ECE 340 Lecture 11
Semiconductor Electronics

Spring 2022
10:00-10:50am
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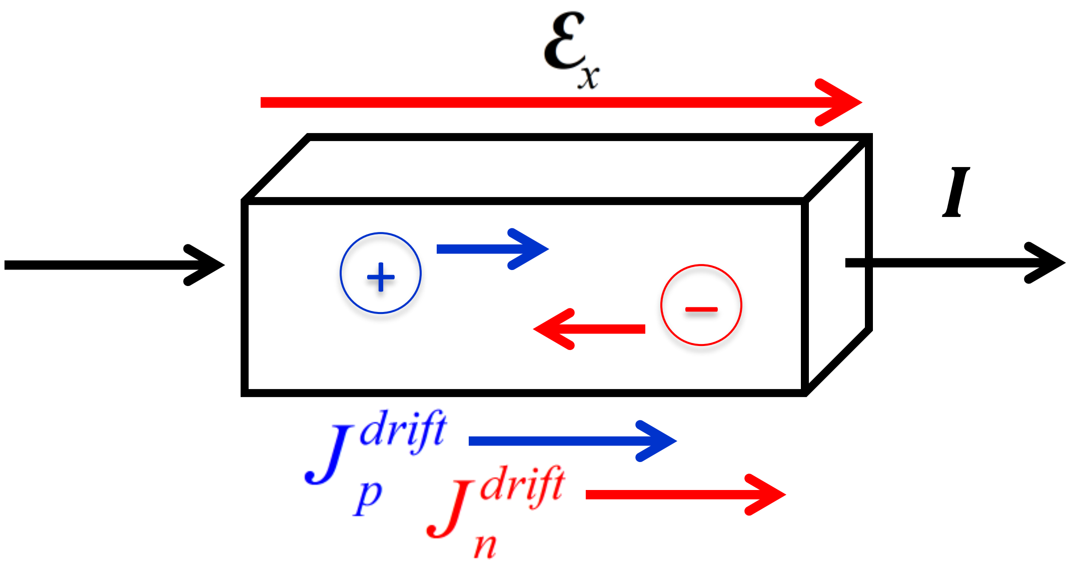
2062 ECE Building

Today’s Discussion

- Semiconductor out of equilibrium
- Conductivity
- Resistance
- Mobility

Define Drift Current Density



J = Charge per unit time per unit area

$$J_n^{drift} = -qn\langle v_{dn}\rangle = qn\mu_n\mathcal{E}_x$$

$$J_p^{drift} = qp\langle v_{dp}\rangle = qp\mu_p\mathcal{E}_x$$

Mobility

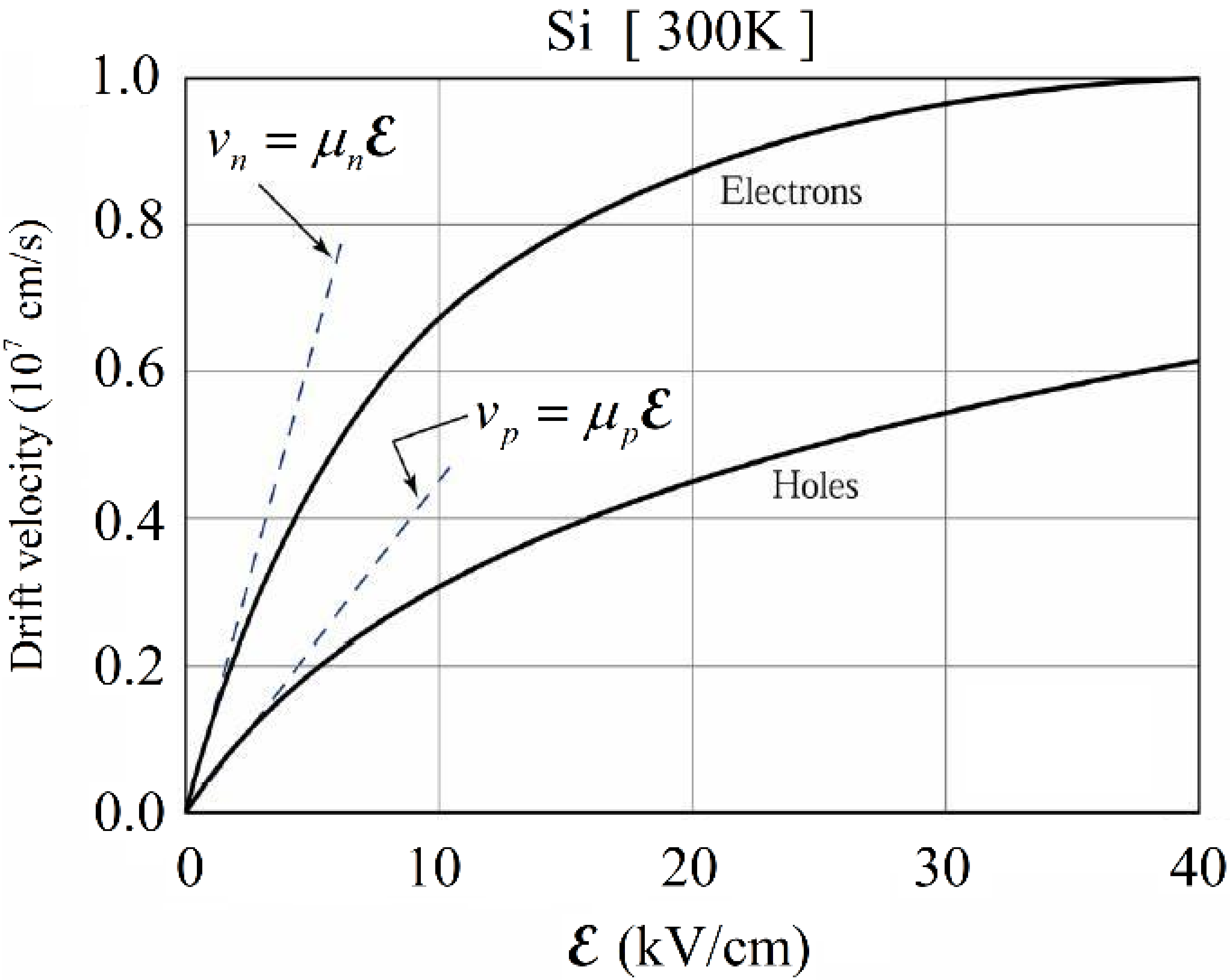
$$\mu_n = -\frac{\langle v_{dn} \rangle}{\mathcal{E}_x} = \frac{q\tau_c}{m_n^*}$$

$$\mu_p = \frac{\langle v_{dp} \rangle}{\mathcal{E}_x} = \frac{q\tau_c}{m_p^*}$$

units

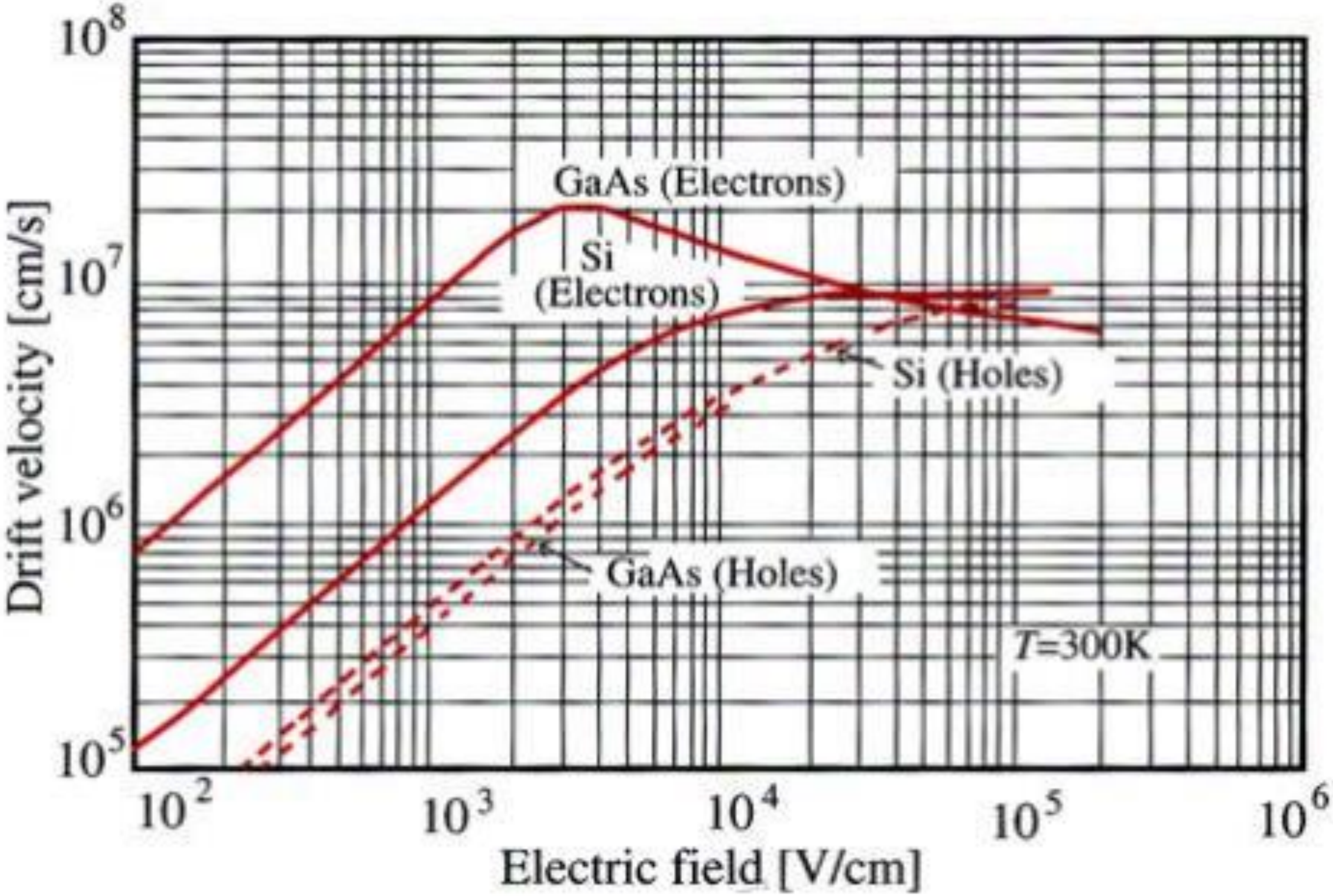
$$\left[\frac{\text{cm}^2}{\text{V}\cdot\text{s}}\right]$$

Low Field Mobility

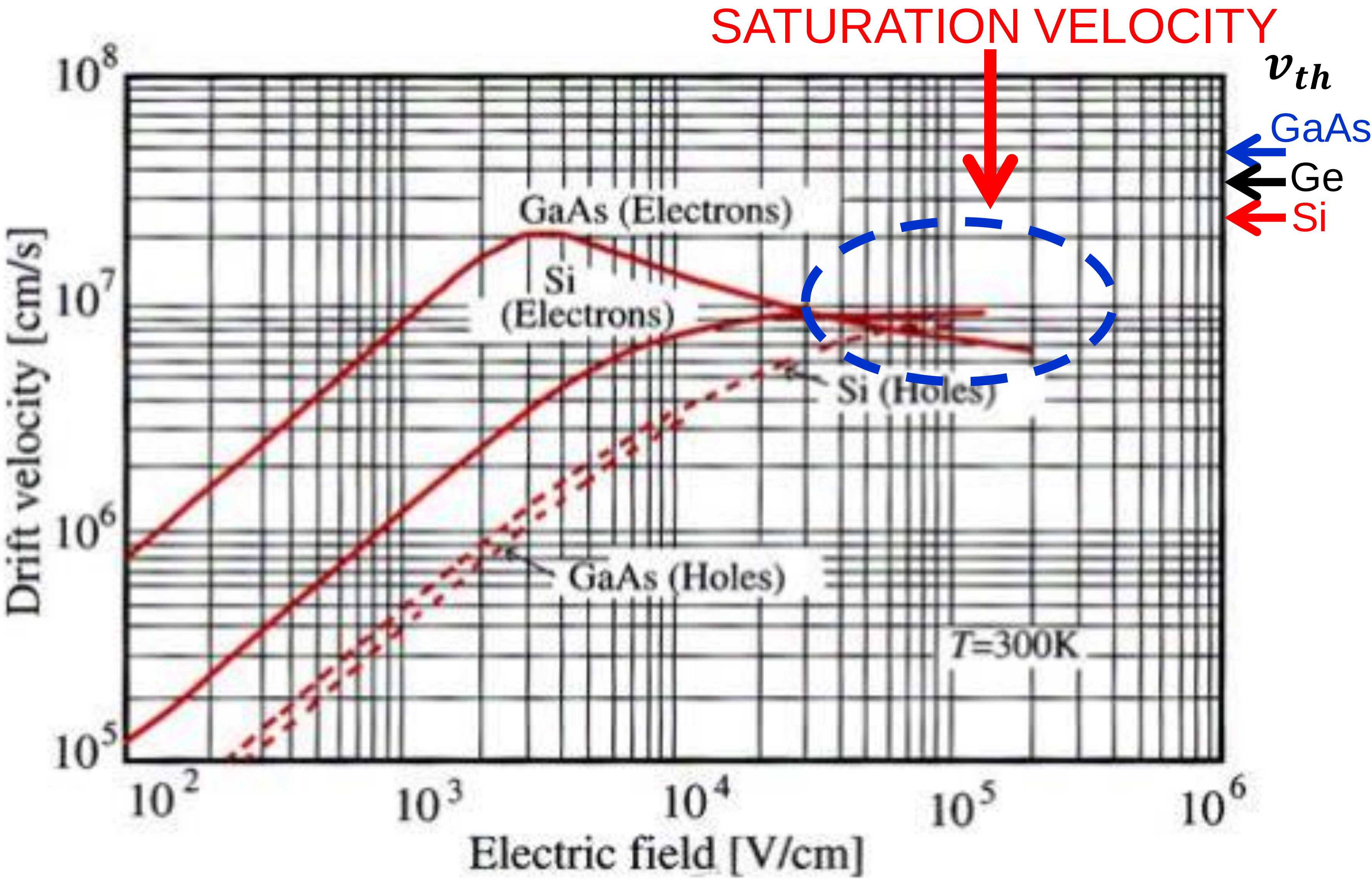


μ is the slope of the curve at $\mathcal{E}$=0 and is usually called low-field mobility

Drift velocity in high field conditions



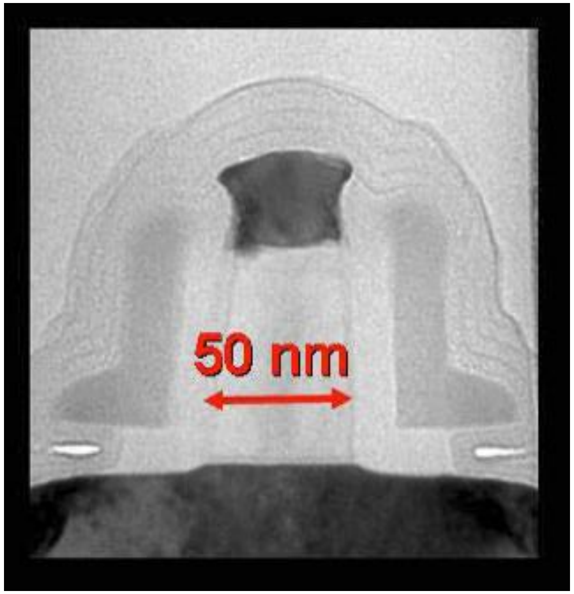
Drift velocity in high field conditions



Saturation velocity

- In devices which are much longer than the mean free path (average distance between collisions) the velocity saturation is quickly established in the conduction path where high fields are present.
- These device behave approximately like bulk material.

- In small devices comparable with the mean free path, as in highly scaled integrated circuits, carrier transport does not reach a bulk-like steady state.
- Transport in these devices must be studied with much more advanced physical models.



Intel (2005)

Conductivity

$$J_x = \sigma \mathcal{E}_x$$

$$J_n^{drift} = qn\mu_n \mathcal{E}_x$$

$$J_p^{drift} = qp\mu_p \mathcal{E}_x$$

$$\sigma_n = qn\mu_n = \frac{nq^2\tau_c}{m_n^*}$$

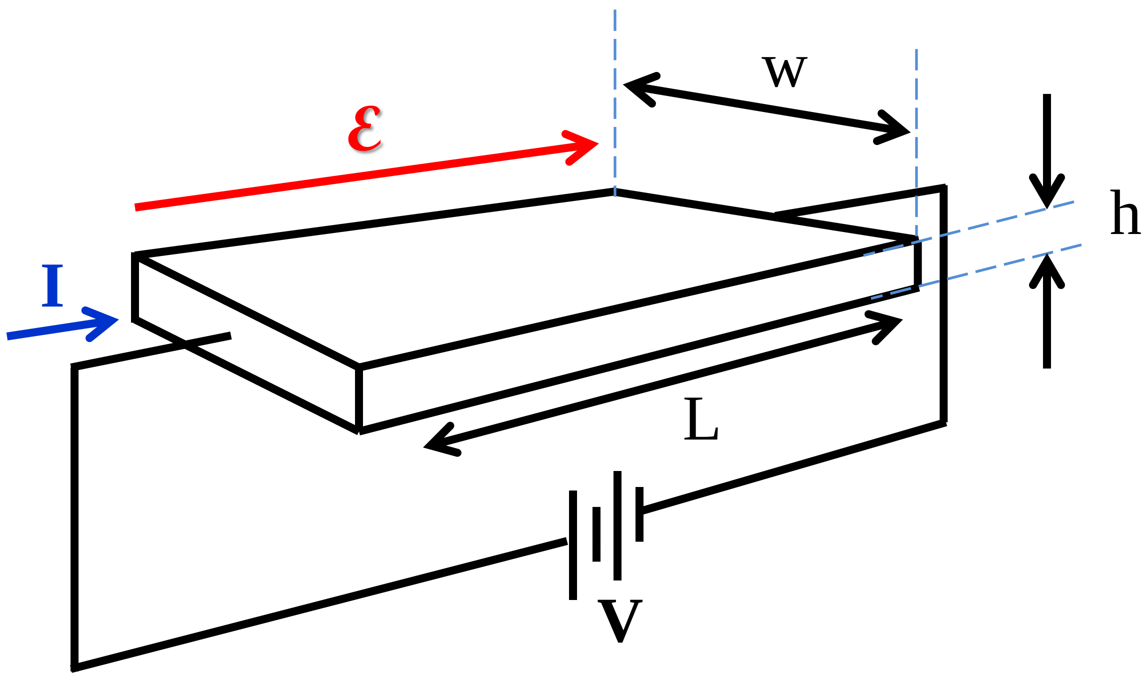
$$\sigma_p = qp\mu_p = \frac{pq^2\tau_c}{m_p^*}$$

$$\sigma = \sigma_n + \sigma_p = q\left(n\mu_n + p\mu_p\right)$$

$$J_x = q\left(n\mu_n + p\mu_p\right)\mathcal{E}_x = \sigma\,\mathcal{E}_x$$

Resistance

$$\sigma = \frac{1}{\rho} = \text{conductivity}\left[\frac{\text{S}}{\text{m}}\right] \qquad \rho = \text{resistivity}\ [\Omega\ \text{m}]$$



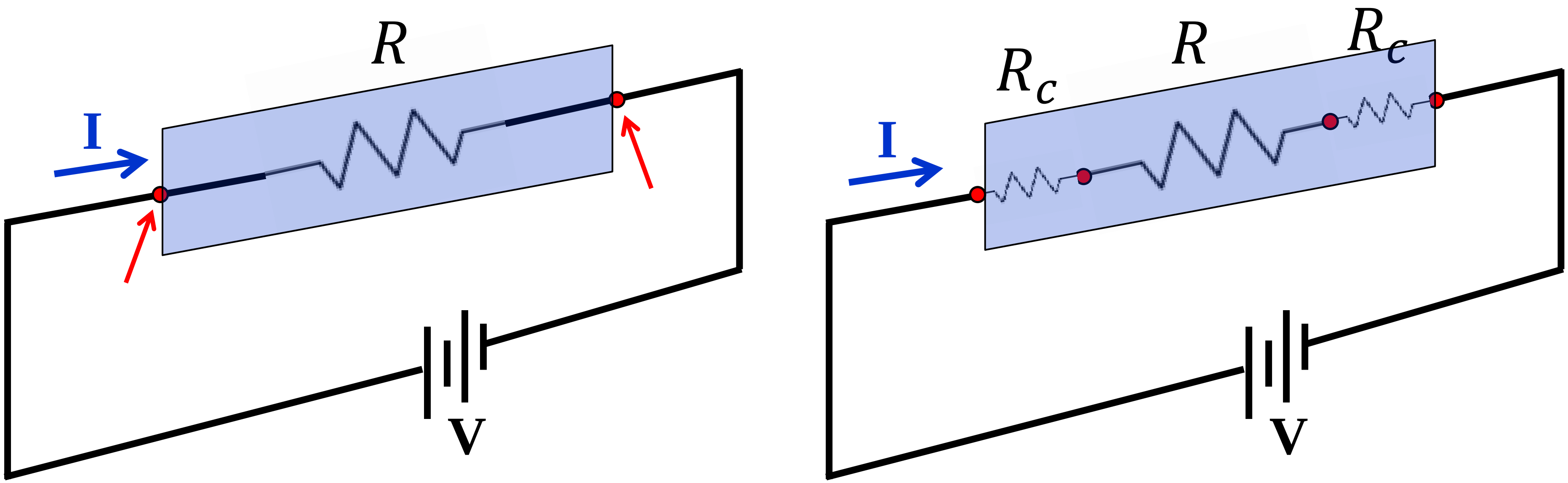
$$R = \rho\frac{Length}{Area} = \rho\frac{L}{w \times h}$$

Ohmic contact

Ohmic contacts do not add to the resistance

ideal ohmic contacts

imperfect ohmic contacts have contact resistance R_c



$$R = \rho \frac{Length}{Area} = \rho \frac{L}{w \times h} = \frac{1}{q(n\mu_n + p\mu_p)} \frac{L}{wh}$$

