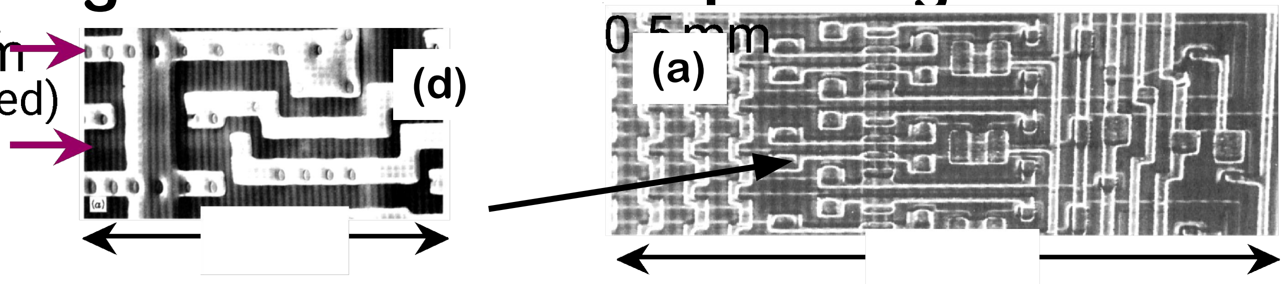
CHAPTER 18: ELECTRICAL PROPERTIES

ISSUES TO ADDRESS...

- How are electrical conductance and resistance characterized?
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, T, and deformation?
- For semiconductors, how is conductivity affected by impurities (doping) and T?

VIEW OF AN INTEGRATED CIRCUIT

- Scanning electron microscope images of an IC:



- A dot map showing location of Si (a semiconductor):
    --Si shows up as light regions.

- A dot map showing location of Al (a conductor):
    --Al shows up as light regions.

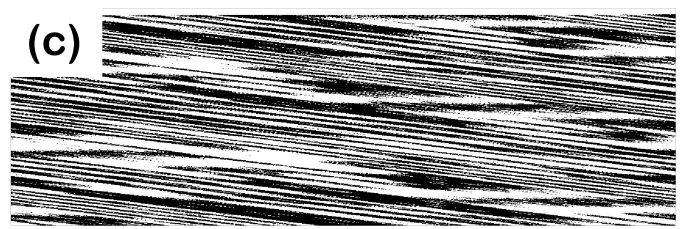


Fig. (d) from Fig. 18.25, *Callister 6e*. (Fig. 18.25 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

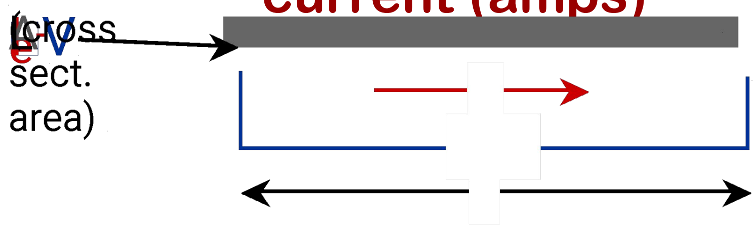
Fig. (a), (b), (c) from Fig. 18.0, *Callister 6e*.

ELECTRICAL CONDUCTION

- **Ohm's Law:**

$$\Delta V = I\,R$$

voltage drop (volts) → ΔV; current (amps) → I; resistance (Ohms) → R



- **Resistivity, ρ and Conductivity, σ:**
  --geometry-independent forms of Ohm's Law

$$\frac{\Delta V}{L} = \frac{I}{A}\,\rho$$

E: electric field intensity → $\frac{\Delta V}{L}$; J: current density → $\frac{I}{A}$; resistivity (Ohm-m) → ρ

conductivity → $\sigma = \frac{1}{\rho}$

- **Resistance:**

$$R = \frac{\rho L}{A} = \frac{L}{A\sigma}$$

CONDUCTIVITY: COMPARISON

• Room T values $(Ohm\text{-}m)^{-1}$

conductors

Polyethylene 10 -17

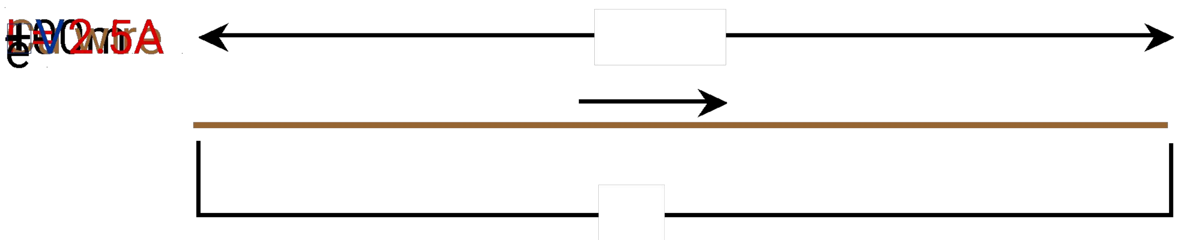
Aluminum oxide 10 -13

Selected values from Tables 18.1, 18.2, and 18.3, *Callister 6e*.

EX: CONDUCTIVITY PROBLEM

- Question 18.2, p. 649, *Callister*

6e:



What is the minimum diameter (D) of the wire so that

$\Delta V < 1.5V$?

$$R = \frac{L}{As} = \frac{DV}{I}$$

- 100m → L
- < 1.5V → DV
- 2.5A → I
- $\frac{pD^2}{4}$ → A
- 6.07×10^7 (Ohm-m)$^{-1}$ → s

Solve to get **D > 1.88 mm**

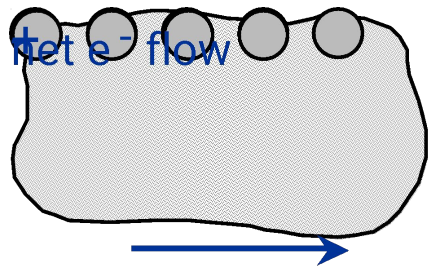
CONDUCTION & ELECTRON TRANSPORT

- **Metals:**

-- Thermal energy puts many electrons into a higher energy state.

- **Energy States:**

-- the cases below for metals show that nearby energy states are accessible by thermal fluctuations.



ENERGY STATES: INSULATORS AND SEMICONDUCTORS

- **Insulators:**

  --Higher energy states not

- **Semiconductors:**

  --Higher energy states separated by a smaller gap

METALS: RESISTIVITY VS T, IMPURITIES

- **Imperfections increase resistivity**
  - --grain boundaries
  - --dislocations
  - --impurity atoms

These act to scatter electrons so that they take a less direct path.

- **Resistivity increases with:**
  - --temperature
  - --wt% impurity
  - --%CW

$$r = r_{thermal} + r_{thermal} + r_{def}$$

Adapted from Fig. 18.8, *Callister 6e*. (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* 5, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

EX: ESTIMATING CONDUCTIVITY

- Question: Estimate the electrical conductivity of a Cu-Ni

Adapted from Fig. 7.14(b), *Callister 6e.*

$$r = 30x10^{-8}\ \text{Ohm} - \text{m}$$

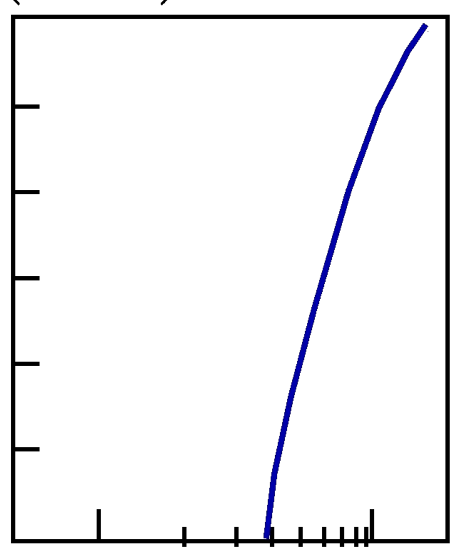
$$s = \frac{1}{r} = 3.3x10^{6}\ (\text{Ohm} - \text{m})^{-1}$$

Adapted from Fig. 18.9, *Callister 6e.*

PURE SEMICONDUCTORS: CONDUCTIVITY VS T

- Data for Pure Silicon:
  - --σ increases with T
  - --opposite to metals

$$\sigma_{undoped} \propto e^{-E_{gap}/kT}$$



electrons can cross gap at higher T

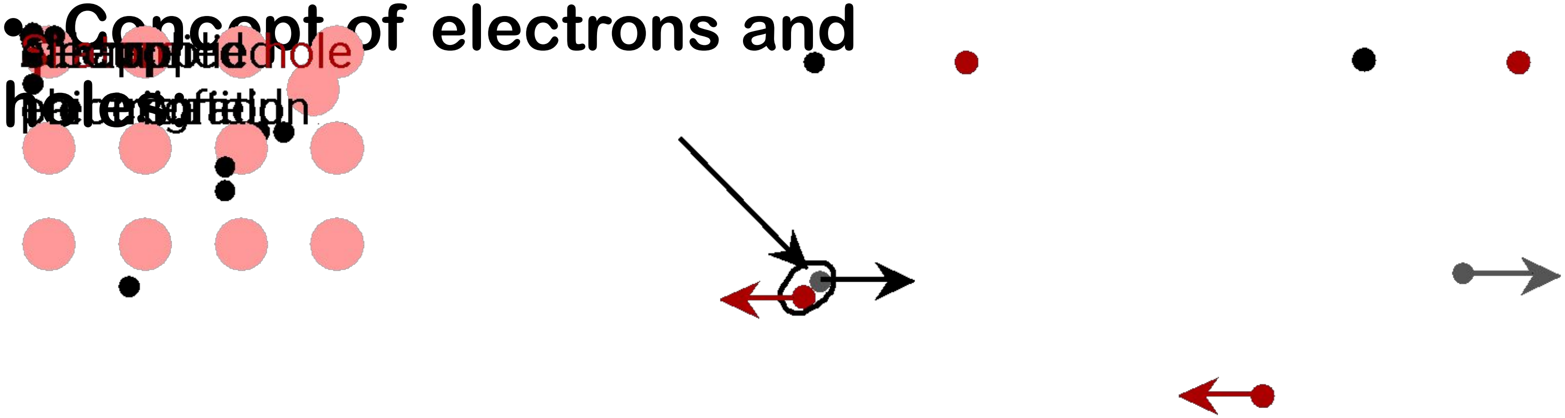
material	band gap (eV)
Si	1.11
Ge	0.67
GaP	2.25
CdS	2.40

Selected values from Table 18.2, *Callister 6e*.

Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* 75, p. 865, 1949.)

CONDUCTION IN TERMS OF ELECTRON AND HOLE MIGRATION

- Concept of electrons and holes:



Adapted from Fig. 18.10, *Callister 6e.*

- Electrical Conductivity given by:

$$s = n|e|m_e + p|e|m_h$$

holes/m^3

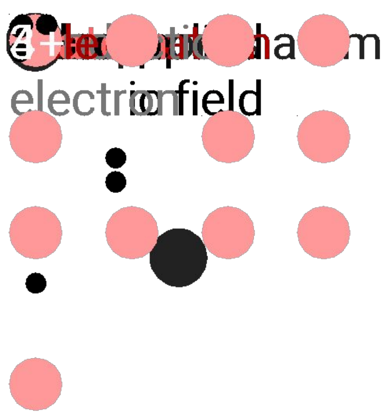
hole mobility

electrons/m^3

electron mobility

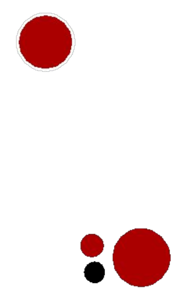
INTRINSIC VS EXTRINSIC CONDUCTION

- **Intrinsic:**
  # electrons = # holes (n = p)
  --case for pure Si
- **Extrinsic:**
  --n ≠ p
  --occurs when impurities are added with a different # valence electrons than the host (e.g., Si atoms)
- **N-type** Extrinsic: (n >> p)



$\sigma \approx n|e|\mu_e$

- **P-type** Extrinsic: (p >> n)



$\sigma \approx p|e|\mu_h$

DOPED SEMICON: CONDUCTIVITY VS T

- **Data for Doped Silicon:**
  - --σ increases doping
  - --reason: imperfection sites lower the activation energy to produce mobile electrons.

- **Comparison: intrinsic vs extrinsic conduction...**
  - --extrinsic doping level: $10^{21}/m^3$ of a n-type donor impurity (such as P).
  - --for T < 100K: "freeze-out" thermal energy insufficient to excite electrons.
  - --for 150K < T < 450K: "extrinsic"
  - --for T >> 450K: "intrinsic"

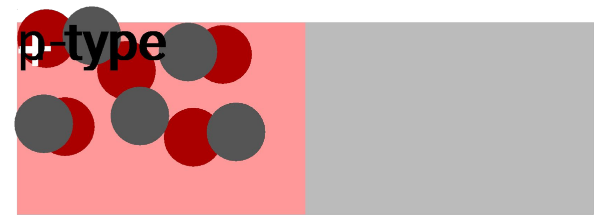
Adapted from Fig. 18.16, *Callister 6e*. (Fig. 18.16 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* 75, p. 865, 1949.)

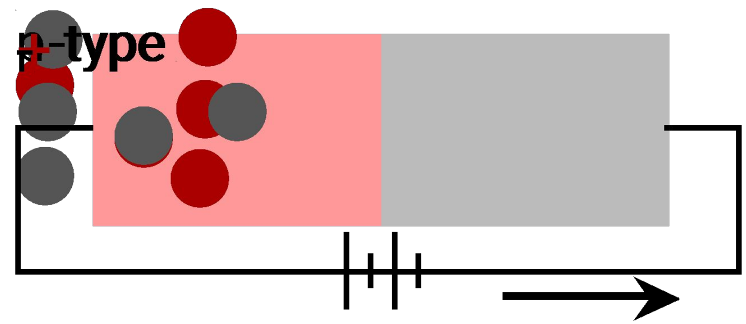
P-N RECTIFYING JUNCTION

- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.
- Processing: diffuse P into one side of a B-doped crystal.
- Results:

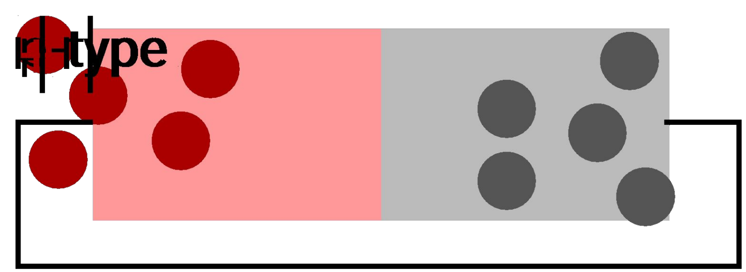
--No applied potential:
no net current flow.



--Forward bias: carrier
flow through p-type and
n-type regions; holes and
electrons recombine at
p-n junction; current
flows.



--Reverse bias: carrier
flow away from p-n junction;
carrier conc. greatly
reduced
at junction; little current
flow.



SUMMARY

- Electrical conductivity and resistivity are:
  - --material parameters.
  - --geometry independent.
- Electrical resistance is:
  - --a geometry and material dependent parameter.
- Conductors, semiconductors, and insulators...
  - --different in whether there are accessible energy states for conductance electrons.
- For metals, conductivity is increased by
  - --reducing deformation
  - --reducing imperfections
  - --decreasing temperature.
- For pure semiconductors, conductivity is increased by
  - --increasing temperature
  - --doping (e.g., adding B to Si (p-type) or P to Si (n-type).

ANNOUNCEMENTS

Reading:

Core
Problems:

Self-help
Problems: