Lecture #17

ANNOUNCEMENTS

- Reference text (Rabaey *et al.*) posted online
- Instructions for Linux users posted online

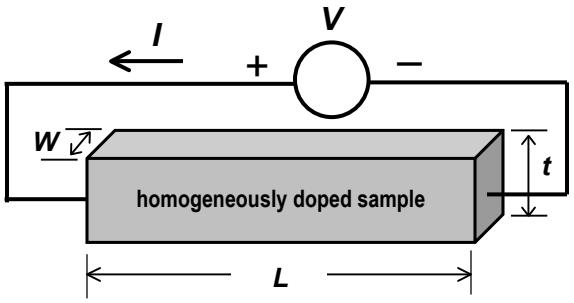
OUTLINE

- Semiconductor materials
- Properties of silicon
- Doping

Reading

Chapter 3.1 (Rabaey)

Electrical Resistance

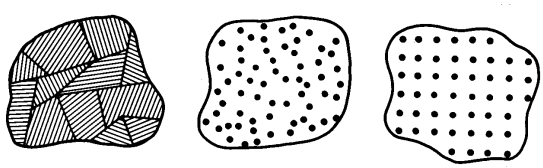


Resistance $$R \equiv \frac{V}{I} = \rho \frac{L}{Wt}$$ **(Units: Ω)**

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:

Alloy:

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

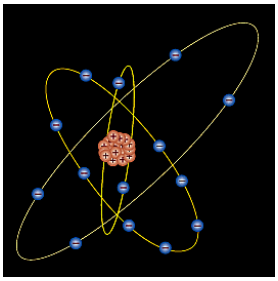
66 Dy	67 Ho	68 Er	69 Tm	70 Yb
98 Cf	99 Es	100 Fm	101 Md	102 No

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

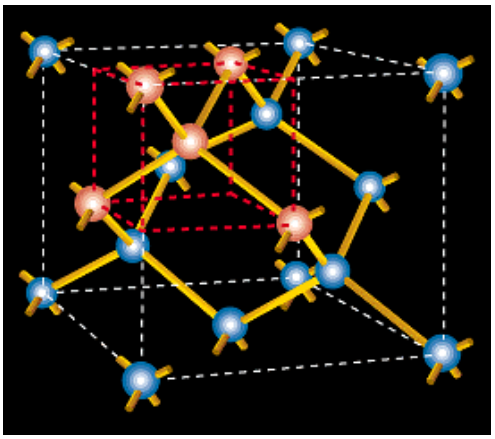
To minimize the overall energy, the 3s and 3p orbitals hybridize to form 4 tetrahedral 3sp orbitals

Each has one electron and is capable of forming a bond with a neighboring atom



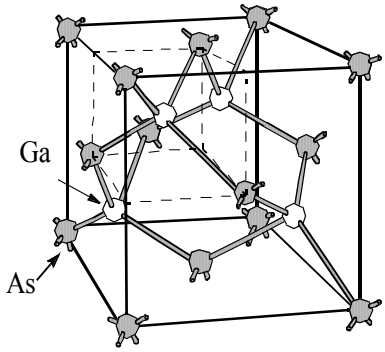
The Si Crystal

"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.

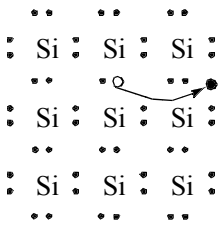
- **There are 2 types of mobile charge-carriers in Si:**
  Conduction electrons are negatively charged.
  Holes are positively charged.

- **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 electrons per cm^3

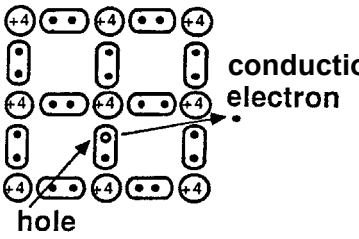
p = number of holes per cm^3

n_i = intrinsic carrier concentration (#/cm^3)

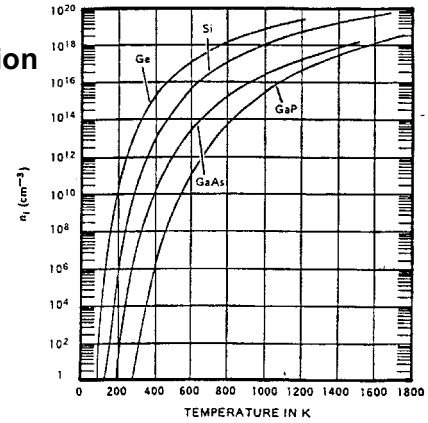
In a pure semiconductor,

$$n = p = n_i$$

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.



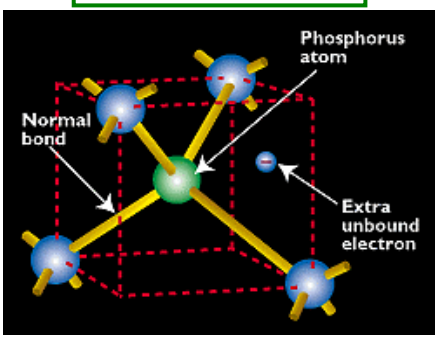
$$Si: \quad n_i = 3.9 \times 10^{16} T^{3/2} e^{-\frac{0.605eV}{kT}} /cm^3$$

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

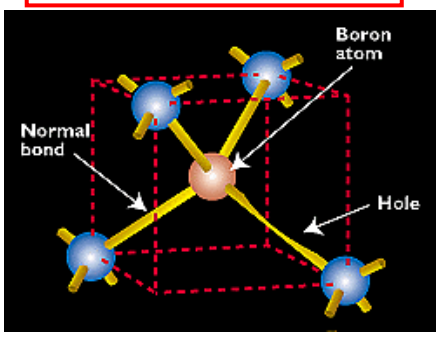
Doping

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

Donors: P, As, Sb



Acceptors: 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 $N_D - N_A >> n_i$)**:**

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

$n >> p$ → material is "n-type"

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

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

$p >> n$ → 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

Summary

- **Crystalline Si:**
  - 4 valence electrons per atom
  - diamond lattice: each atom has 4 nearest neighbors
  - 5×10^{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***