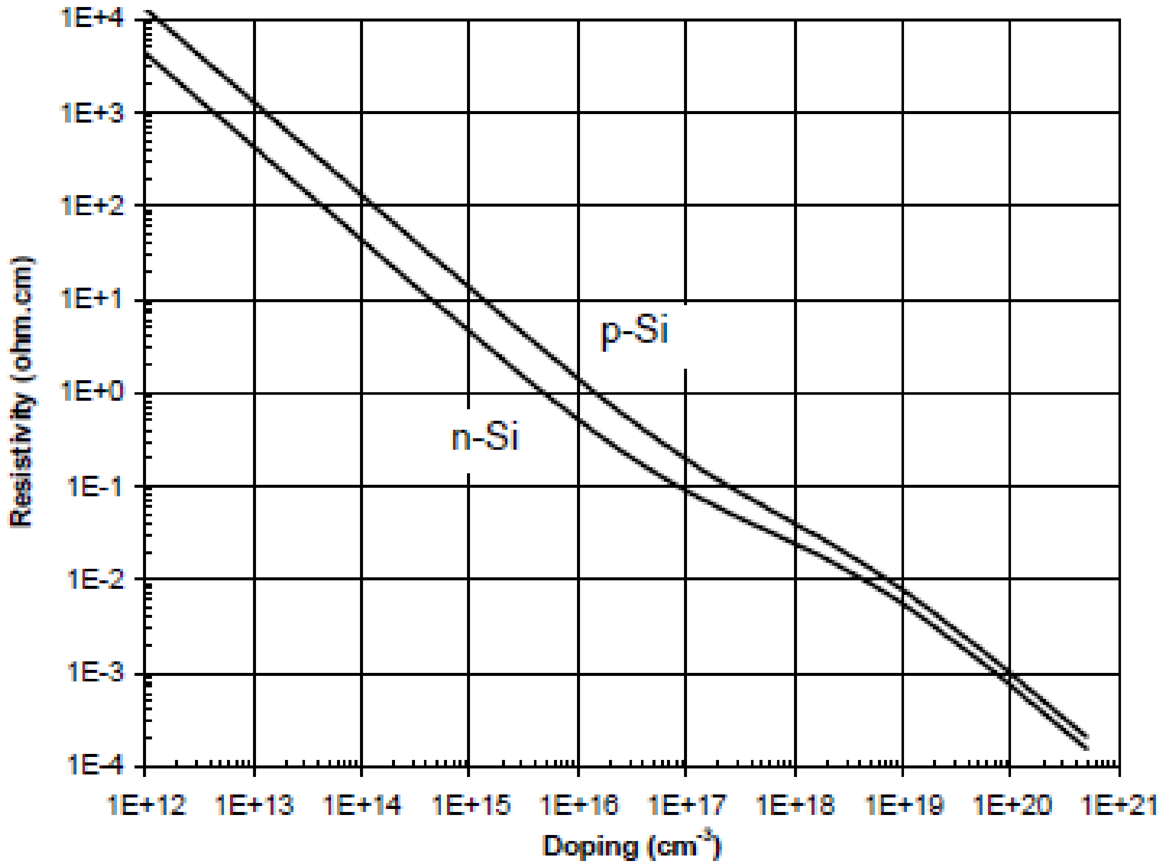
Resistance in extrinsic material

$$N_D \gg n_i$$

$$\rho = \frac{1}{q\mu_n N_D}$$

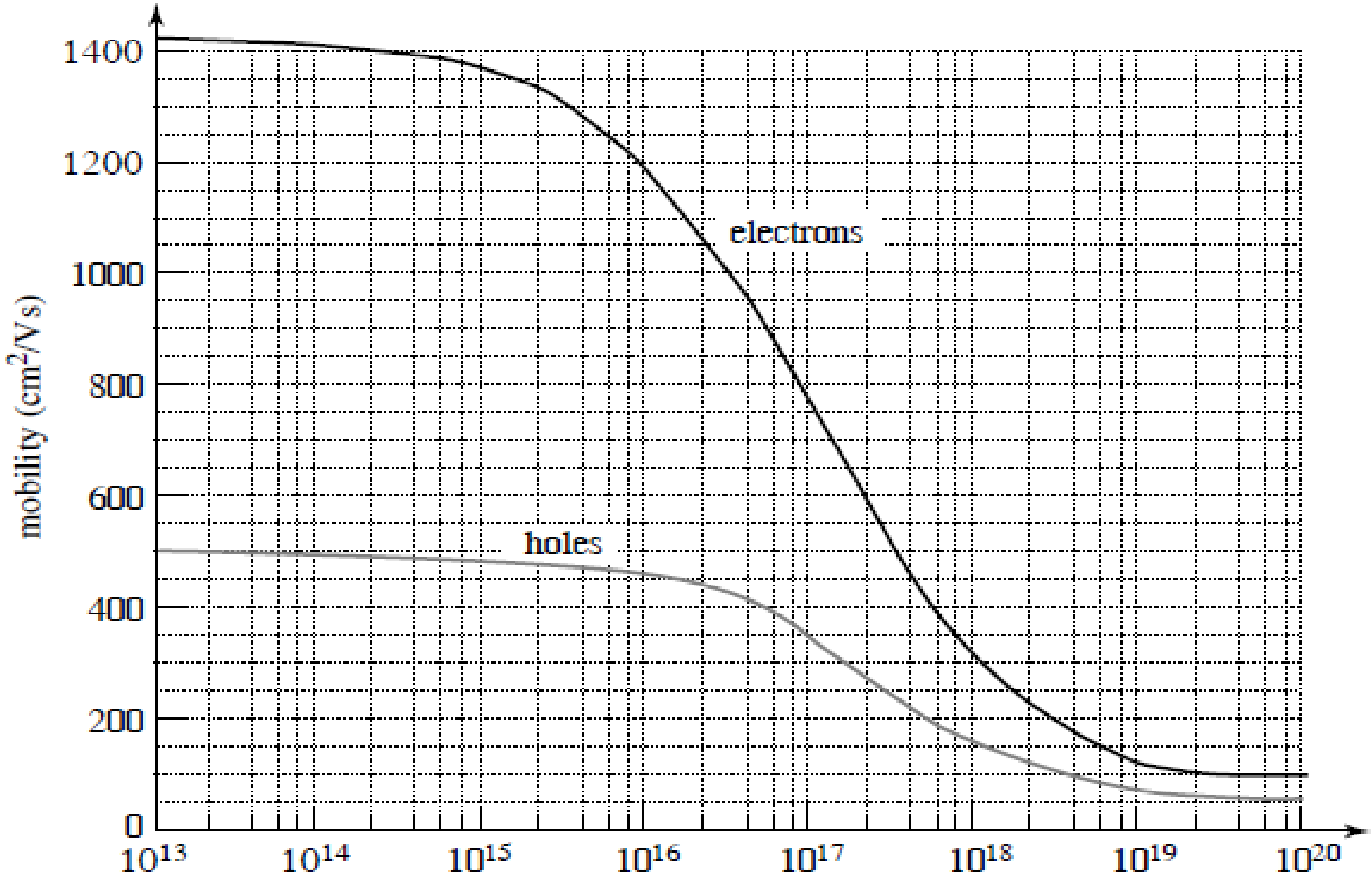
$$N_A \gg n_i$$

$$\rho = \frac{1}{q\mu_p N_A}$$



Mobility dependence on dopants

Si at 300K



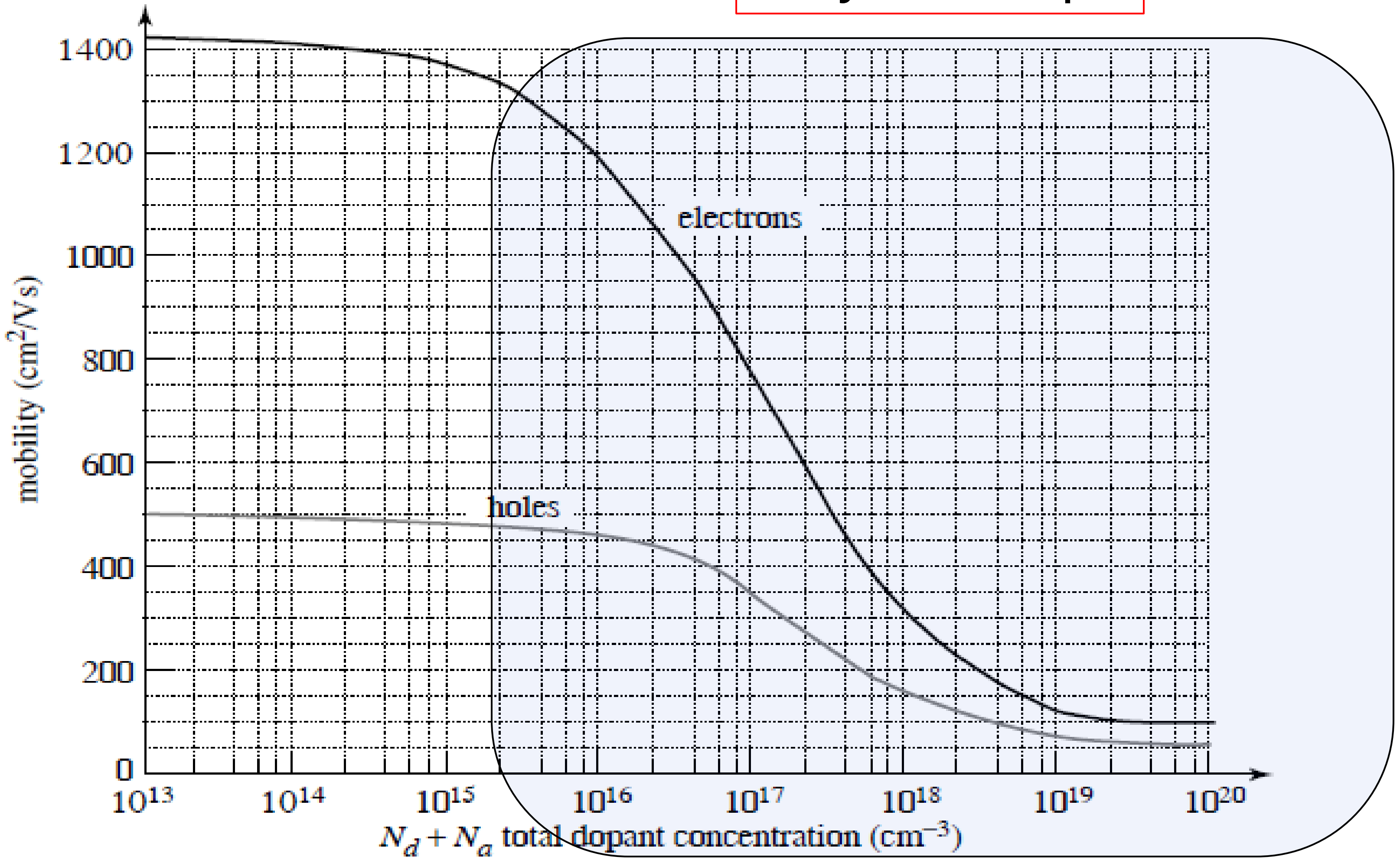
$N_d + N_a$ total dopant concentration (cm^{-3})

Note: compensation does not "work" here, you need all impurity atoms

Mobility dependence on dopants

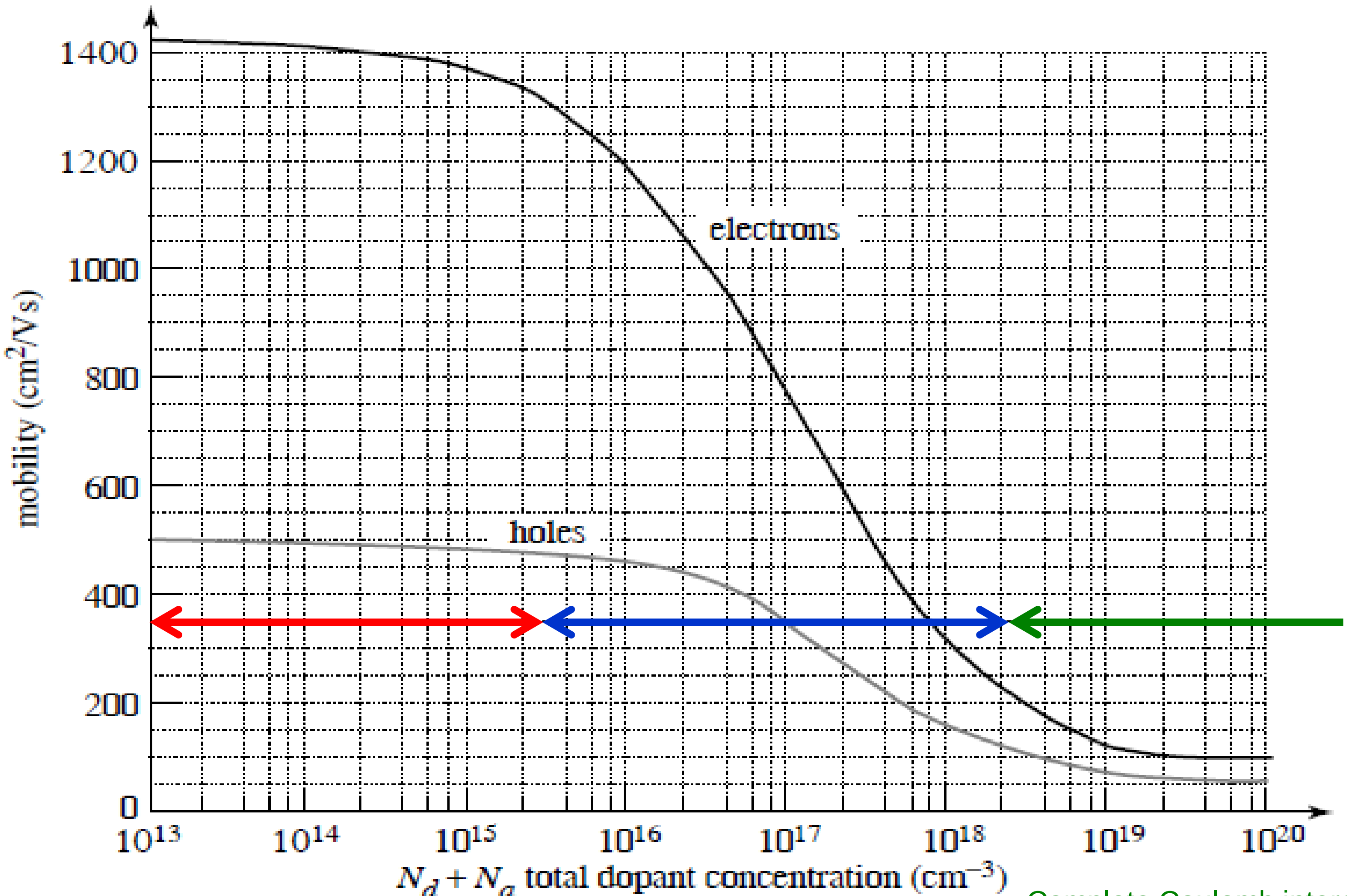
Si at 300K

Why this drop?



Mobility dependence on dopants

Si at 300K



Lattice phonon scattering dominates

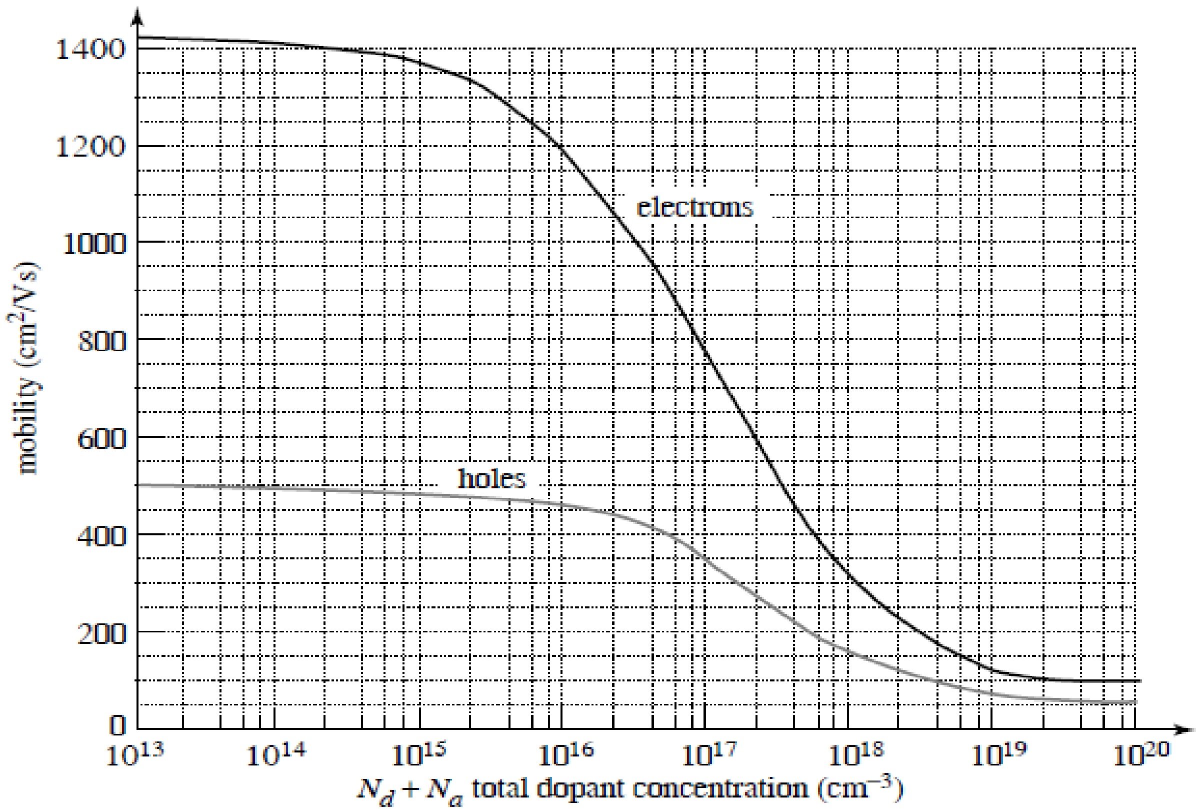
Scattering with single ionized impurity dominates

Complete Coulomb interaction with impurities and other charged carriers dominates

Mobility dependence on dopants

- Example:

Si sample doped with 10^{16} cm^{-3} Boron. Find the resistivity.



Example 1

Si sample doped with 10^{16} cm^{-3} Boron. Find the resistivity.

$N_D + N_A = 10^{16}\ \mathrm{cm}^{-3}$

$$N_A = 10^{16}\ \mathrm{cm}^{-3}$$

$$N_D = 0$$

$$p \approx 10^{16}\ \mathrm{cm}^{-3}$$

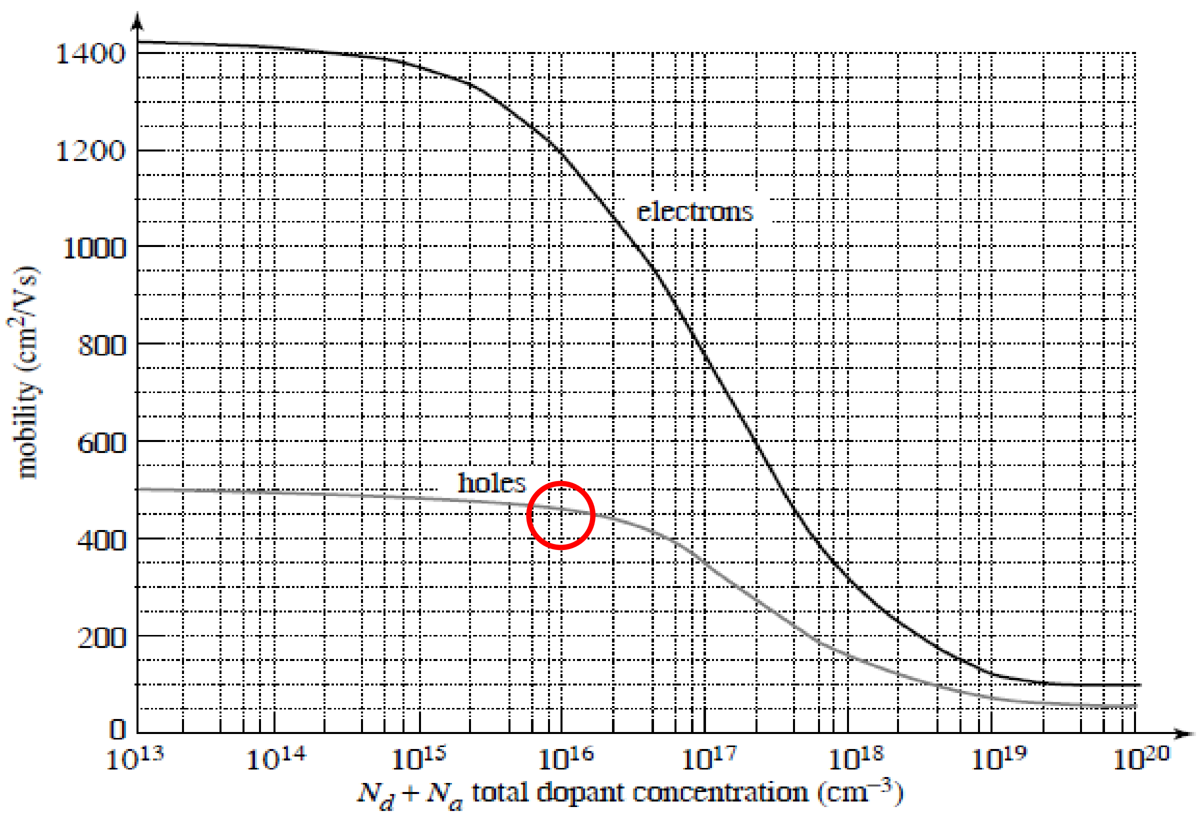
$$n \approx \frac{n_i^2}{p} = \frac{2.25\times10^{20}}{10^{16}} =$$

