VE320 – Summer 2024

Introduction to Semiconductor Devices

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Chapter 5 Carrier Transport Phenomena

Outline

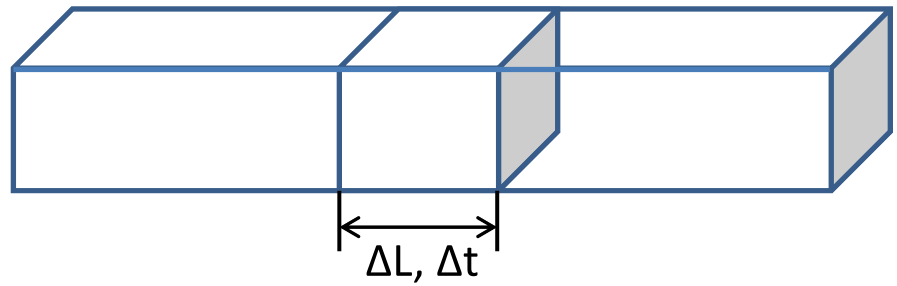
5.1 Carrier drift

5.2 Carrier diffusion

5.3 Graded impurity distribution

5.1 Carrier drift

<u>Drift current density</u>



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

Drift current

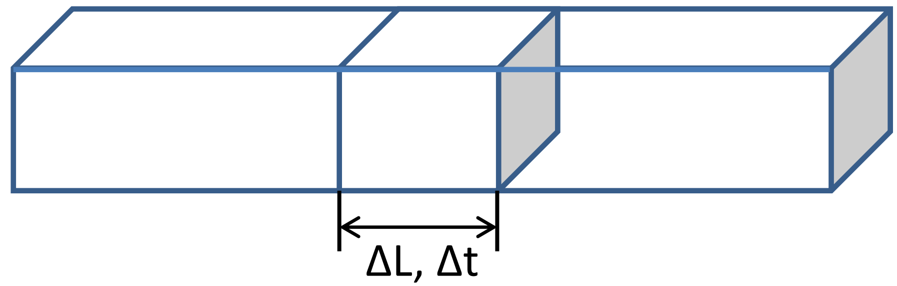
$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0A_c\Delta L}{\Delta t} = qp_0A_cv_d$$

$\rho: charge\ density$

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

5.1 Carrier drift (current in an ideal case)

<u>Drift current density</u>



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

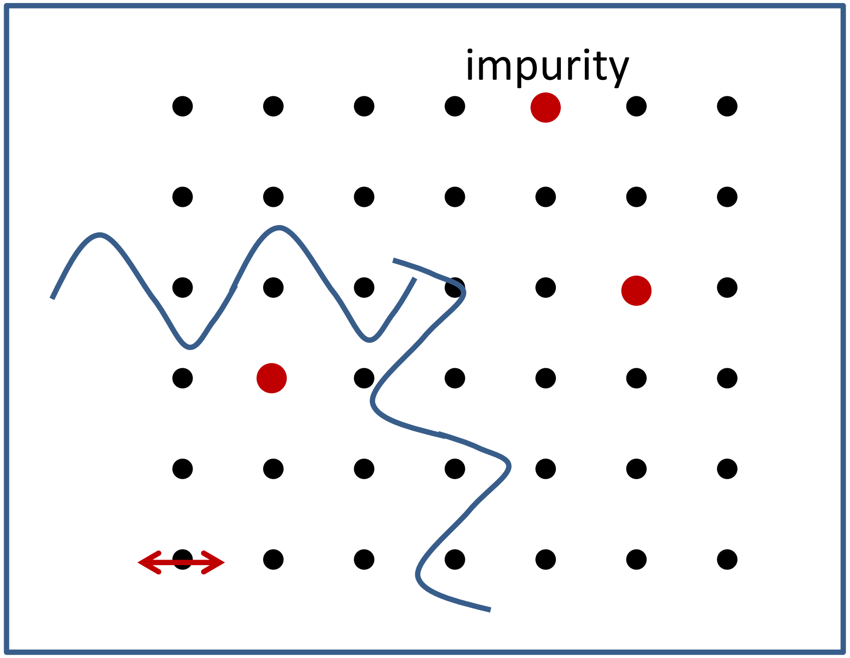
Drift current

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0 A_c \Delta L}{\Delta t} = qp_0 A_c v_d$$

$\rho: charge\ density$

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{qp_0 \Delta L A_c}{\Delta t} = p_0 q v_d A_c$$

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:

