Lecture #4

ANNOUNCEMENTS

• Prof. King will not hold office hours this week, but will hold an extra office hour next Mo (2/3) from 11AM-12:30PM

• Quiz #1 will be given at the **beginning** of class on Th 2/6
  – covers material in Chapters 1 & 2 (HW#1 & HW#2)
  – closed book; one page of notes allowed

OUTLINE

– Drift (Chapter 3.1)
  » carrier motion
  » mobility
  » resistivity

Nondegenerately Doped Semiconductor

• Recall that the expressions for *n* and *p* were derived using the Boltzmann approximation, *i.e.* we assumed

$$E_v + 3kT \le E_F \le E_c - 3kT$$

The semiconductor is said to be ***nondegenerately doped*** in this case.

Degenerately Doped Semiconductor

- If a semiconductor is very heavily doped, the Boltzmann approximation is not valid.

In Si at T=300K: E_c-E_F < 3kT if N_D > 1.6x10^{18} cm^{-3}

E_F-E_v < 3kT if N_A > 9.1x10^{17} cm^{-3}

The semiconductor is said to be ***degenerately doped*** in this case.

$$E_v + 3kT \le E_F \le E_c - 3kT$$

Band Gap Narrowing

- If the dopant concentration is a significant fraction of the silicon atomic density, the energy-band structure is perturbed

→ the band gap is reduced by ΔE_G

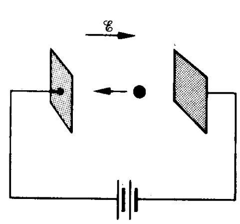
N = 10^{18} cm^{-3}:

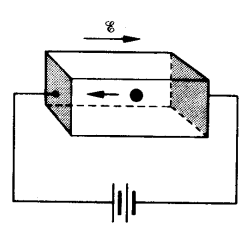
N = 10^{19} cm^{-3}:

Free Carriers in Semiconductors

- Three primary types of carrier action occur inside a semiconductor:
  - drift
  - diffusion
  - recombination-generation

Electrons as Moving Particles





$F = (-q)\mathcal{E} = m_o a$

$F = (-q)\mathcal{E} = m_n^* a$

where
m_n^* is the electron effective mass

Carrier Effective Mass

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

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

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

Electron and hole conductivity effective masses:

	Si	Ge	GaAs
m_n/m_0	0.26	0.12	0.068
m_p/m_0	0.39	0.30	0.50

Thermal Velocity

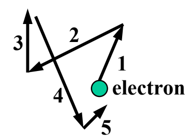
Average electron or hole kinetic energy $= \frac{3}{2}kT = \frac{1}{2}m^* v_{th}^2$

$$v_{th} = \sqrt{\frac{3kT}{m^*}} = \sqrt{\frac{3 \times 0.026 \text{ eV} \times (1.6 \times 10^{-19} \text{ J/eV})}{0.26 \times 9.1 \times 10^{-31} \text{ kg}}}$$

$$= 2.3 \times 10^5 \text{ m/s} = 2.3 \times 10^7 \text{ cm/s}$$

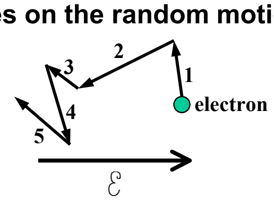
Carrier Scattering

- **Mobile electrons and atoms in the Si lattice are always in random thermal motion.**
  - **Electrons make frequent collisions with the vibrating atoms**
    - **"lattice scattering" or "phonon scattering"**
      - **increases with increasing temperature**
  - **Average velocity of thermal motion for electrons: ~10^7 cm/s @ 300K**
- **Other scattering mechanisms:**
  - **deflection by ionized impurity atoms**
  - **deflection due to Coulombic force between carriers**
    - **"carrier-carrier scattering"**
    - **only significant at high carrier concentrations**
- **The net current in any direction is zero, if no electric field is applied.**



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**

Electron Momentum

- With every collision, the electron loses momentum

$$m_n{}^* v_d$$

- Between collisions, the electron gains momentum

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

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

Carrier Mobility

$$m_n{}^* v_d = (-q)\mathcal{E}\tau_{mn}$$

$$|v_d| = q\mathcal{E}\tau_{mn} / m_n{}^* = \mu_n \mathcal{E}$$

- $\mu_n \equiv [q\tau_{mn} / m_n{}^*]$ is the ***electron mobility***

Similarly, for holes: $|v_d| = q\mathcal{E}\tau_{mp} / m_p{}^* \equiv \mu_p \mathcal{E}$

- $\mu_p \equiv [q\tau_{mp} / m_p{}^*]$ is the ***hole mobility***

Electron and Hole Mobilities

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 intrinsic semiconductors (*T*=300K)

	Si	Ge	GaAs	InAs
μ_n (cm^2/V·s)	1400	3900	8500	30000
μ_p (cm^2/V·s)	470	1900	400	500

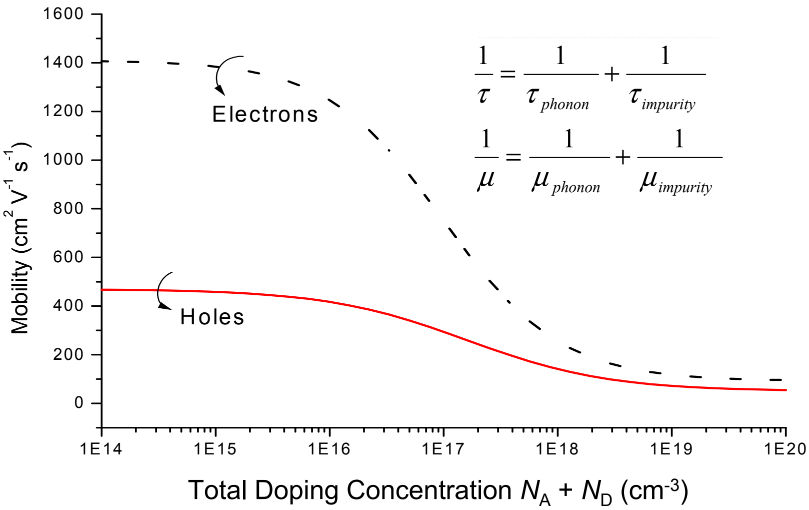
Example: Drift Velocity Calculation

Find the hole drift velocity in an intrinsic Si sample for $\mathcal{E} = 10^3$ V/cm.

What is τ_{mp}, and what is the distance traveled between collisions?

Solution:

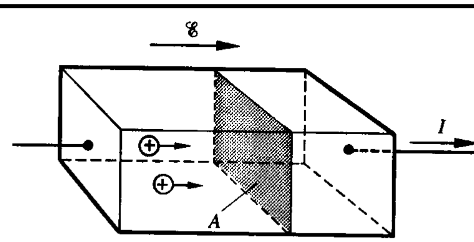
Mobility Dependence on Doping



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

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

Drift Current



$v_d\, t\, A$ = volume from which all holes cross plane in time t

$p\, v_d\, t$ A = # of holes crossing plane in time t

$q\, p\, v_d\, t$ A = charge crossing plane in time t

$q\, p\, v_d\, A$ = charge crossing plane per unit time = hole current

➔ **Hole current per unit area $J = q\, p\, v_d$**

Conductivity and Resistivity

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

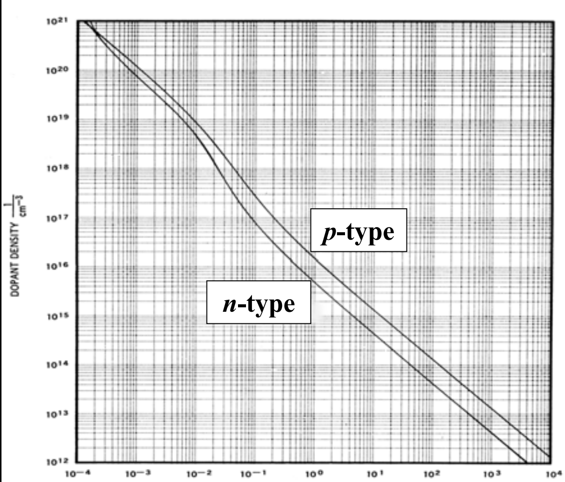
$$J_{p,drift} = qpv = qp\mu_p\mathcal{E}$$

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

Conductivity of a semiconductor is $\sigma \equiv qn\mu_n + qp\mu_p$

Resistivity $\rho \equiv 1/\sigma$ **(Unit: ohm-cm)**

Resistivity Dependence on Doping



For n-type mat'l:

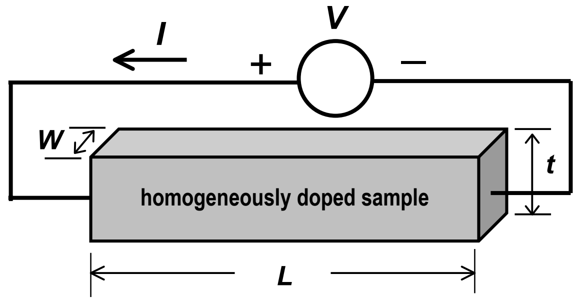
$$\rho \cong \frac{1}{qn\mu_n}$$

For p-type mat'l:

$$\rho \cong \frac{1}{qp\mu_p}$$

Note: This plot does not apply for compensated material!

Electrical Resistance



Resistance $$R \equiv \frac{V}{I} = \rho \frac{L}{Wt}$$ **(Unit: ohms)**

where ρ is the resistivity

Example

Consider a Si sample doped with 10^{16}/cm^3 Boron. What is its resistivity?

Answer:

$N_A = 10^{16}$/cm^3 , $N_D = 0$ **($N_A >> N_D$ → p-type)**

→ $p \approx 10^{16}$/cm^3 and $n \approx 10^4$/cm^3

$$\rho = \frac{1}{qn\mu_n + qp\mu_p} \cong \frac{1}{qp\mu_p}$$

$$= \left[(1.6\times10^{-19})(10^{16})(450)\right]^{-1} = 1.4\,\Omega-\text{cm}$$

Example: Dopant Compensation

Consider the same Si sample, doped *additionally* with 10^{17}/cm^3 Arsenic. What is its resistivity?

Answer:

$N_A = 10^{16}$/cm^3, $N_D = 10^{17}$/cm^3 ($N_D >> N_A$ → n-type)

→ $n \approx 9\times10^{16}$/cm^3 and $p \approx 1.1\times10^{3}$/cm^3

$$\rho = \frac{1}{qn\mu_n + qp\mu_p} \cong \frac{1}{qn\mu_n}$$

$$= \left[(1.6\times10^{-19})(9\times10^{16})(600)\right]^{-1} = 0.12\,\Omega-\text{cm}$$

Summary

- Electrons and holes moving under the influence of an electric field can be modelled as quasi-classical particles with average drift velocity

$$|v_d| = \mu\,\mathcal{E}$$

- The conductivity of a semiconductor is dependent on the carrier concentrations and mobilities

$$\sigma = qn\mu_n + qp\mu_p$$

- Resistivity $\rho = \dfrac{1}{\sigma} = \dfrac{1}{qn\mu_n + qp\mu_p}$