$$= 2.25\times10^{4}\ \mathrm{cm}^{-3}$$

$$\rho = \frac{1}{q\mu_p N_A} =$$

$$= \frac{1}{1.6\times10^{-19}\times455\times10^{16}} =$$

$$= 1.37\ \Omega\cdot\mathrm{cm}$$

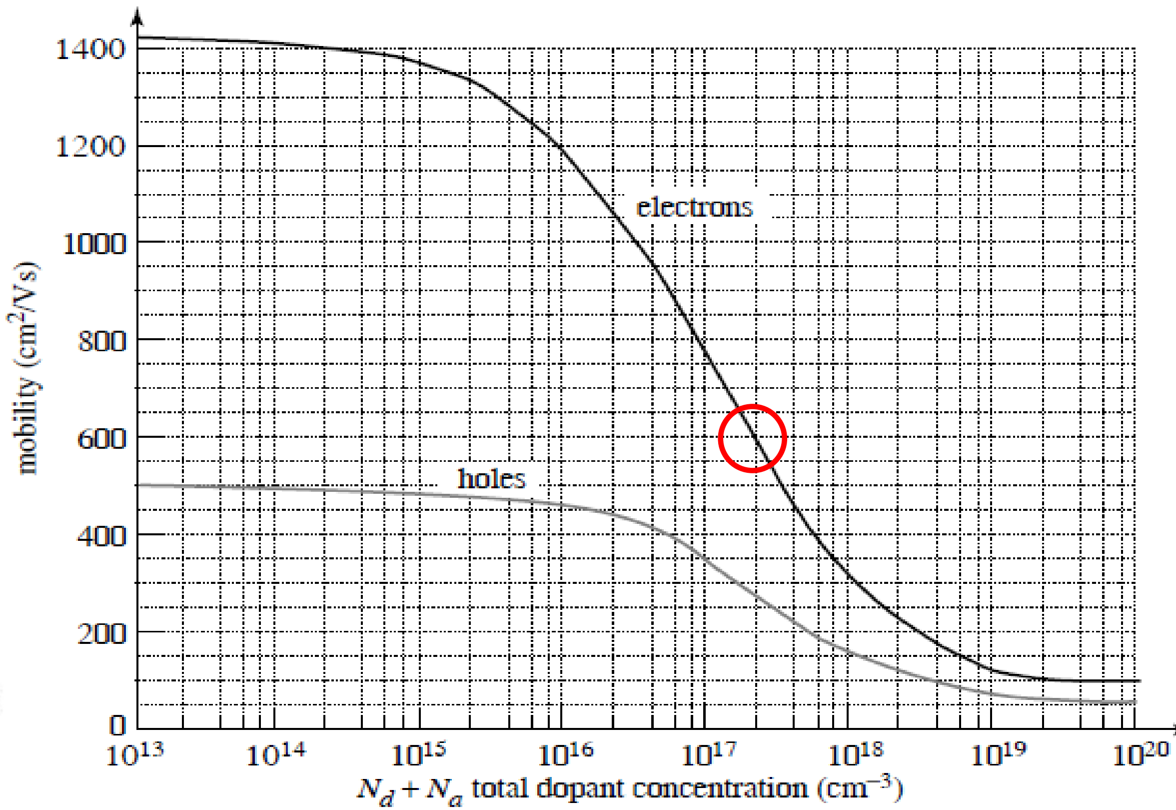


Example 2

Now, add $2\text{x}10^{17}$ cm^{-3} Arsenic. Find the resistivity.

$N_D + N_A = 2.1 \times 10^{17}\,\text{cm}^{-3}$

$$N_A = 10^{16}\ \text{cm}^{-3}$$
$$N_D = 2\times10^{17}\ \text{cm}^{-3}$$
$$n \approx 1.9\times10^{17}\ \text{cm}^{-3}$$
$$p \approx \frac{n_i^2}{n} = \frac{2.25\times10^{20}}{1.9\times10^{17}} = $$
$$= 1.2\times10^{3}\ \text{cm}^{-3}$$
$$\rho = \frac{1}{q\mu_n n} = $$
$$= \frac{1}{1.6\times10^{-19}\times600\times1.9\times10^{17}} = $$
$$= 0.055\,\Omega\cdot\text{cm}$$



Example 3

Instead, add $2x10^{16}$ cm^{-3} Arsenic. Find the resistivity.

$N_D + N_A = 3 \times 10^{16} \text{cm}^{-3}$

$$N_A = 10^{16}\text{cm}^{-3}$$

$$N_D = 2\times10^{16}\text{cm}^{-3}$$

$$n \approx 10^{16}\text{cm}^{-3}$$

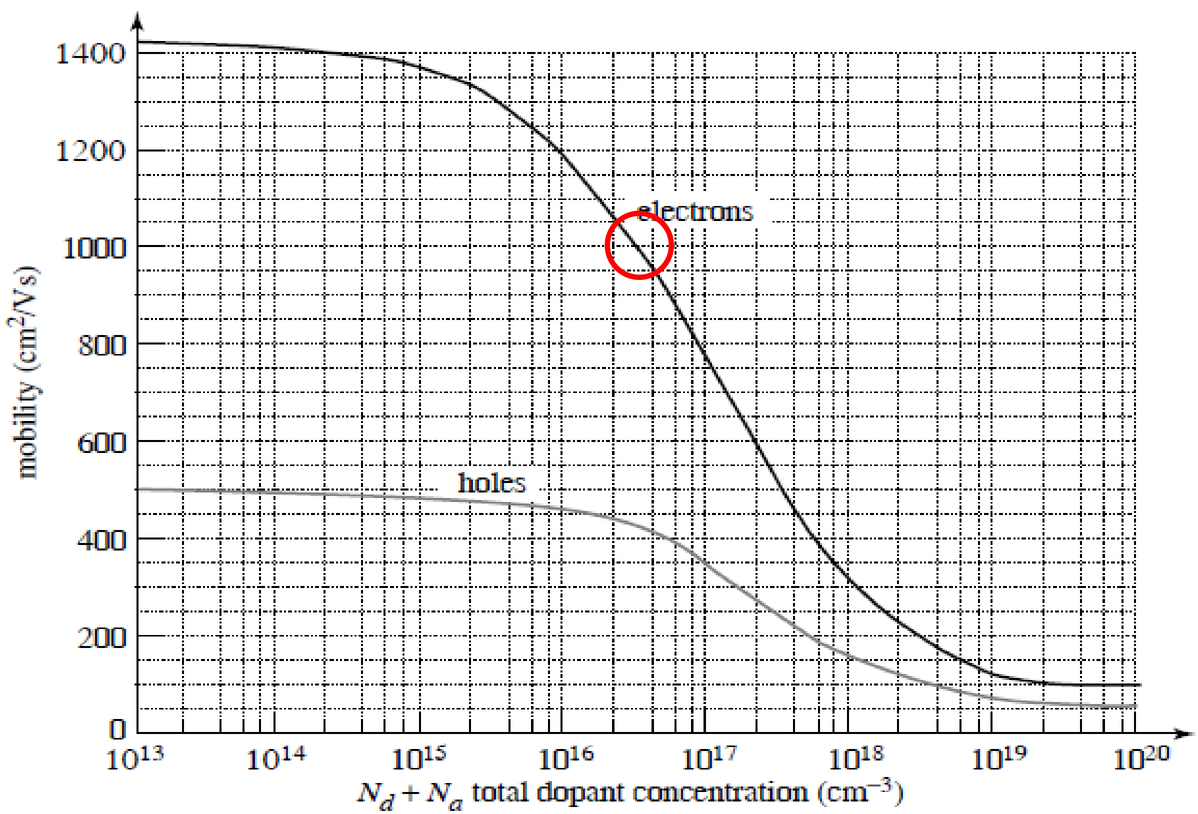
$$p \approx \frac{n_i^2}{n} = \frac{2.25\times10^{20}}{10^{16}} =$$

$$= 2.25\times10^{4}\text{cm}^{-3}$$

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

$$= \frac{1}{1.6\times10^{-19}\times1000\times10^{16}} =$$

$$= 0.625\Omega\cdot\text{cm}$$



Example 4

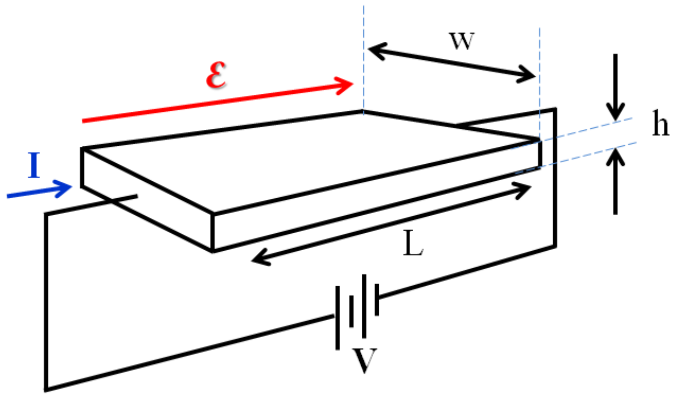
Consider a Si bar doped with 10^{17} cm^{-3} Arsenic. Find the current when a bias of 10V is applied and T = 300K.

