Lecture #18

OUTLINE

– Generation and recombination
– Charge-carrier transport in silicon
– Resistivity as a function of doping

Reference Texts on reserve in Engr. Library

- **Howe & Sodini**
  Chapter 2.1: Pure semiconductors
  Chapter 2.2: Generation, recombination, thermal equilibrium
  Chapter 2.3: Doping
  Chapter 2.4: Carrier Transport
  Chapter 2.6: IC Resistors
- **Schwarz and Oldham**
  Chapter 13: Semiconductor Devices

Generation

- We have seen that conduction (mobile) electrons and holes can be created in pure (intrinsic) silicon by ***thermal generation***.
  – Thermal generation rate increases exponentially with temperature ***T***
- Another type of generation process which can occur is ***optical generation***
  – The energy absorbed from a photon frees an electron from covalent bond
    - In Si, the minimum energy required is 1.1eV, which corresponds to ~1 μm wavelength (infrared region)
- Note that conduction electrons and holes are continuously generated, if $T > 0$

Recombination

- When a conduction electron and hole meet, each one is eliminated. The energy lost by the conduction electron (when it "falls" back into the covalent bond) can be released in 2 ways:

  1. to the semiconductor lattice (vibrations)
     "thermal recombination" → semiconductor is heated
  2. to photon emission
     "optical recombination" → light is emitted
     - Optical recombination is negligible in Si. It is significant in compound semiconductor materials, and is the basis for light-emitting diodes and laser diodes.

Generation and Recombination Rates

- The generation rate is dependent on temperature ***T***, but it is independent of ***n*** and ***p*** : $G = G_{thermal}(T) + G_{optical}$
- The recombination rate is proportional to both ***n*** and ***p***:

$$R \propto np$$

- In steady state, a balance exists between the generation and recombination rates.

$$G = R \quad \Rightarrow \quad np = f(T)$$

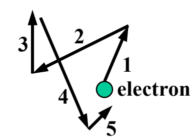
- A special case of the steady-state condition is ***thermal equilibrium***: no optical or electrical sources

$$\boxed{np = n_i^2(T)}$$

Carrier Scattering

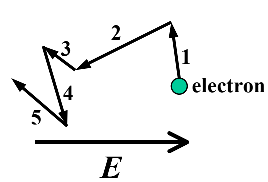
- **Mobile electrons and atoms in the Si lattice are always in random thermal motion.**
  - **Average velocity of thermal motion for electrons in Si: ~10^7 cm/s @ 300K**
  - **Electrons make frequent collisions with the vibrating atoms**
    - **"lattice scattering" or "phonon scattering"**
  - **Other scattering mechanisms:**
    - **deflection by ionized impurity atoms**
    - **deflection due to Coulombic force between carriers**

- **The average 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 *E*-field → Current flows**

❖ **Because of scattering, electrons in a semiconductor do not achieve constant acceleration. However, they can be viewed as classical particles moving at a constant average *drift velocity*.**

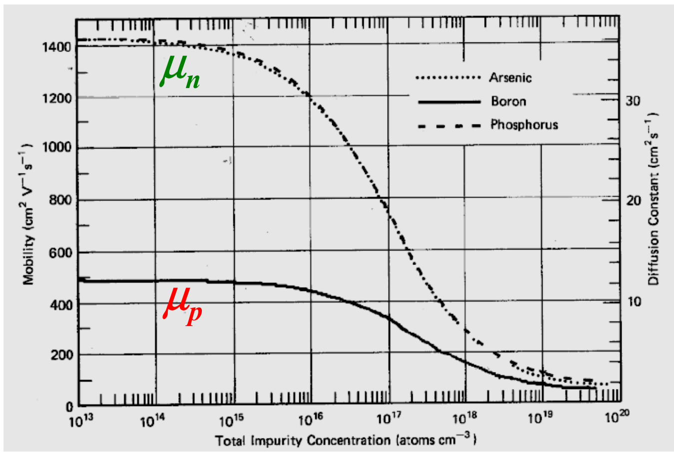
Drift Velocity and Carrier Mobility

Mobile charge-carrier drift velocity is proportional to applied *E*-field:

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

μ is the ***mobility***

(Units: cm²/V•s)

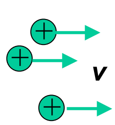


Note: Carrier mobility depends on *total* dopant concentration ($N_D + N_A$) !