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

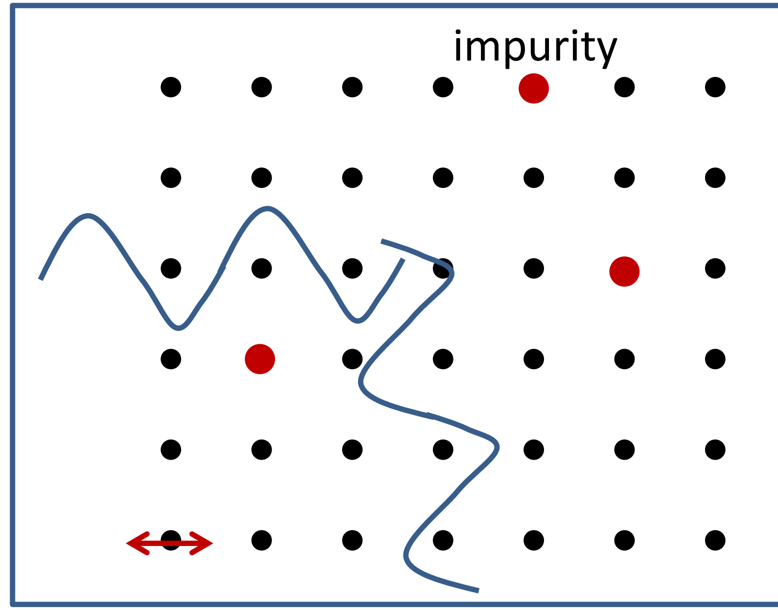
Table 5.1 | Typical mobility values at T = 300 K and low doping concentrations

	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)

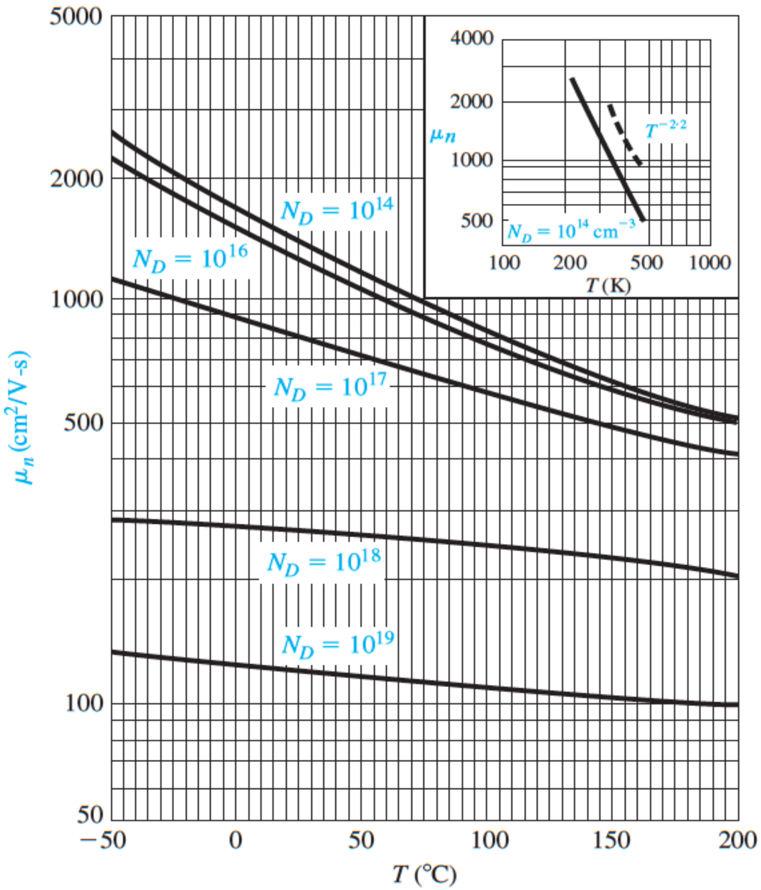
Conclusions:

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

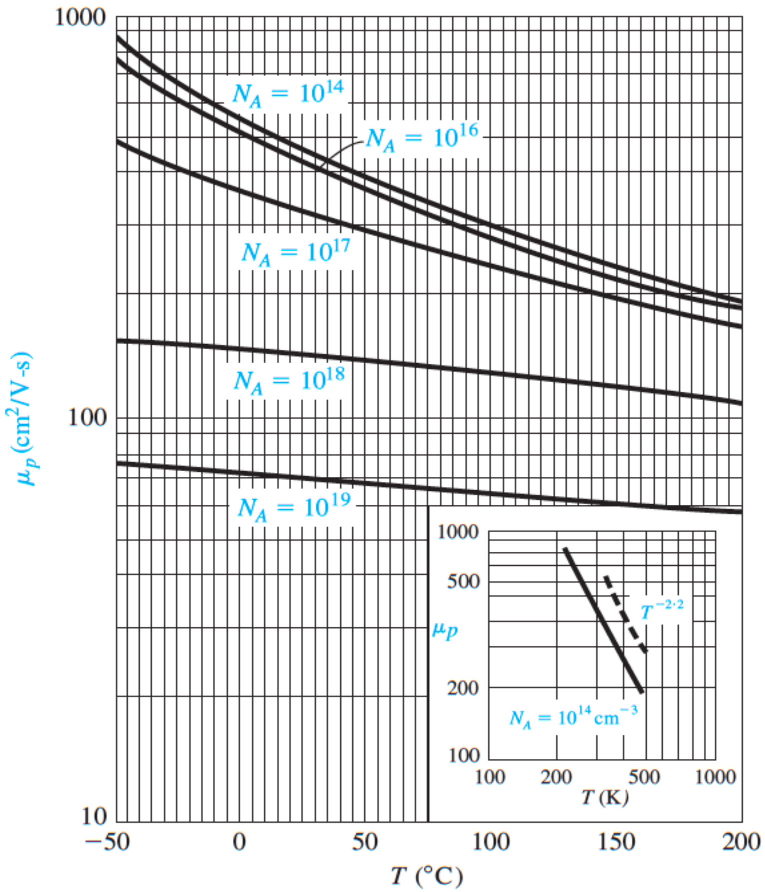
5.1 Carrier drift

Mobility effect: higher T and higher doping → lower mobility

Electron mobility in n-type doping



Hole mobility in p-type doping



5.1 Carrier drift

Conductivity

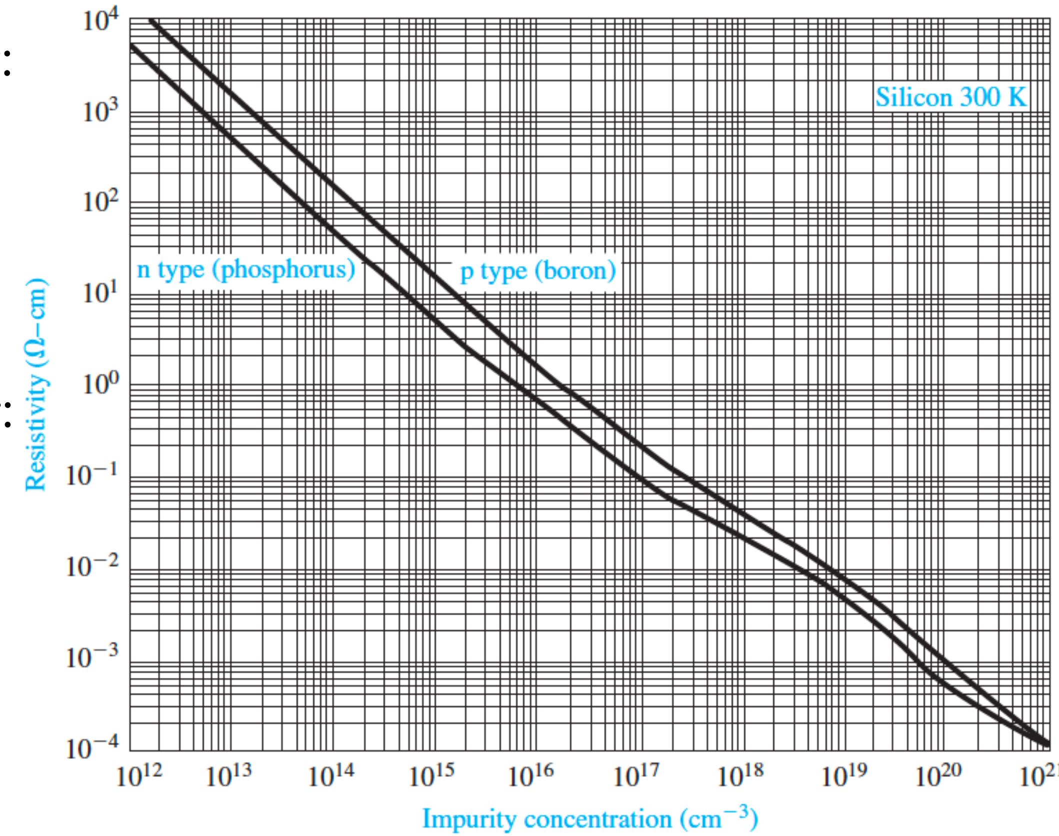
$$J_{drf} = q(p_0\mu_p + n_0\mu_n)E \;\Rightarrow\; \rho = \frac{1}{\sigma} = \frac{1}{q(\mu_n n + \mu_p p)}$$

For n-type doped semiconductor:

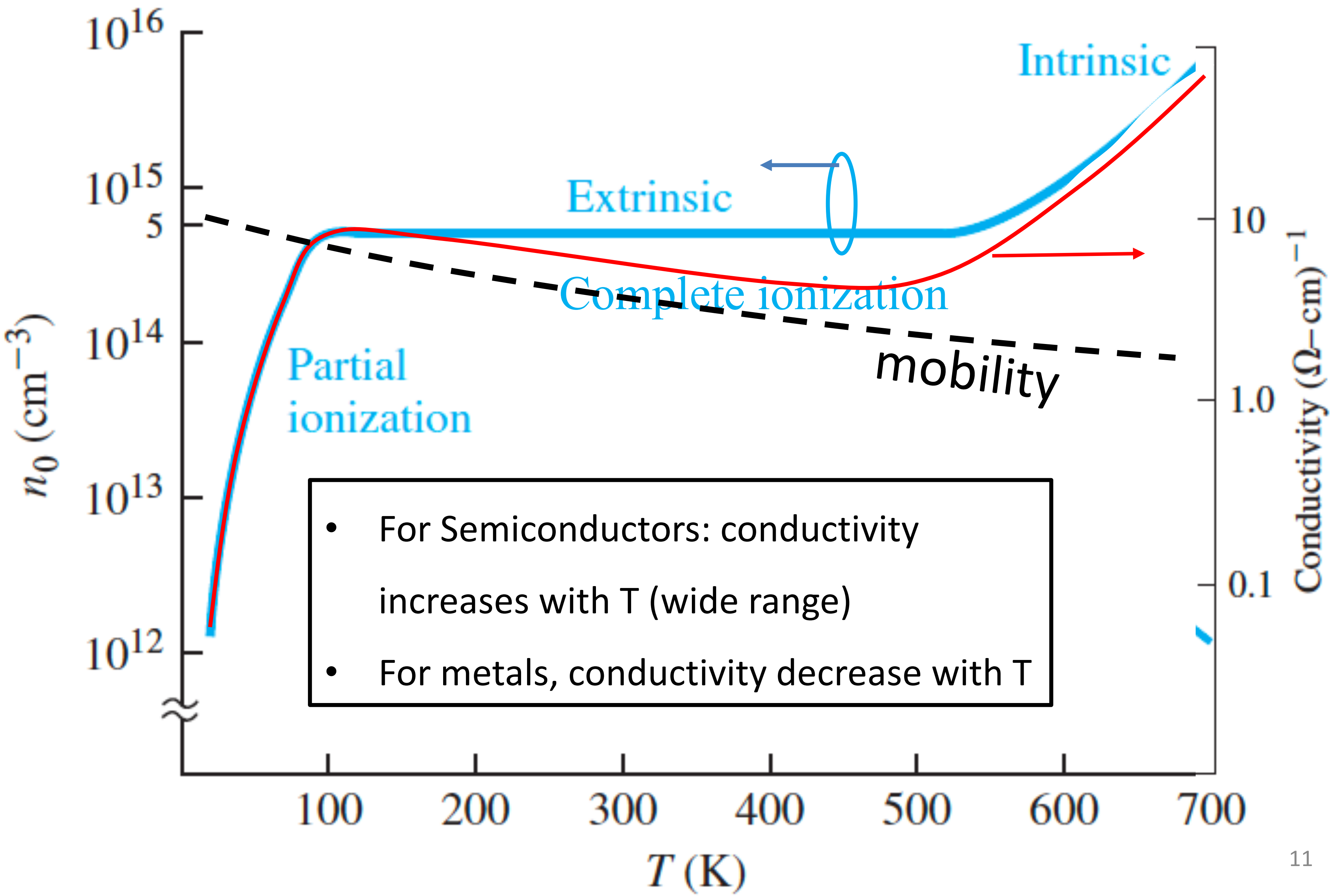
$$\rho = \frac{1}{\sigma} = \frac{1}{q\mu_n n} = \frac{1}{q\mu_n N_d}$$

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

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

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

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

$$\Rightarrow E = \frac{v_d}{\mu_n} = \frac{10^7 cm/s}{1350cm^2/(Vs)} = 7\times10^3\ V/cm$$

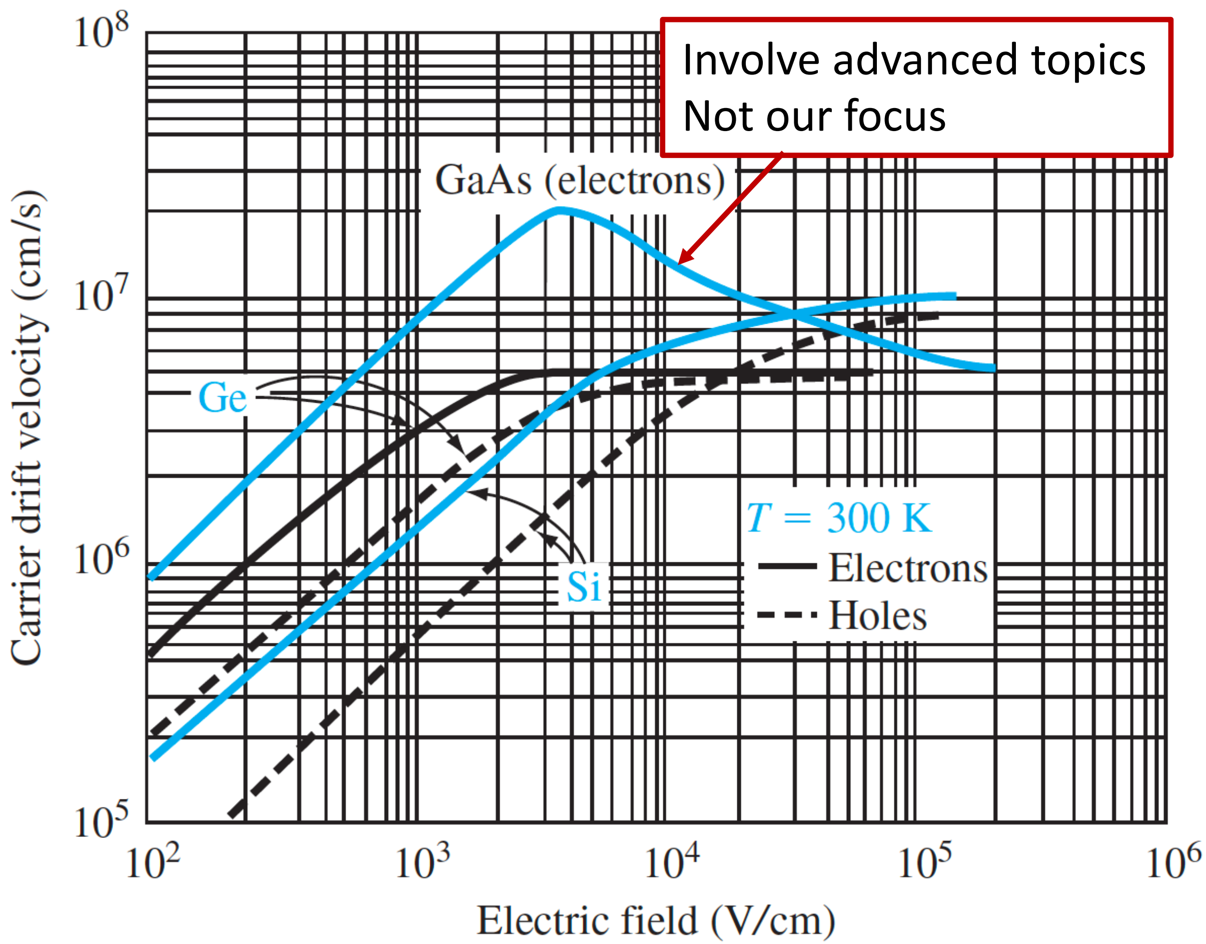
5.1 Carrier drift

Velocity saturation

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

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

Involve advanced topics
Not our focus



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

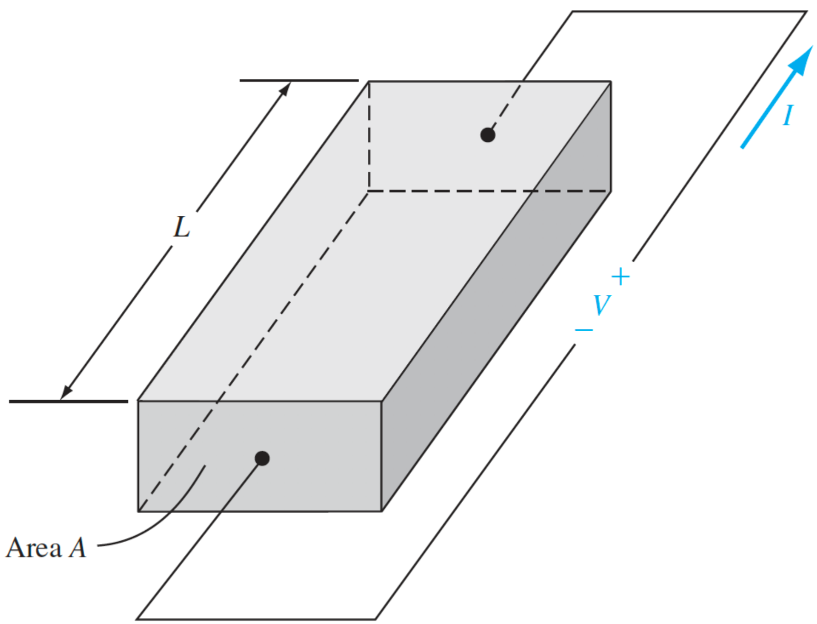
$$v_p = \frac{v_s}{\left[1 + \left(\frac{E_{op}}{E}\right)^{2}\right]^{1/2}}$$

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?



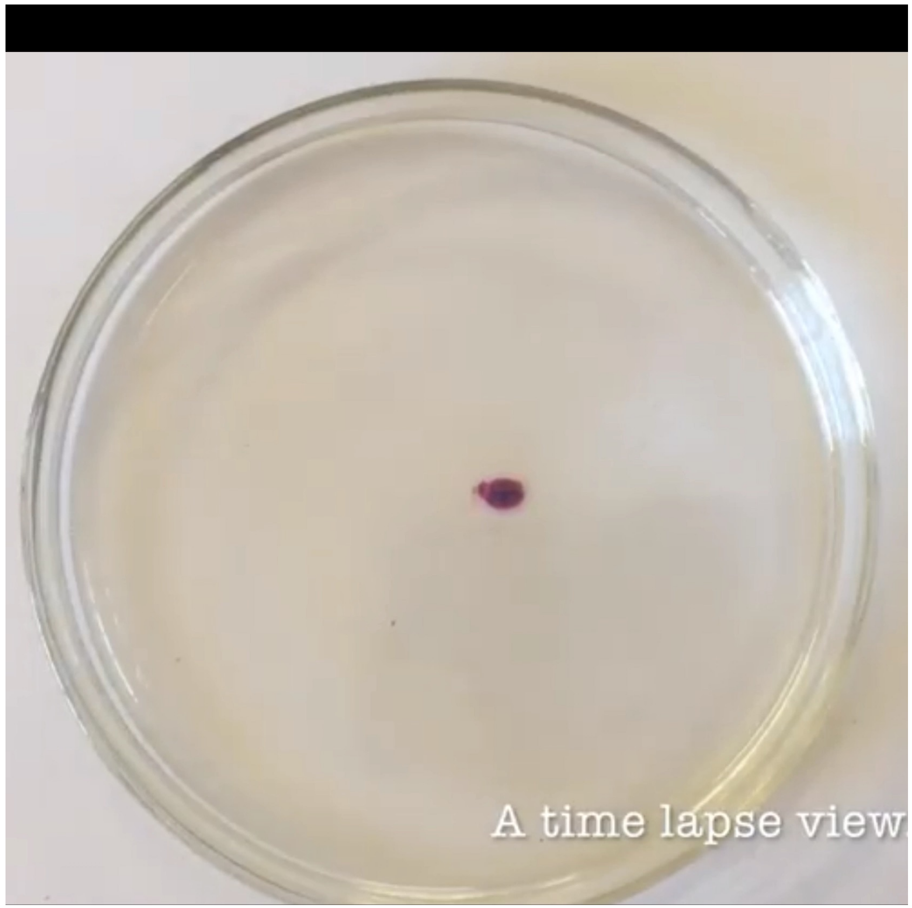
Outline

5.1 Carrier drift

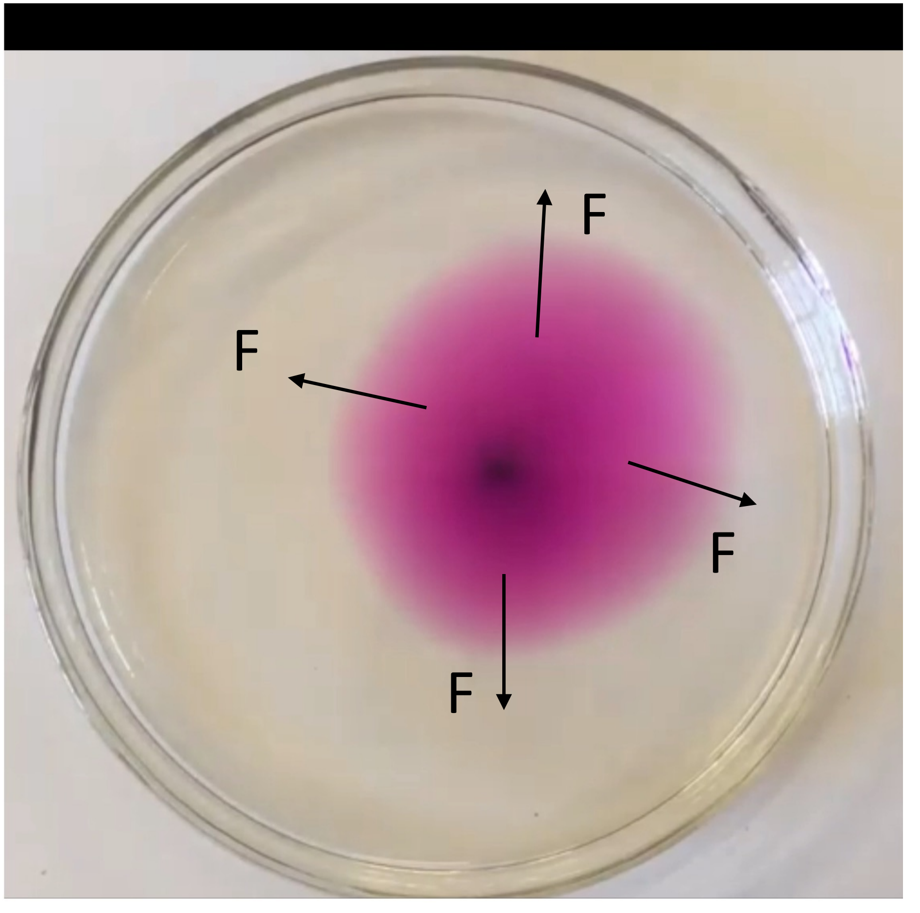
5.2 Carrier diffusion

5.3 Graded impurity distribution

5.2 Carrier diffusion



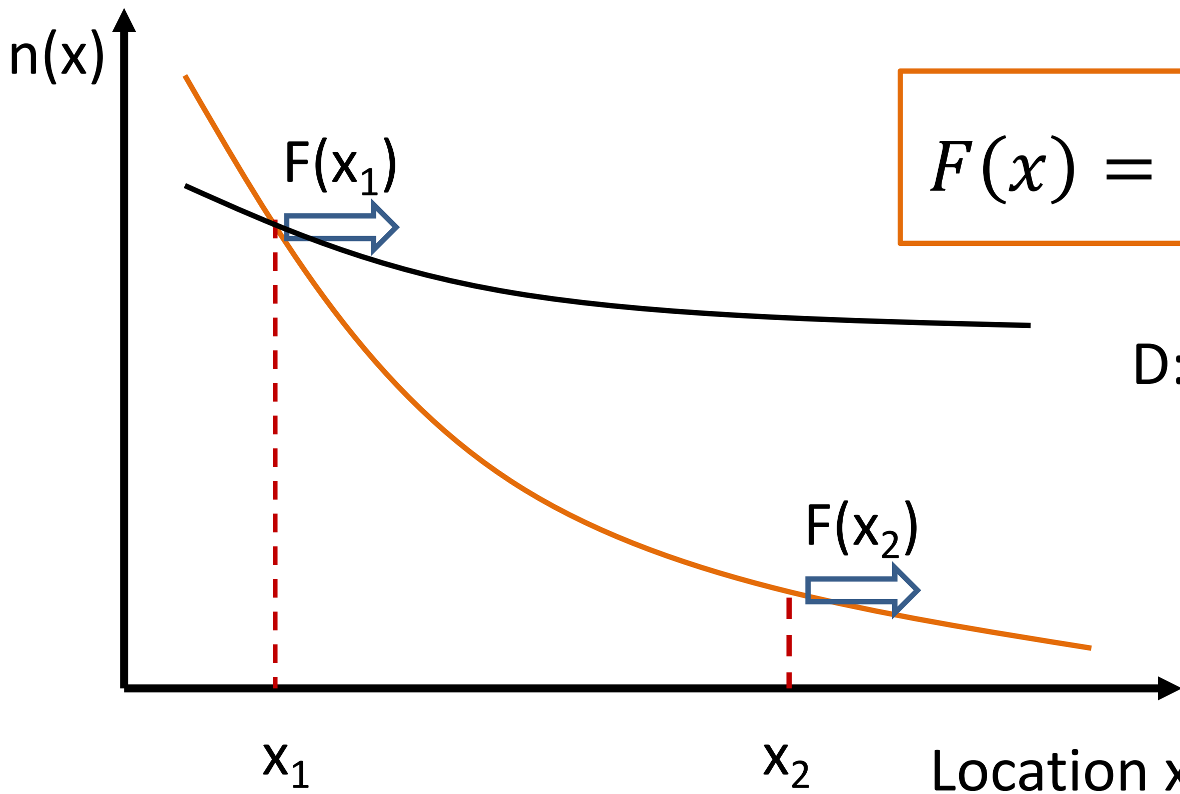
5.2 Carrier diffusion



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

5.2 Carrier diffusion

Particle concentration n (cm^{-3})



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

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

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

<u>Total current density</u>

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 $D_p = 8 cm^2/s$. Determine the hole current density at $x = 2 \times 10^{-4}$ cm.

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

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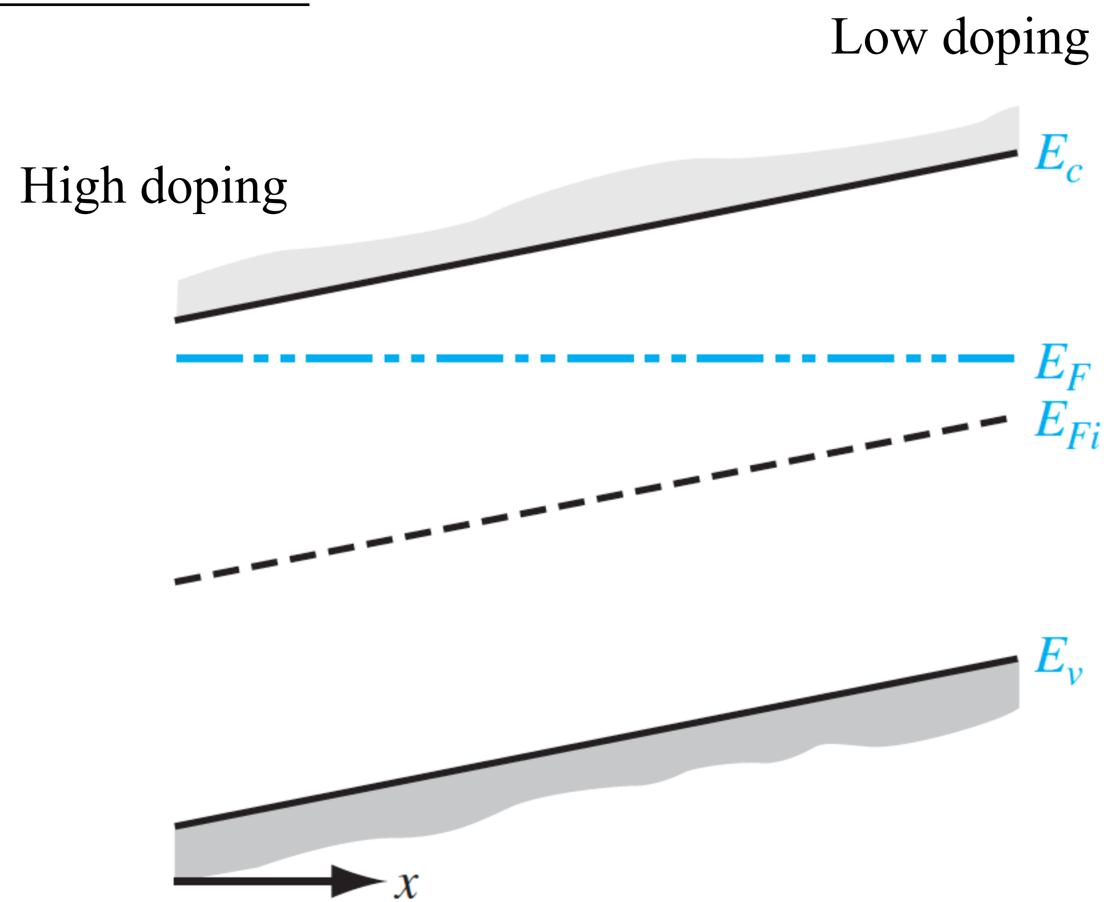
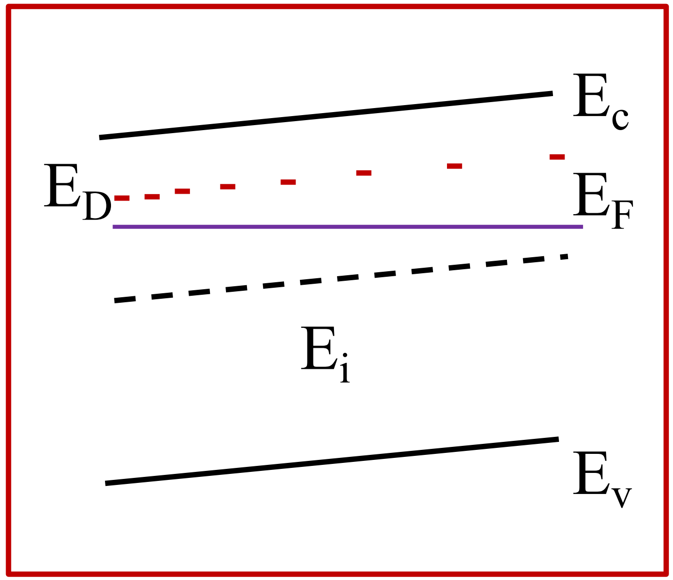
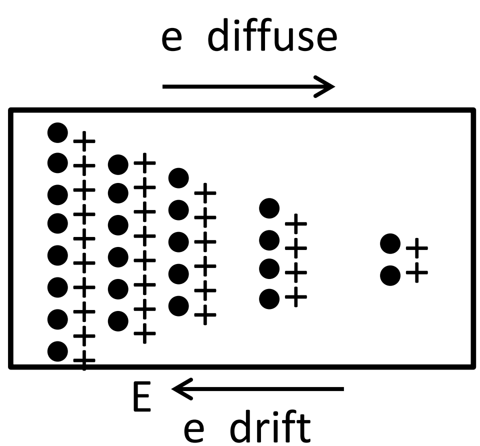
Induced electric field



5.3 Graded impurity distribution

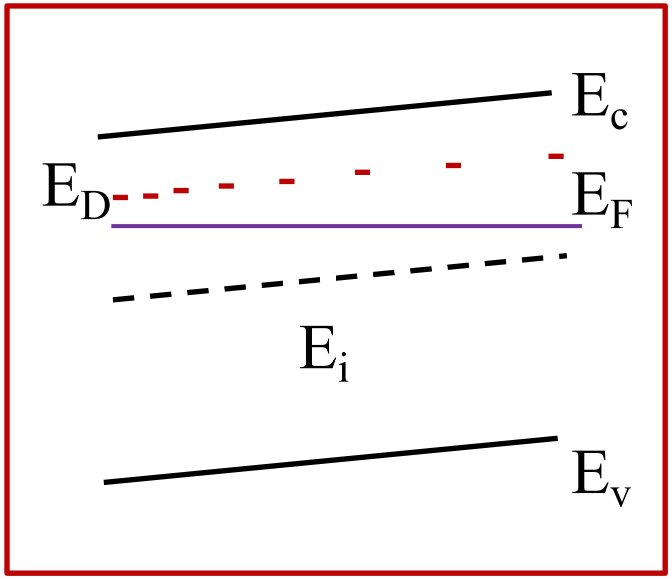
- Induced electric field

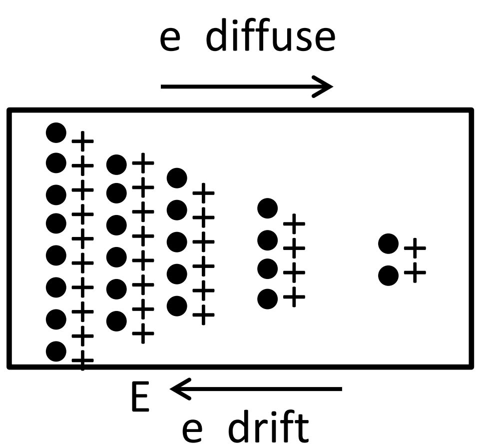




5.3 Graded impurity distribution

- The Einstein relation





5.3 Graded impurity distribution

- The Einstein relation

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.

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