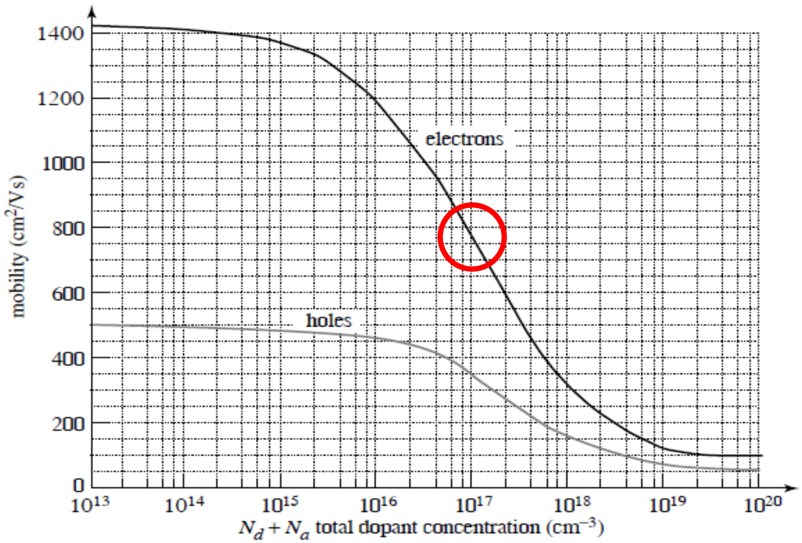
$$L = 0.1\ \text{cm}$$

$$A = w \times h = 100\ \mu m^2 = 10^{-8}\ \text{cm}^{-2}$$

$$N_D = 10^{17}\ \text{cm}^{-3}$$

$$\rho = \frac{1}{q \mu_n N_D}$$





Example 4

Consider a Si bar doped with 10^{17} cm^{-3} Arsenic. Find the current when a bias of 10V is applied and T = 300K.

$$L = 0.1\text{ cm}$$

$$A = w \times h = 100\ \mu\text{m}^2 = 10^{-8}\text{ cm}^{-2}$$

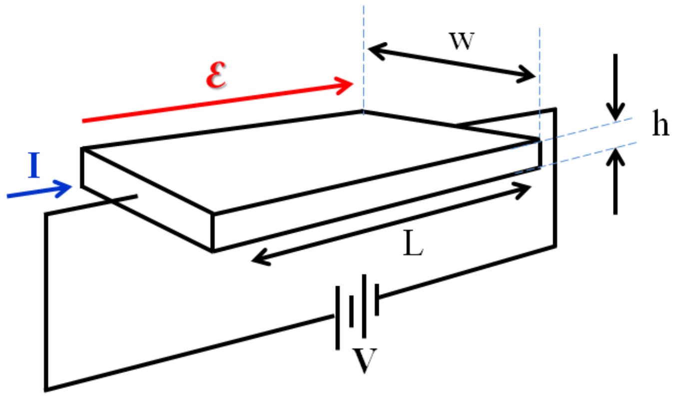
$$N_D = 10^{17}\text{ cm}^{-3}$$

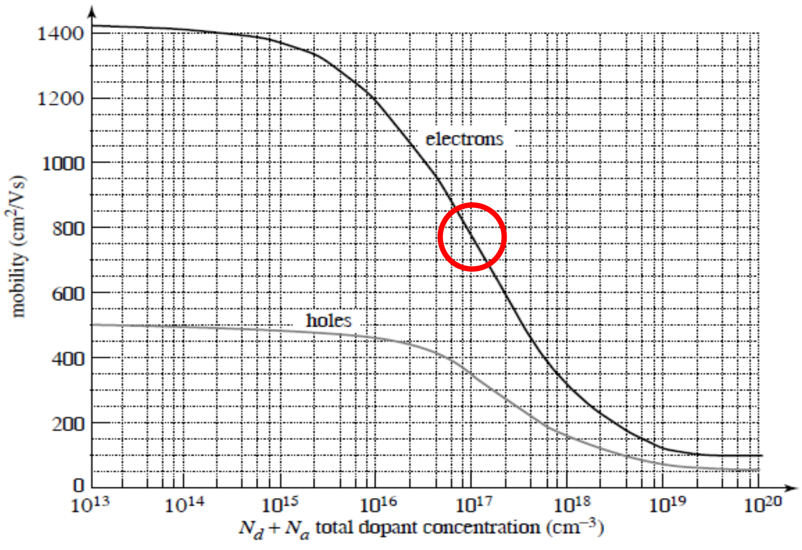
$$\rho = \frac{1}{q\mu_n N_D}$$

$$= \frac{1}{1.6\times10^{-19}\times770\times10^{17}} = 0.0812\ \Omega\cdot\text{cm}$$

$$R = \frac{\rho L}{A} = \frac{0.0812\times0.1}{100\times10^{-8}} = 8.12\text{ k}\Omega$$

$$I = \frac{V}{R} = \frac{10}{8.12\times10^{3}} = 1.23\text{ mA}$$





Mobility dependence on Temperature

There are two competing phenomena which give rise to two mobility component:

Impurity scattering

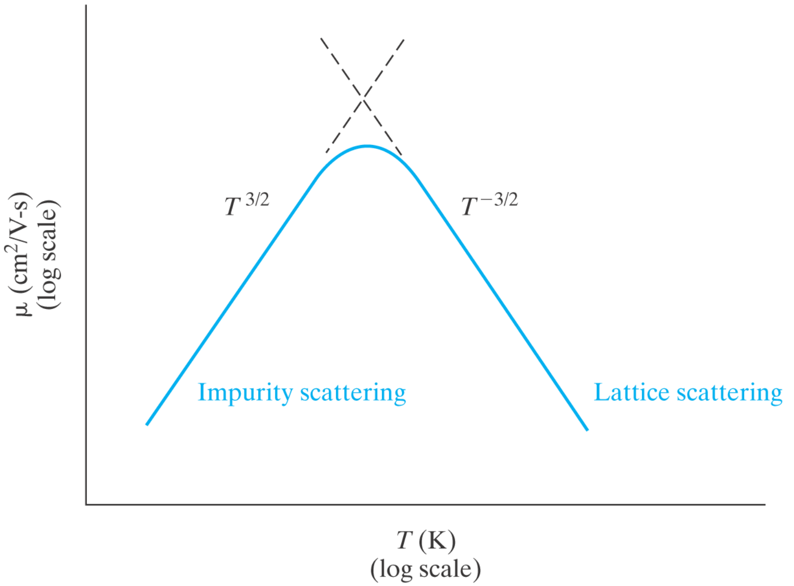
$$\mu_{imp} \propto \frac{T^{\frac{3}{2}}}{N_D + N_A}$$

Phonon scattering

$$\mu_{phon} \propto T^{-\frac{3}{2}}$$

Matthiessen's rule

$$\frac{1}{\mu} \approx \frac{1}{\mu_{imp}} + \frac{1}{\mu_{phon}}$$



Note:

- Validity of Matthiessen's rule applied to semiconductors is limited to conditions not too far from equilibrium, since the relaxation times (mean free times between collisions) are not simple functions of temperature and energy in realistic conditions. For more advanced applications, it will be better to use:

$$\frac{1}{\tau_c} \approx \frac{1}{\tau_{imp}} + \frac{1}{\tau_{phon}} + \dots$$

and then calculate the mobility from τ_c