Current Density

The current density ***J*** is the current per unit area
(***J*** = ***I*** / ***A*** ; ***A*** is the cross-sectional area of the conductor)

If we have ***N*** positive charges per unit volume moving with average speed ***v*** in the +***x*** direction, then the current density in the +***x*** direction is just ***J*** = ***qNv***

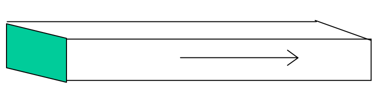


Example:

2 x10^{16} holes/cm^3 moving to the right at 2 x10^4 cm/sec

J = 1.6x10^{-19} x 2x10^{16} x 2x10^4 = 64 A/cm^2

Suppose this occurs in a conductor 2 μm wide and 1 μm thick:



$I = J \times A$ = 64 x (2x10^{-4} x 1x10^{-4})

= 1.28 μA

Electrical Conductivity σ

When an electric field is applied, current flows due to drift of mobile electrons and holes:

electron current density: $J_n = (-q)nv_n = qn\mu_n E$

hole current density: $J_p = (+q)pv_p = qp\mu_p E$

total current density: $J = J_n + J_p = (qn\mu_n + qp\mu_p)E$

$J = \sigma E$

conductivity $\boxed{\sigma \equiv qn\mu_n + qp\mu_p}$

Electrical Resistivity ρ

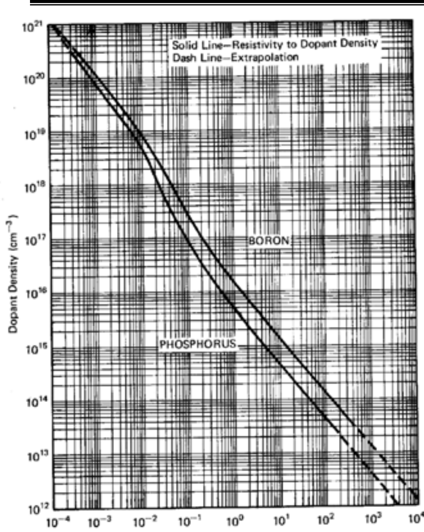


Figure 1.14 Dopant density versus resistivity at 23°C (296 K) for silicon doped with phosphorus and with boron. The curves can be used with little error to represent conditions at 300 K. [W. R.

$$\boxed{\rho \equiv \frac{1}{\sigma} = \frac{1}{qn\mu_n + qp\mu_p}}$$

$\rho \cong \dfrac{1}{qn\mu_n}$ **for n-type mat'l**

$\rho \cong \dfrac{1}{qp\mu_p}$ **for p-type mat'l**

(Units: ohm-cm)

Note: This plot does not apply for compensated material (doped with both donors and acceptors)

Example

Consider a Si sample doped with 10^{16}/cm³ Boron. What is its resistivity?

Answer:

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

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

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

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

From μ vs. ($N_A + N_D$) plot

Example (cont'd)

Consider the same Si sample, doped *additionally* with 10^{17}/cm³ Arsenic. What is its resistivity?

Answer:

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

$\rightarrow n \approx 9\text{x}10^{16}/\text{cm}^3$ and $p \approx 1.1\text{x}10^3/\text{cm}^3$

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

$$= \left[(1.6\times10^{-19})(9\times10^{16})(700)\right]^{-1} = 0.10\,\Omega-\text{cm}$$

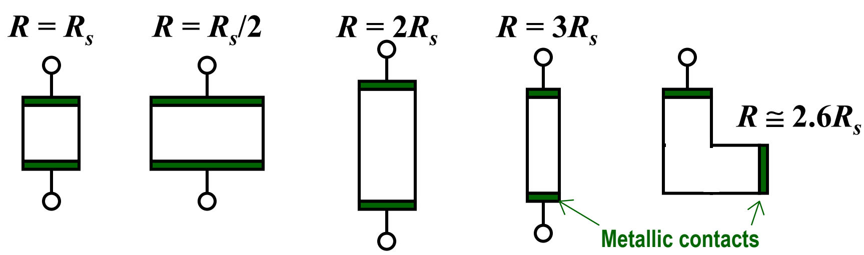
The sample is converted to n-type material by adding more donors than acceptors, and is said to be "compensated".

Sheet Resistance R_s

$$R = \rho \frac{L}{Wt} = R_s \frac{L}{W} \quad \Rightarrow \quad \boxed{R_s \equiv \frac{\rho}{t}}$$ **(Unit: ohms/square)**

R_s is the resistance when $W = L$

- The R_s value for a given layer in an IC technology is used
  - for design and layout of resistors
  - for estimating values of parasitic resistance in a circuit



Velocity Saturation

At *high electric fields*, the average velocity of carriers is NOT proportional to the field; it saturates at ~10^7 cm/sec for both electrons and holes: