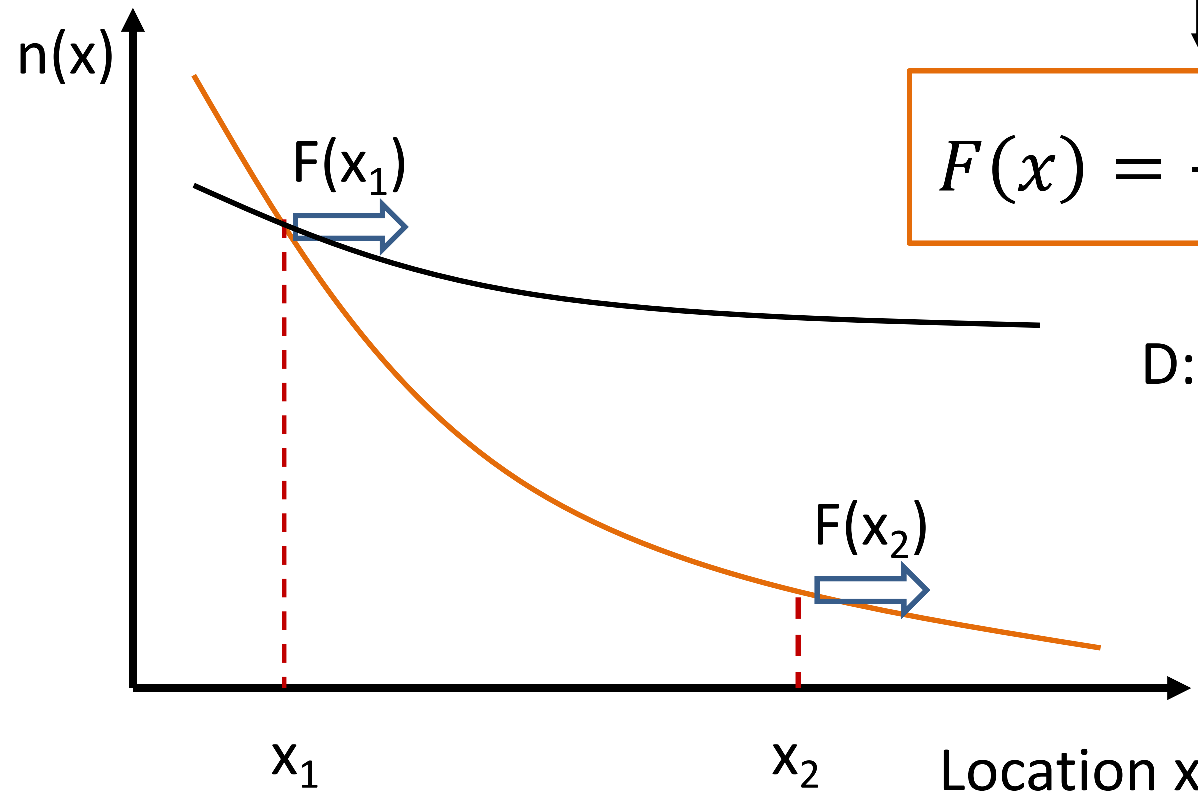
5.2 Carrier diffusion



Flux F: number of particles passing through a unit area per second

5.2 Carrier diffusion

Particle concentration n (cm^{-3})



$$\boxed{F(x) \sim \frac{dn(x)}{dx}}$$

$$\boxed{F(x) = -D\frac{dn(x)}{dx}}$$

D: Diffusivity

5.2 Carrier diffusion

Diffusion current density

Electron diffusion current density: $J_{nx|dif} = -qF_n = qD_n \frac{dn}{dx}$

D_n is called the electron diffusion coefficient

Hole diffusion current density: $J_{px|dif} = qF_p = -qD_p \frac{dp}{dx}$

D_p is called the hole diffusion coefficient

5.2 Carrier diffusion

Total current density

$$J = J_{drf} + J_{dif} = J_{n|drf} + J_{p|drf} + J_{n|dif} + J_{p|dif}$$

$$= qn\mu_n E_x + qp\mu_p E_x + qD_n \frac{dn}{dx} - qD_p \frac{dp}{dx}$$

$$\mathrm{J} = qn\mu_n E_x + qp\mu_p E_x + qD_n \nabla \mathrm{n} - qD_p \nabla p$$

5.2 Carrier diffusion

Problem Example #2

The hole density in silicon is given by $p(x) = 10^{16} \exp(-x/L_p)$ $(x \geq 0)$ where $L_p = 2 \times 10^{-4}$ cm. Assume the hole diffusion coefficient is $D_p = 8 \text{cm}^2/\text{s}$. Determine the hole current density at $x = 2 \times 10^{-4}$ cm.

$$J_{p|diff} = -qD_p \frac{dp}{dx}$$

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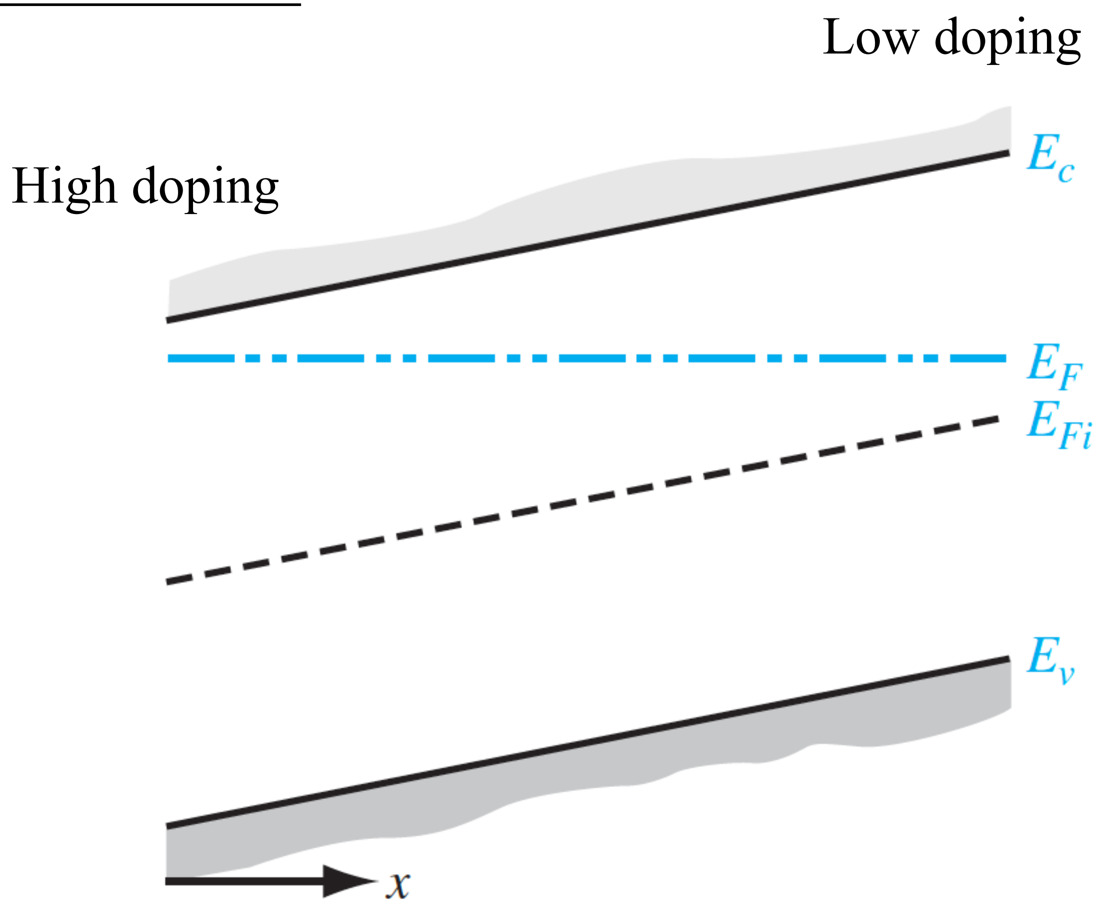
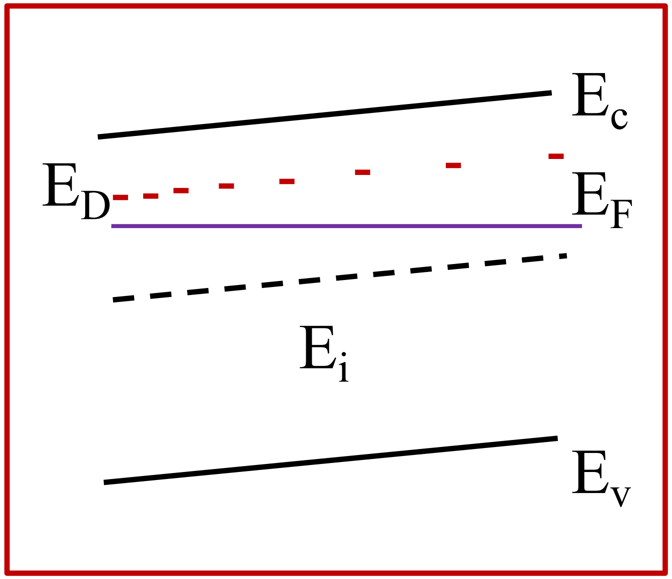
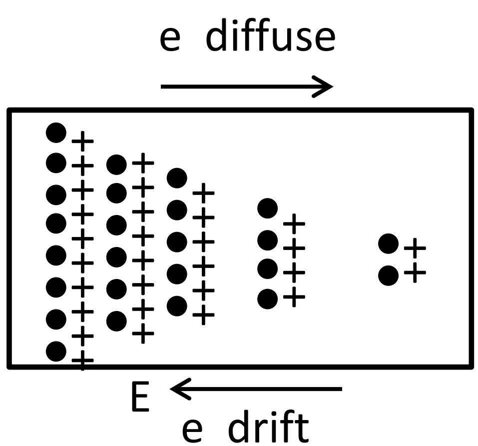
Induced electric field



5.3 Graded impurity distribution

- Induced electric field



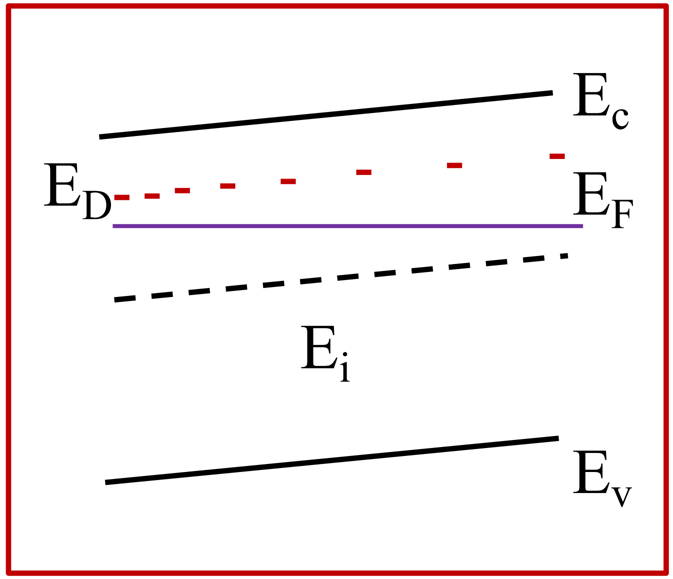


5.3 Graded impurity distribution

- The Einstein relation

$$E_x = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

$$= \frac{-1}{q}\frac{kT}{n(x)}\frac{dn(x)}{dx}$$



$$\phi = \frac{1}{q}(E_F - E_i)$$

$$E_x = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

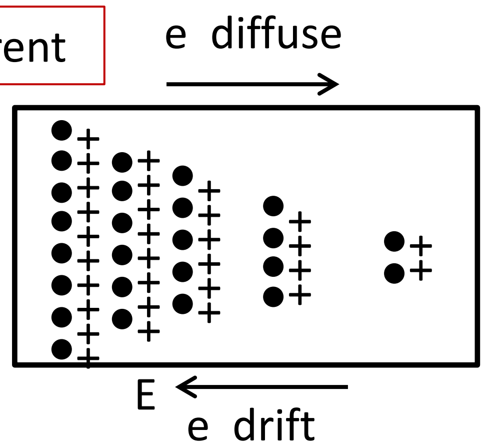
$$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

$$E_F - E_i = kT ln(n/n_i)$$

Drift current = diffusion current

$$J_{n,drift} = qn(x)\mu_n|E|$$

$$J_{n,diff} = qD_n\frac{dn(x)}{dx}$$



5.3 Graded impurity distribution

- The Einstein relation

$$J_{n,drift} = qn(x)\mu_n|E| = qD_n\frac{dn(x)}{dx} = J_{n,diff}$$

$$qn(x)\mu_n\left(\frac{1}{q}\frac{kT}{n(x)}\frac{dn(x)}{dx}\right) = qD_n\frac{dn(x)}{dx}$$

$$\cancel{q}\cancel{n(x)}\mu_n\left(\frac{1}{q}\frac{kT}{\cancel{n(x)}}\frac{\cancel{dn(x)}}{\cancel{dx}}\right) = \cancel{q}D_n\frac{\cancel{dn(x)}}{\cancel{dx}}$$

$$E_x = -\frac{d\phi}{dx} = \frac{1}{e}\frac{dE_i}{dx}$$

$$= \frac{1}{q}\frac{kT}{n(x)}\frac{dn(x)}{dx}$$

$$\boxed{D_n = \frac{\mu_n kT}{q}}$$

Chenk your understanding

Problem Example #3

Assume the donor concentration in an n-type semiconductor at T =300K is given by $N_d(x) = 10^{16}\exp(-x/L)$ where $L = 2 \times 10^{-2}$ cm. Determine the induced electric field and drift current density in the semiconductor at $x = 2 \times 10^{-2}$ cm. Note $\mu_n \approx$ 1350 cm^2/Vs and 1200 cm^2/Vs near the doping concentration of 3.68×10^{15} cm^{-3} and 10^{16} cm^{-3}, respectively.

$$E_x = \frac{1}{q}\frac{kT}{n(x)}\frac{dn(x)}{dx}$$