VE320 – Summer 2022

Introduction to Semiconductor Devices

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Chapter 5 Carrier Transport Phenomena

Outline

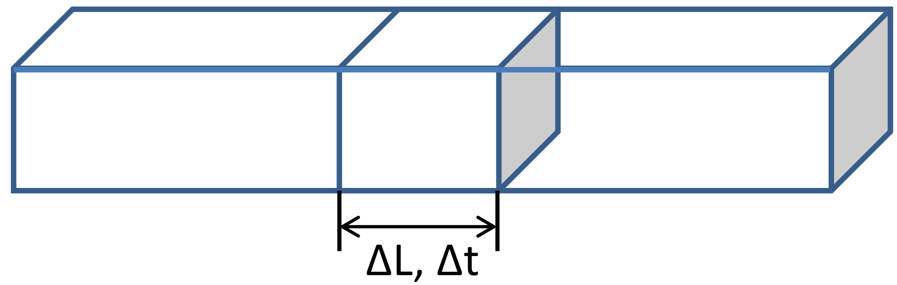
5.1 Carrier drift

5.2 Carrier diffusion

5.3 Graded impurity distribution

5.1 Carrier drift

Drift current density



for p type semiconductor, $p_0 \gg n_0$

$$n_0 = N_c \times \frac{-1+\sqrt{\quad}}{4\exp(\quad)}$$

Drift current

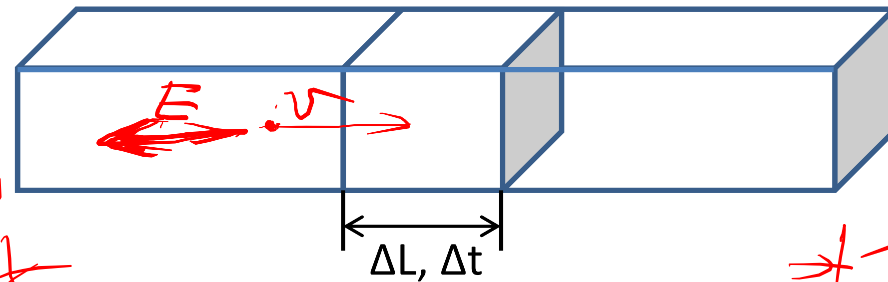
$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{q p_0 A_c \Delta L}{\Delta t} = q p_0 A_c v_d$$

ρ: *charge density*

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

5.1 Carrier drift (current in an ideal case)

Drift current density



Drift current

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

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

$I \sim \sqrt{V}$ $\quad I \sim V$

$\rho: charge\ density$

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

$m \cdot a = F = q \cdot E$

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

$\sqrt{2La}$

$a = \frac{q \cdot E}{m^*}$

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

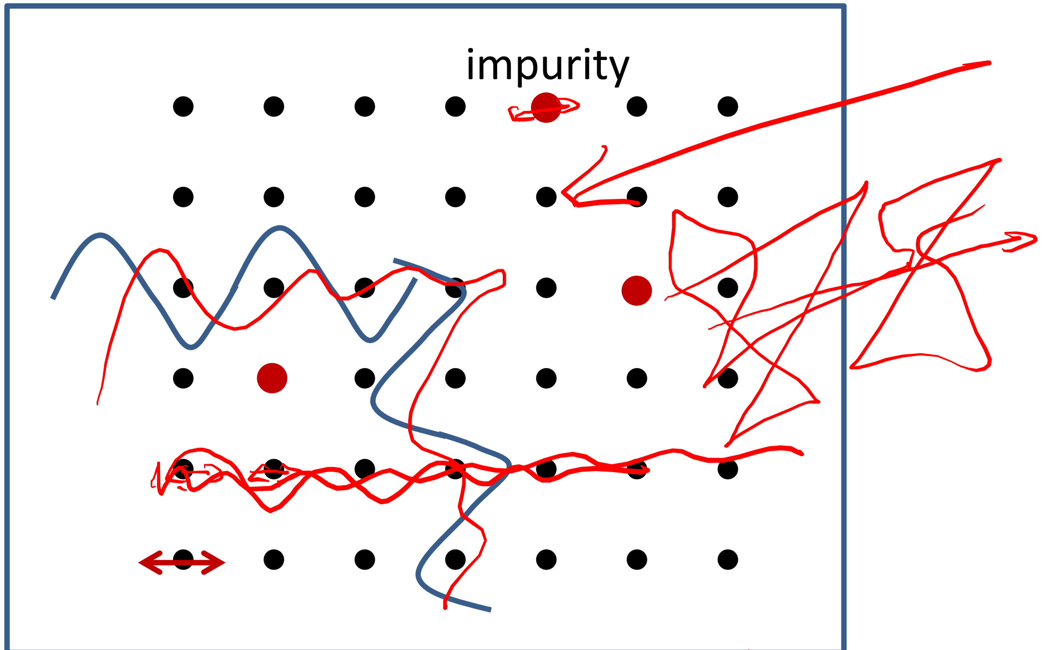
$$E = V/L$$

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

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

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

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

$\boxed{scatterings}$

E instant

$\downarrow$

$\boxed{v \sim E}$

~~$v_d \sim \sqrt{E}$~~

$\downarrow$

$\boxed{v = \mu E}$

$v_d = \mu \cdot E$

mobility

$\boxed{v_n = \mu_n E}$

Electrons

$\boxed{v_p = \mu_p E}$

Holes

$$I_{drf} = \frac{\Delta Q}{\Delta t} = \frac{q p_0 A_c \Delta L}{\Delta t} = q p_0 A_c v = q p_0 A_c \mu_p E = q p_0 A_c \mu_p \frac{V}{L} = \sigma \cdot V$$

