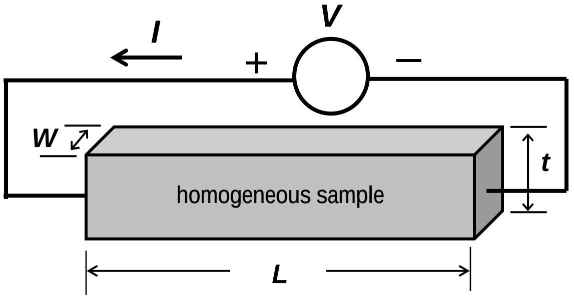
Introduction to Semiconductor Devices and Circuit Model

Reading:
Chapter 2 of Howe and Sodini

Electrical Resistance

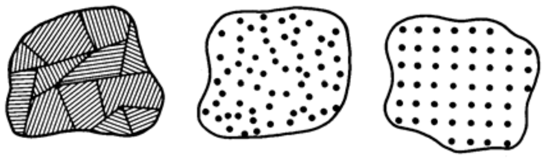


Resistance $$\boxed{R \equiv \frac{V}{I} = \rho \frac{L}{Wt}}$$ **(Units: Ω)**

where ρ is the ***resistivity*** **(Units: Ω-cm)**

What is a Semiconductor?

- Low resistivity => “conductor”
- High resistivity => “insulator”
- Intermediate resistivity => “semiconductor”
  - Generally, the semiconductor material used in integrated-circuit devices is crystalline
    - In recent years, however, non-crystalline semiconductors have become commercially very important

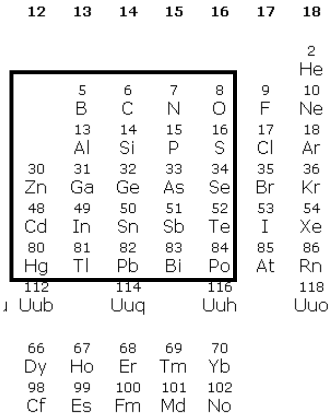


polycrystalline amorphous crystalline

Semiconductor Materials

Elemental:

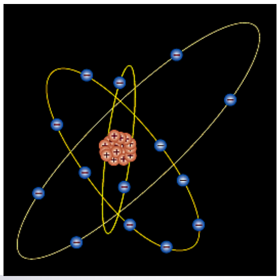
Compound:



12	13	14	15	16	17	18
						2 He
	5 B	6 C	7 N	8 O	9 F	10 Ne
	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
112 Uub		114 Uuq		116 Uuh		118 Uuo
66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
98 Cf	99 Es	100 Fm	101 Md	102 No		

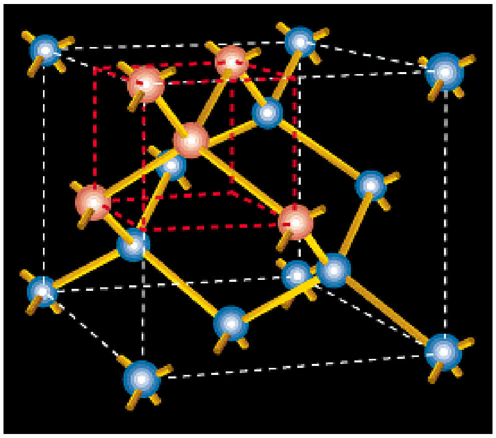
The Silicon Atom

- 14 electrons occupying the 1st 3 energy levels:
  - 1s, 2s, 2p orbitals filled by 10 electrons
  - 3s, 3p orbitals filled by 4 electrons
    - To minimize the overall energy, the 3s and 3p orbitals hybridize to form 4 tetrahedral 3sp orbitals
      - Each has one electron and is capable of forming a bond with a neighboring atom



The Si Crystal

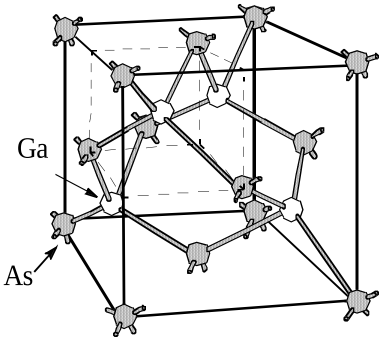
“diamond cubic” lattice



- **Each Si atom has 4 nearest neighbors**
- **lattice constant**

= 5.431Å

Compound Semiconductors



- "zinc blende" structure
- III-V compound semiconductors: GaAs, GaP, GaN, *etc.*
  - ✓ important for optoelectronics and high-speed ICs

Electronic Properties of Si

- **Silicon is a semiconductor material.**

  Pure Si has relatively high resistivity at room temperature.

- **There are 2 types of mobile charge-carriers in Si:**

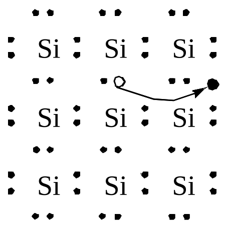
  Conduction electrons are negatively charged.

  Holes are positively charged. They are an "absence of electrons".

- **The concentration of conduction electrons & holes in a semiconductor can be affected in several ways:**
  1. **by adding special impurity atoms (*dopants*)**
  2. **by applying an electric field**
  3. **by changing the temperature**
  4. **by irradiation**

Conduction Electrons and Holes

When an electron breaks loose and becomes a ***conduction electron***, a ***hole*** is also created.



2-D representation

Note: A hole (along with its associated positive charge) is mobile!

Definition of Parameters

n = number of mobile electrons per cm^3

p = number of holes per cm^3

n_i = intrinsic carrier concentration ($\#/\text{cm}^3$)

In a pure semiconductor,

$$n = p = n_i$$

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). 1 eV = energy gained by an electron falling through 1 V potential = $q_e V = 1.6 \times 10^{-19}$ C x 1 V = 1.6×10^{-19} J.
- Note that conduction electrons and holes are continuously generated, if ***T*** > 0

Recombination

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

  1. to the semiconductor lattice (vibrations)

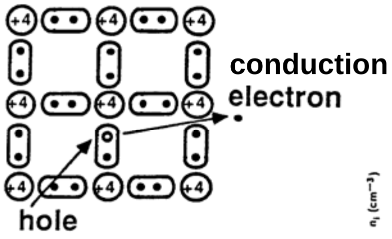
     “thermal recombination” → semiconductor is heated

  2. to photon emission

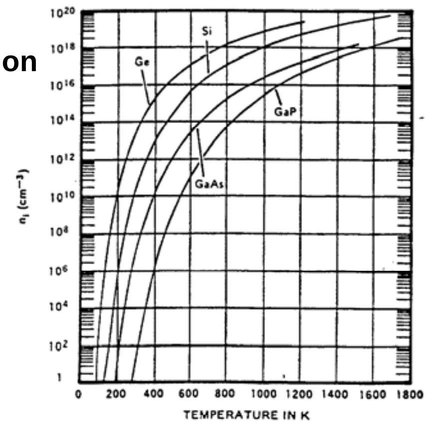
     “optical recombination” → light is emitted

     - Optical recombination is negligible in Si. It is significant in compound semiconductor materials, and is the basis for light-emitting diodes and laser diodes.

Pure Si



Covalent (shared e⁻) bonds exists between Si atoms in a crystal. Since the e⁻ are loosely bound, some will be free at any T, creating hole electron pairs.



Si:

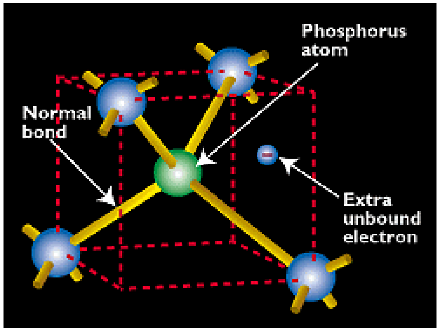
$$n_i = 3.9 \times 10^{16} T^{3/2} e^{-\frac{0.605\text{eV}}{kT}} /\text{cm}^3$$

$n_i \cong 10^{10}$ cm^{-3} at room temperature

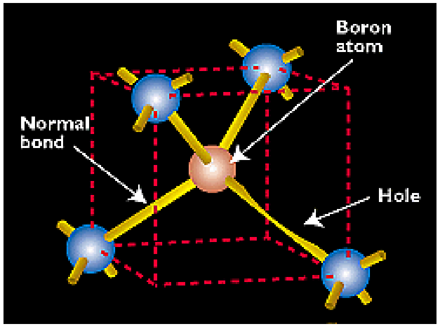
Doping

By <u>substituting</u> a Si atom with a special impurity atom (Column V or Column III element), a conduction electron or hole is created.

<u>Donors</u>: P, As, Sb



<u>Acceptors</u>: B, Al, Ga, **In**



Dopant concentrations typically range from 10^{14} cm^{-3} to 10^{20} cm^{-3}

Charge-Carrier Concentrations

N_D: ionized donor concentration (cm^{-3})
N_A: ionized acceptor concentration (cm^{-3})

Charge neutrality condition: $N_D + p = N_A + n$

At thermal equilibrium, $np = n_i^2$ **("Law of Mass Action")**

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Note: Carrier concentrations depend on *net* dopant concentration (N_D - N_A) !

N-type and P-type Material

If N_D >> N_A (so that $N_D - N_A >> n_i$):

$$n \cong N_D - N_A \quad \textbf{and} \quad p \cong \frac{n_i^2}{N_D - N_A}$$

$n >> p$ → material is "n-type"

If N_A >> N_D (so that $N_A - N_D >> n_i$):

$$p \cong N_A - N_D \quad \textbf{and} \quad n \cong \frac{n_i^2}{N_A - N_D}$$

$p >> n$ → material is "p-type"

Terminology

intrinsic semiconductor: "undoped" semiconductor

electrical properties are native to the material

extrinsic semiconductor: doped semiconductor

electrical properties are controlled by the added impurity atoms

donor: impurity atom that increases the electron concentration

group V elements (P, As)

acceptor: impurity atom that increases the hole concentration

group III elements (B, In)

n-type material: semiconductor containing more electrons than holes

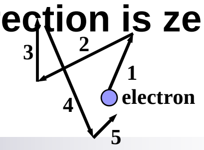
p-type material: semiconductor containing more holes than electrons

majority carrier: the most abundant carrier in a semiconductor sample

minority carrier: the least abundant carrier in a semiconductor sample

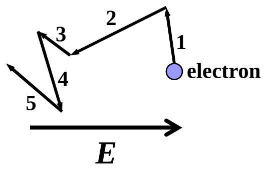
Carrier Scattering

- 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*.

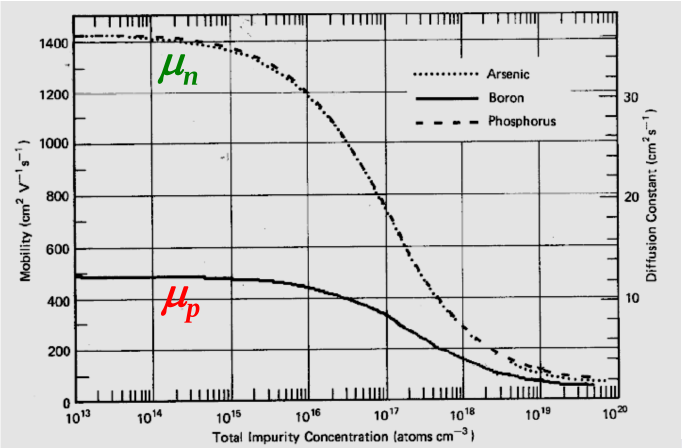
Drift Velocity and Carrier Mobility

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

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

μ is the ***mobility***

(Units: cm^2/V•s)

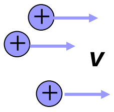


Note: Carrier mobility depends on *total* dopant concentration ($N_D + N_A$) !

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***

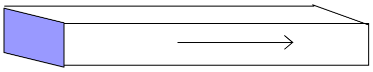


Example:

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* x *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 $\boxed{\sigma \equiv qn\mu_n + qp\mu_p}$ (Units: Ω-cm^{-1})

Electrical Resistivity ρ

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

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

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

(Units: ohm-cm)

Example

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

***Answer*:**

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

→ $p \approx 10^{16}/\text{cm}^3$ 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}/cm^3 Arsenic. What is its resistivity?

Answer:

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

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

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

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

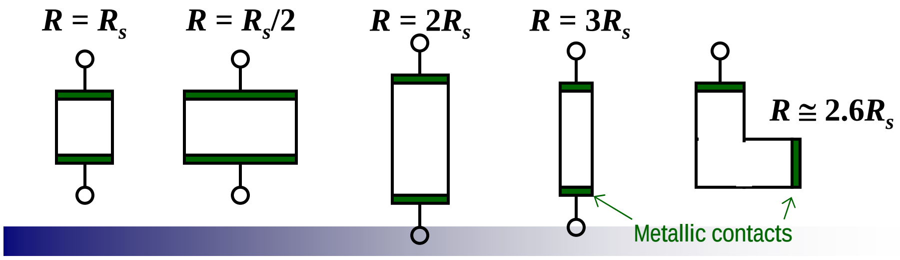
The sample is converted to n-type material by adding more donors than acceptors, and is said to be "compensated".

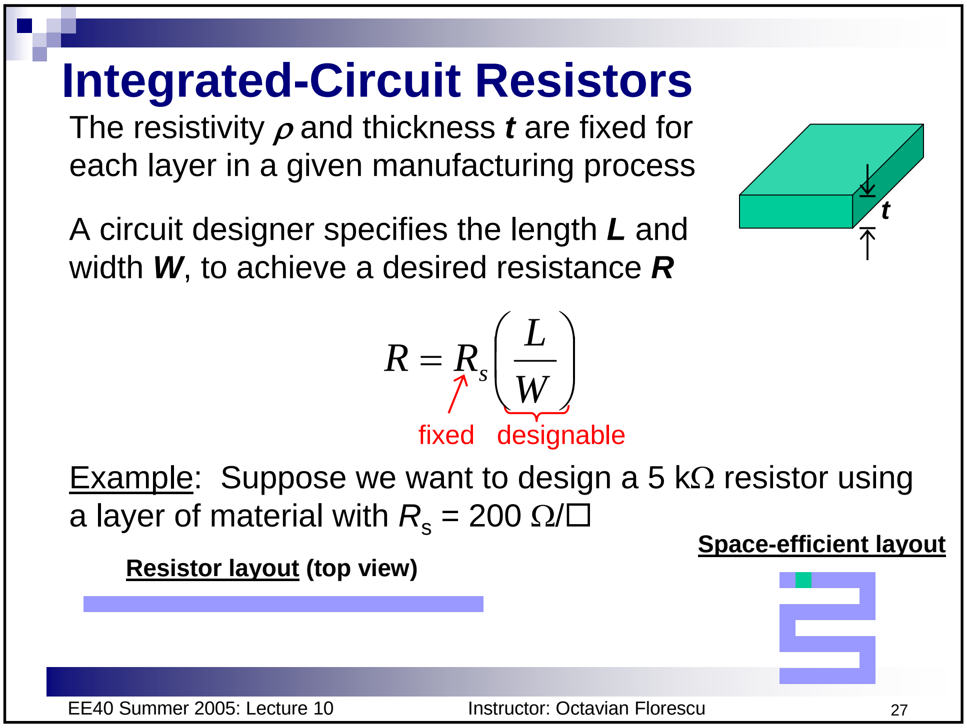
Sheet Resistance R_s

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

(L, W, t = length, width, thickness) 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





Integrated-Circuit Resistors

The resistivity ρ and thickness ***t*** are fixed for each layer in a given manufacturing process

A circuit designer specifies the length ***L*** and width ***W***, to achieve a desired resistance ***R***

$$R = \underset{\text{fixed}}{R_s}\underbrace{\left(\frac{L}{W}\right)}_{\text{designable}}$$

Example: Suppose we want to design a 5 kΩ resistor using a layer of material with R_s = 200 Ω/☐

Resistor layout (top view)

Space-efficient layout

Summary

- **Crystalline Si:**
  - 4 valence electrons per atom
  - diamond lattice: each atom has 4 nearest neighbors
  - 5 x 10^{22} atoms/cm^3

- **In a pure Si crystal, conduction electrons and holes are formed in pairs.**
  - Holes can be considered as positively charged mobile particles which exist inside a semiconductor.
  - Both holes and electrons can conduct current.

- **Dopants in Si:**
  - Reside on lattice sites (substituting for Si)
  - Group V elements contribute conduction electrons, and are called ***donors***
  - Group III elements contribute holes, and are called ***acceptors***