5.1 Carrier drift

Drift current density

Hole drift current density

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

Electron drift current density

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

Both electrons and holes contribute to current:

$$n_0 = \frac{n_i^2}{p_0}$$

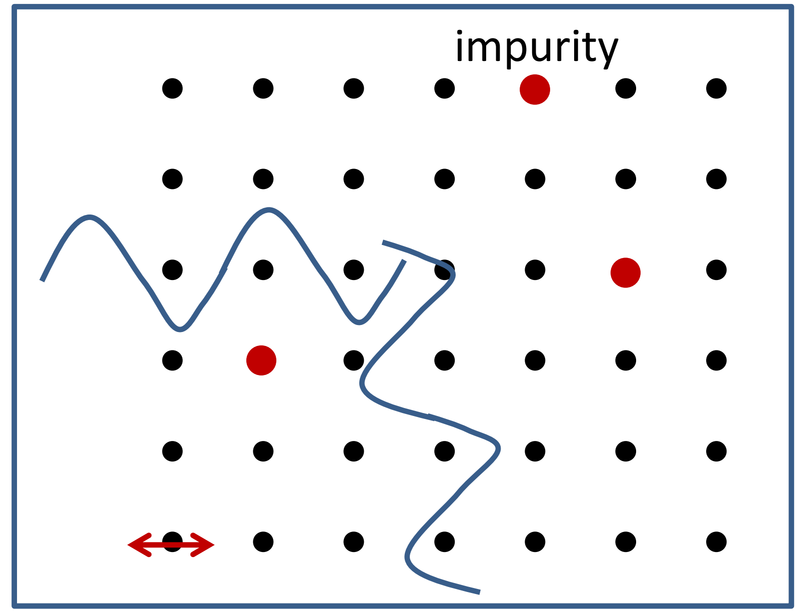
$$J_{drf} = q(p_0\mu_p + n_0\mu_n)E$$

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

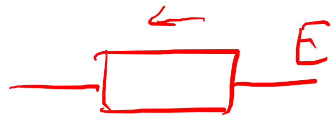
	μ_n (cm²/V-s)	μ_p (cm²/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

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)

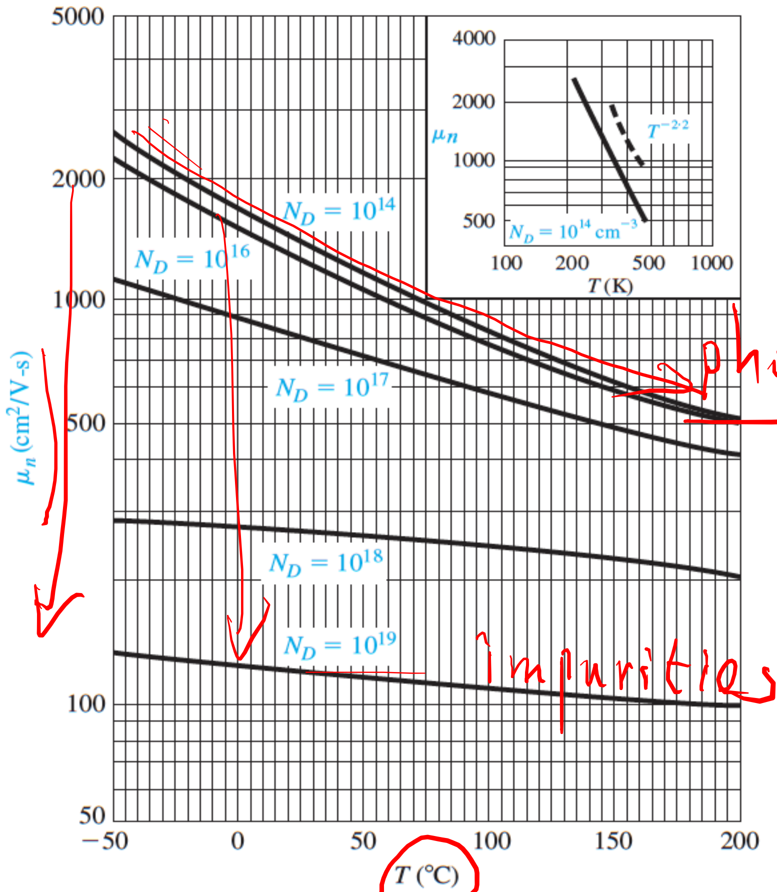
Conclusions:

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

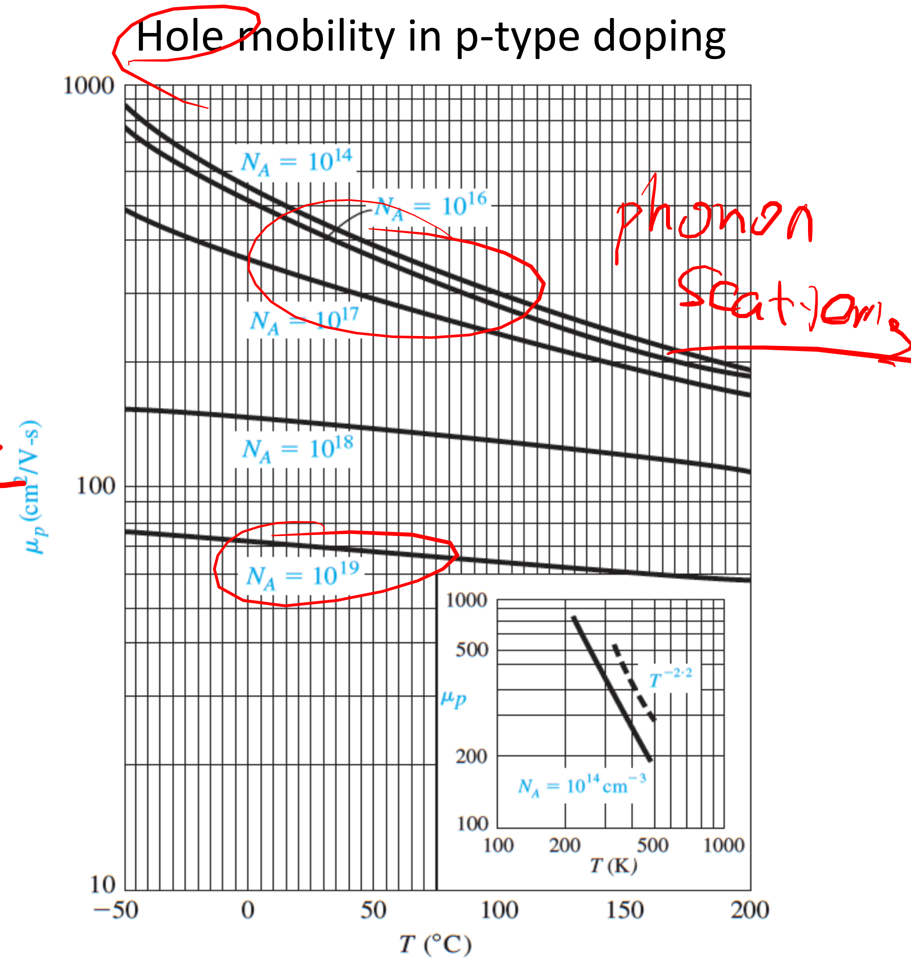
5.1 Carrier drift

<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

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

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

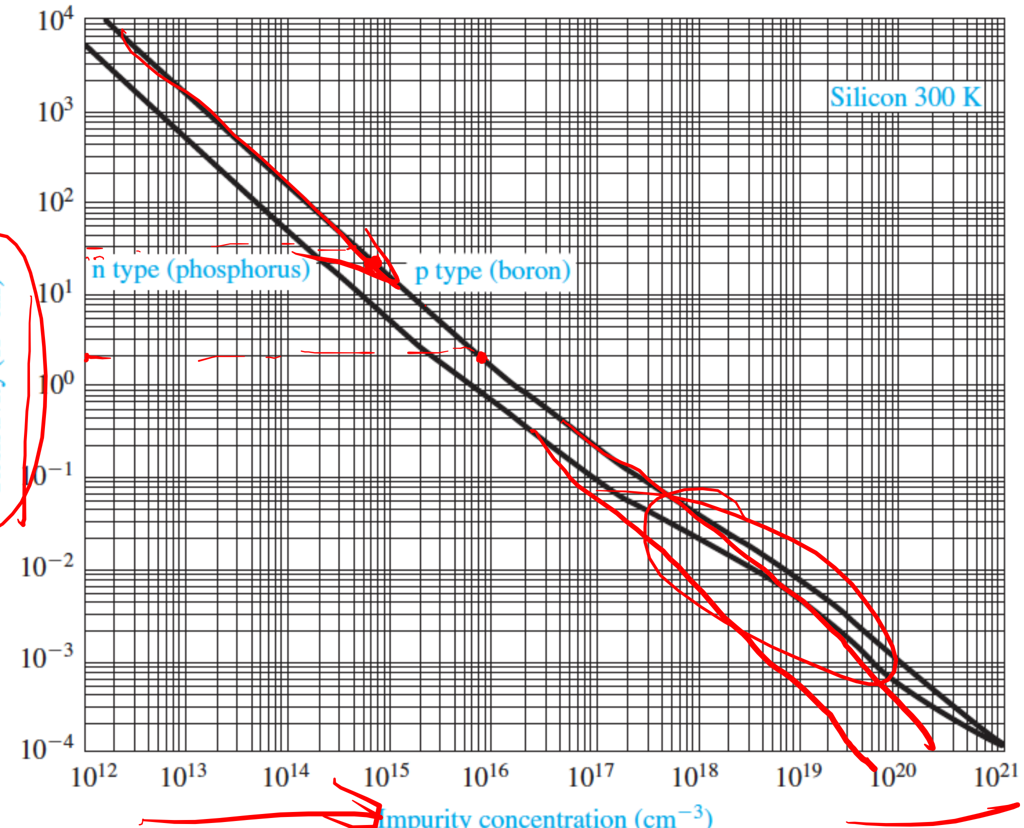
$\rho = \frac{1}{\sigma}$

For n-type doped semiconductor:

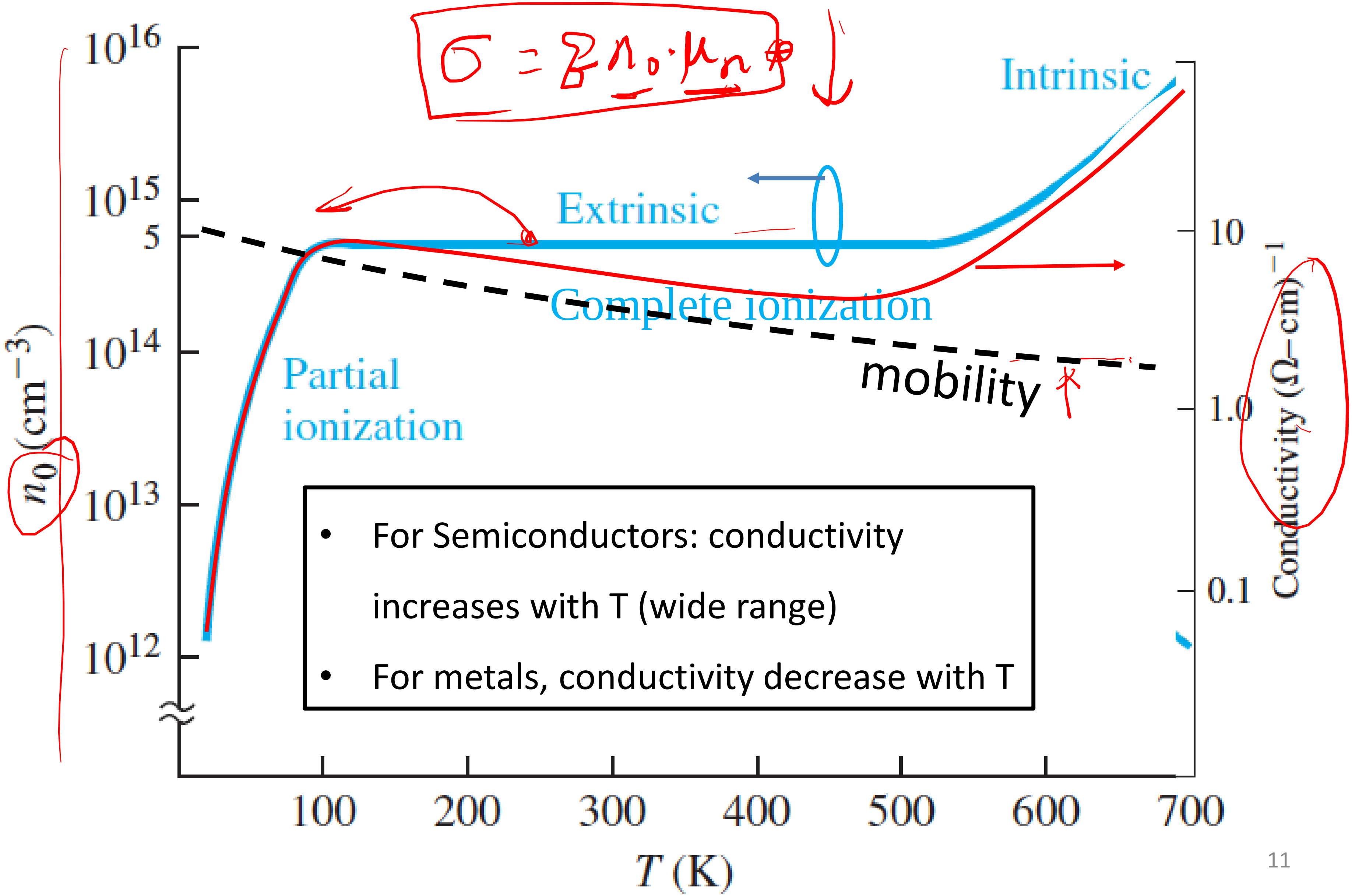
$$\rho = \frac{1}{\sigma} = \frac{1}{q\mu_n n} = \frac{1}{q\mu_n N_d}$$

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

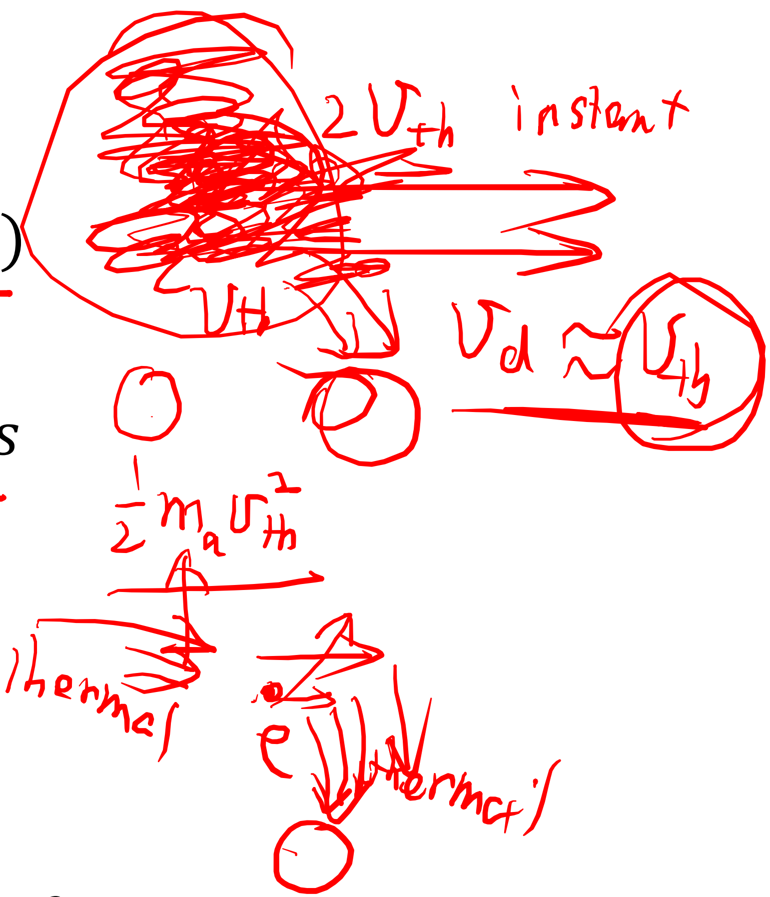
$v_d \sim E$ ✗

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

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

Drift velocity $v_d = \mu_n E = v_{th}$

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

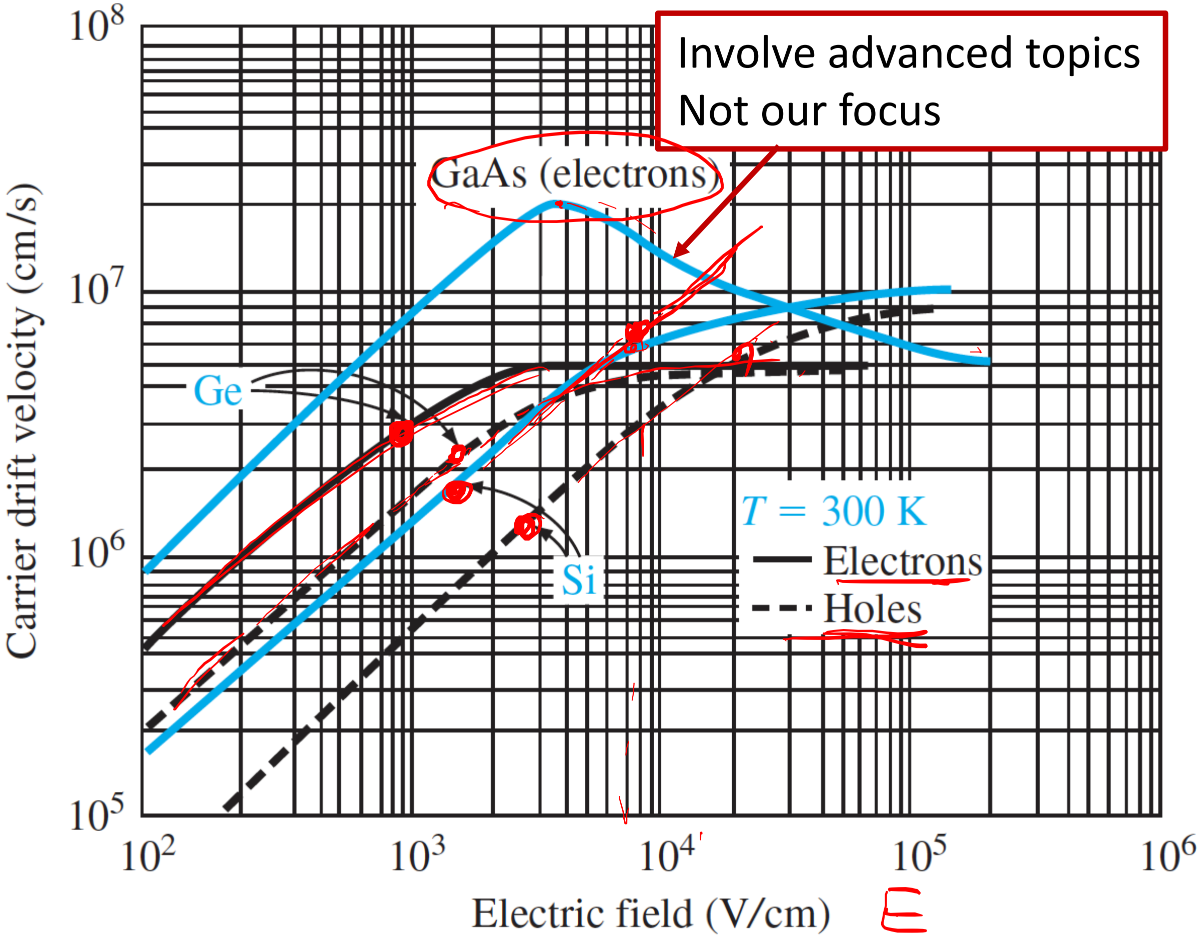


5.1 Carrier drift

Velocity saturation

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

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



7×10^3 V/cm

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

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

Probably a typo in textbook

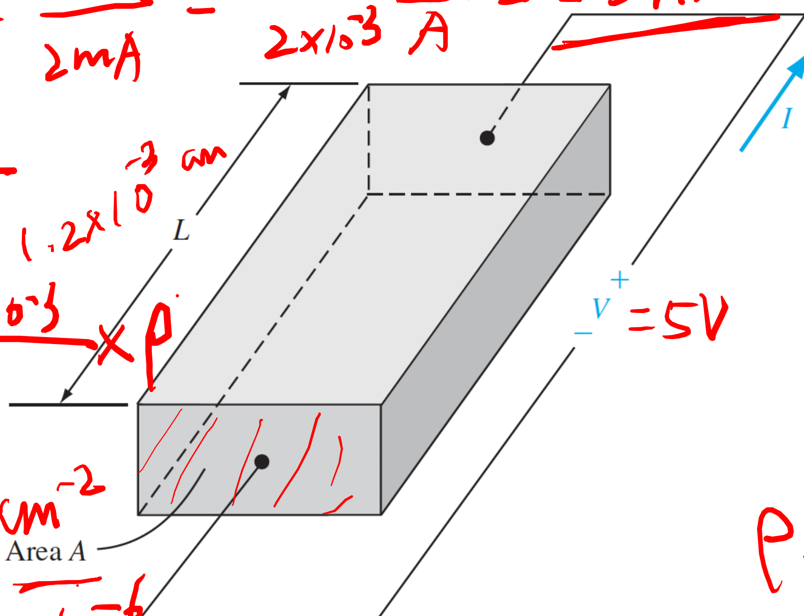
Check your understanding

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 x 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?

$$(a)\ R = \frac{V}{I} = \frac{5V}{2mA} = \cancel{\frac{5}{2\times10^{-3}}}\ \frac{V}{A} = 2.5\,k\Omega$$

$\cancel{I = \sigma}$



2mA

$$J = \sigma \cdot E$$

$$(b)\ R = \rho \cdot \frac{L}{A_c} \quad 1.2\times10^{-3}\ cm$$

$$= \frac{1.2\times10^{-3}}{10^{-6}} \times \rho$$

$$\Rightarrow \rho = \frac{R\times10^{-6}}{1.2\times10^{-3}} \quad 10^{-6}\ cm^{-2}$$

$$= \frac{2.5\times10^{3}\times10^{-6}}{1.2\times10^{-3}} = 2.083\ \Omega\cdot cm$$

$V = 5V$

$$N_a = p_0 = 7\times10^{15}\ cm^{-3}$$

$$\rho = \frac{1}{q\cdot\mu_p\, p_0} \Rightarrow \mu_p = \frac{1}{q\,\mu_p\cdot p_0}$$

$$\mu_p = 428\ cm^2/V.s$$

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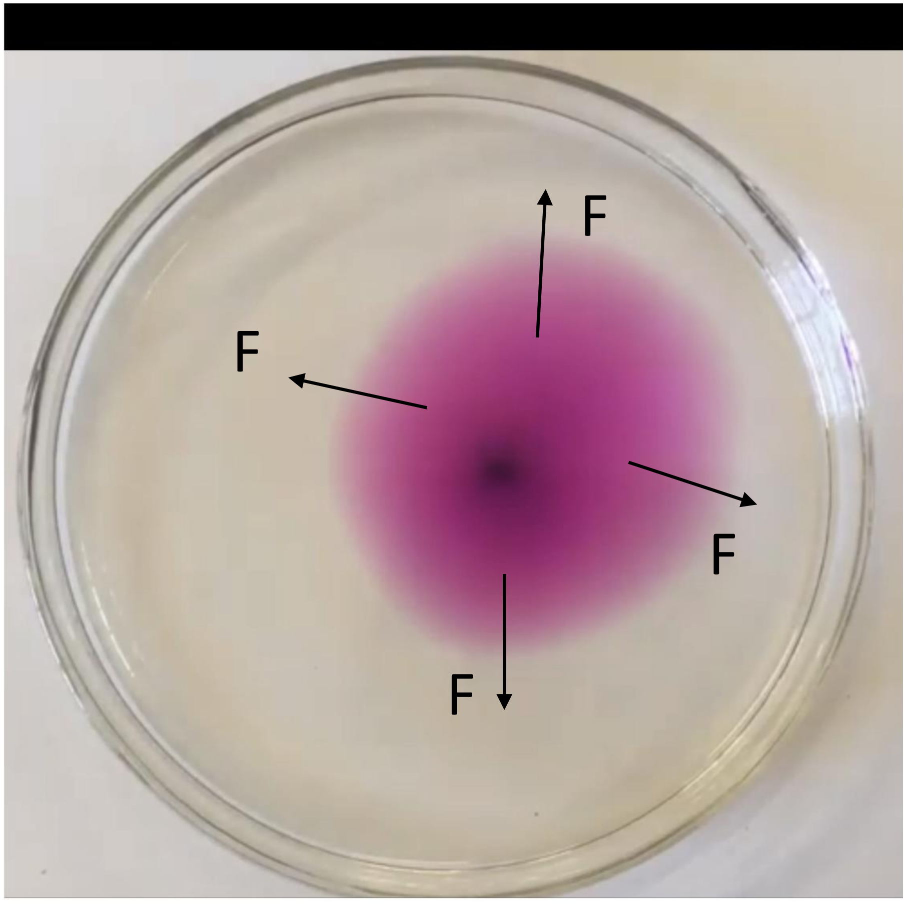
5.2 Carrier diffusion

5.3 Graded impurity distribution

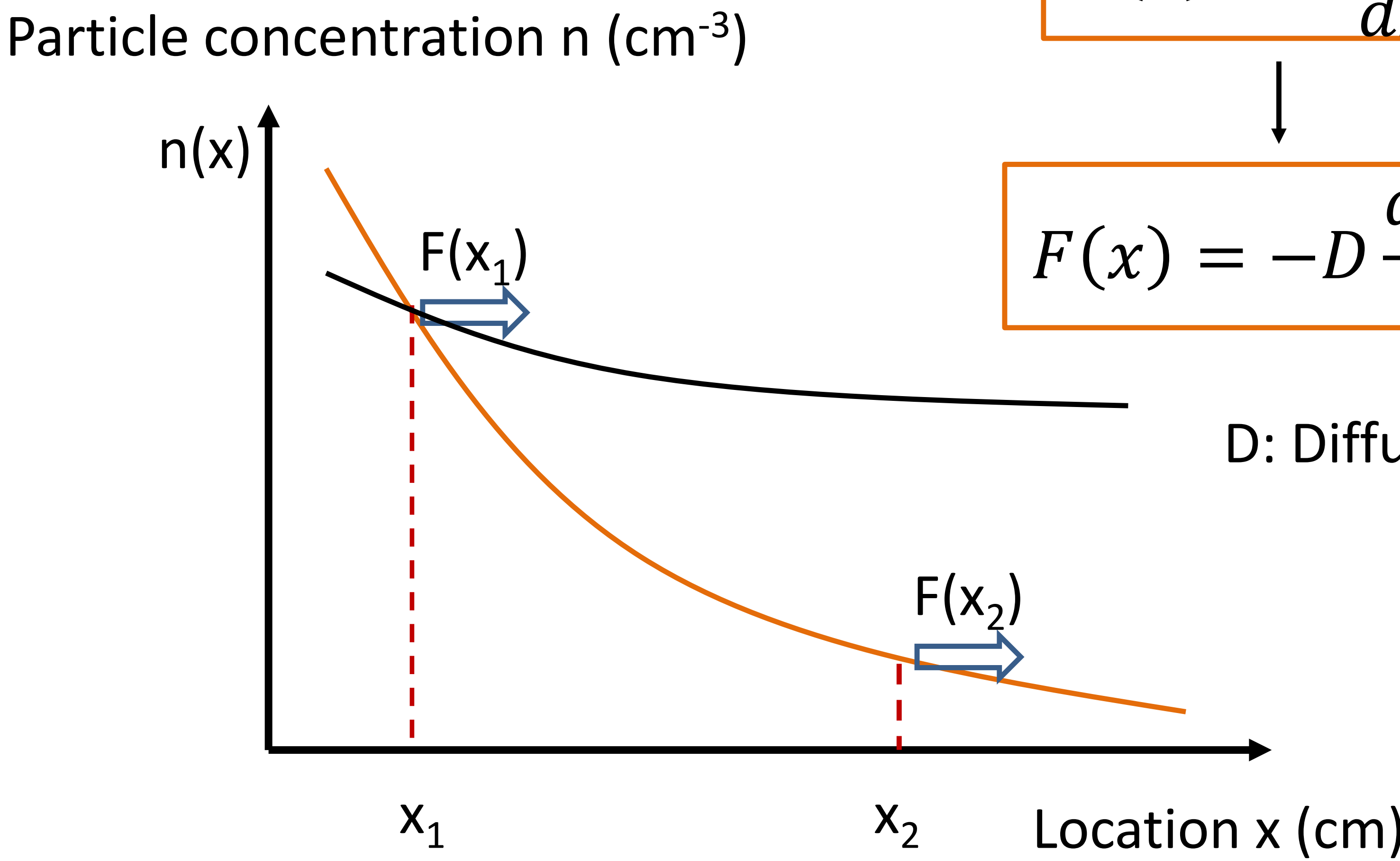
5.2 Carrier diffusion

5.2 Carrier diffusion



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

5.2 Carrier diffusion



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

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

D: Diffusivity

5.2 Carrier diffusion

Diffusion current density

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

D_n is called the electron diffusion coefficient

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

D_p is called the hole diffusion coefficient

5.2 Carrier diffusion

Total current density

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 = 2×10^{-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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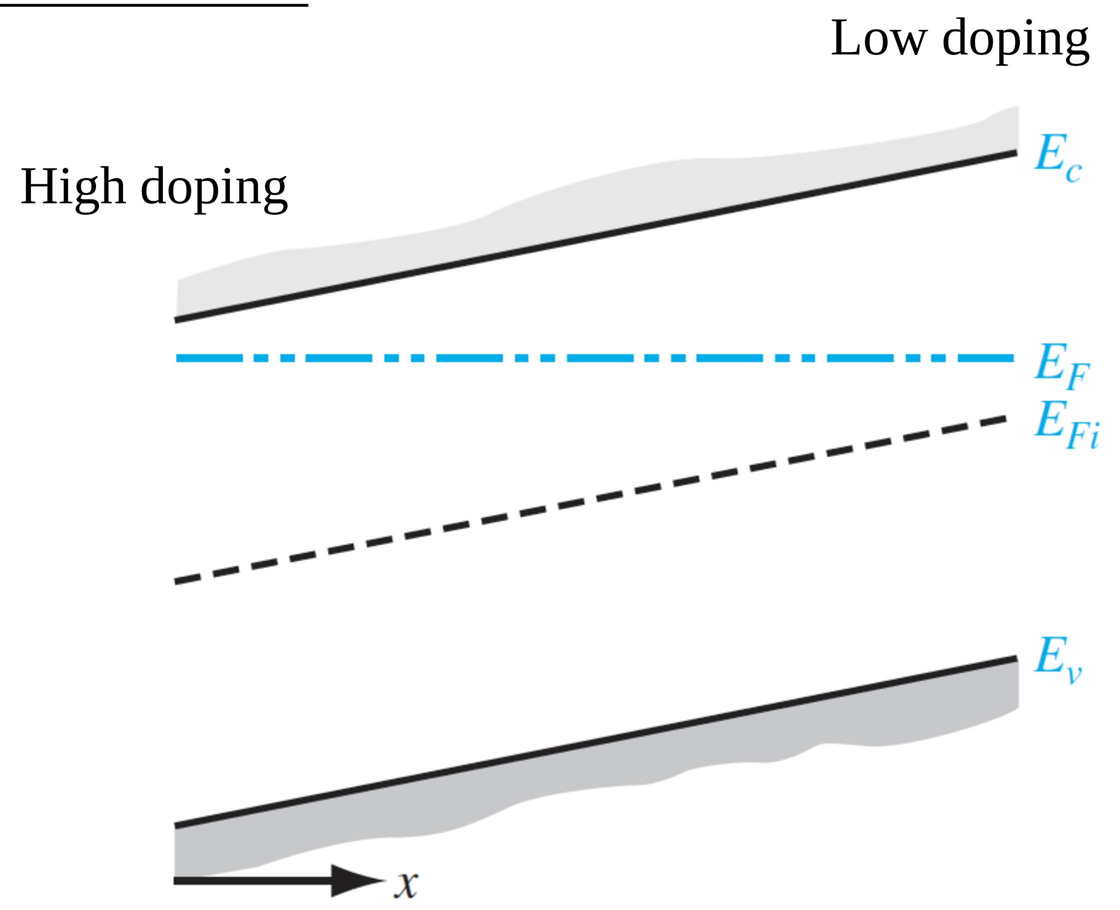
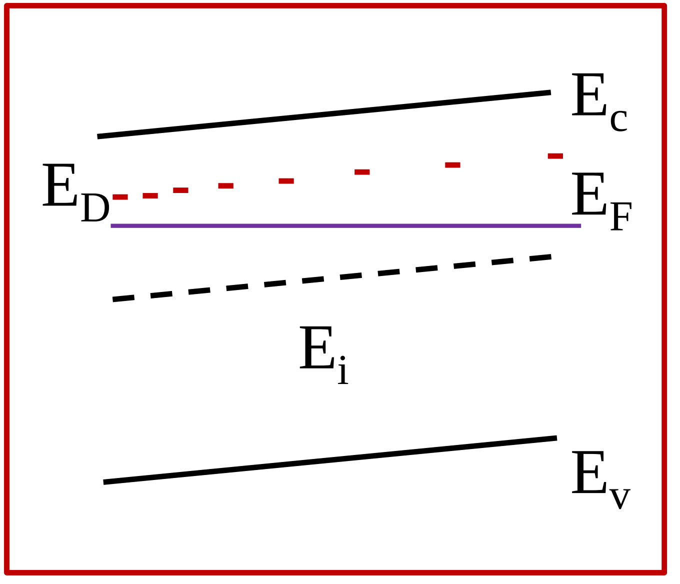
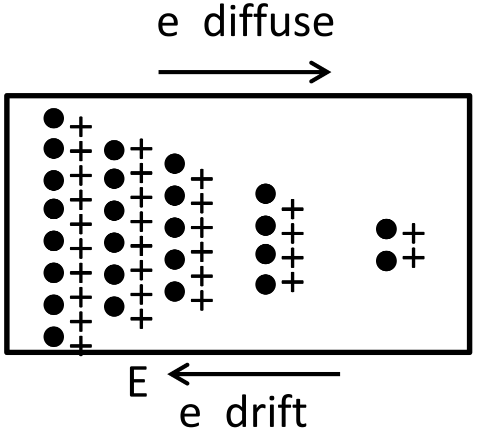
<u>Induced electric field</u>



5.3 Graded impurity distribution

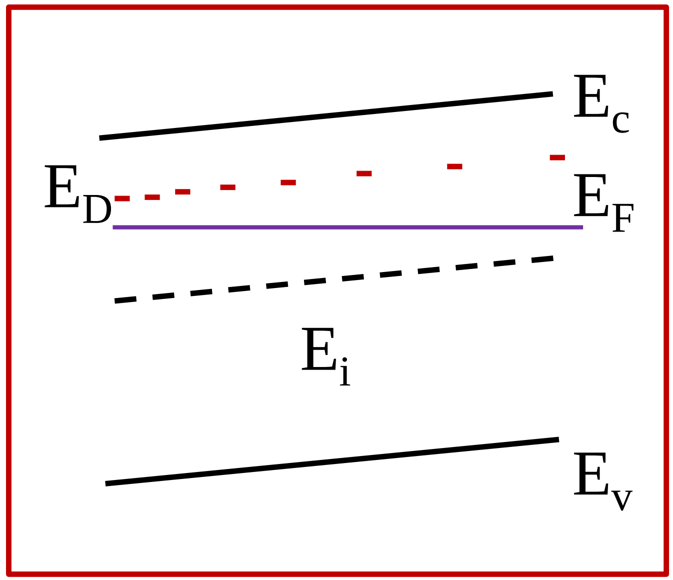
- Induced electric field

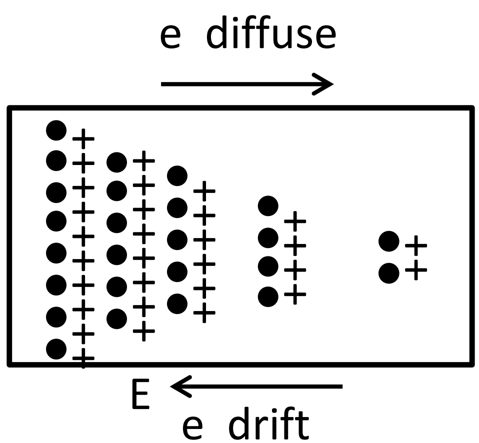




5.3 Graded impurity distribution

- 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.

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