Chemical Engineering 378

Science of Materials Engineering

Lecture 34

Electrical Properties

Spiritual Thought

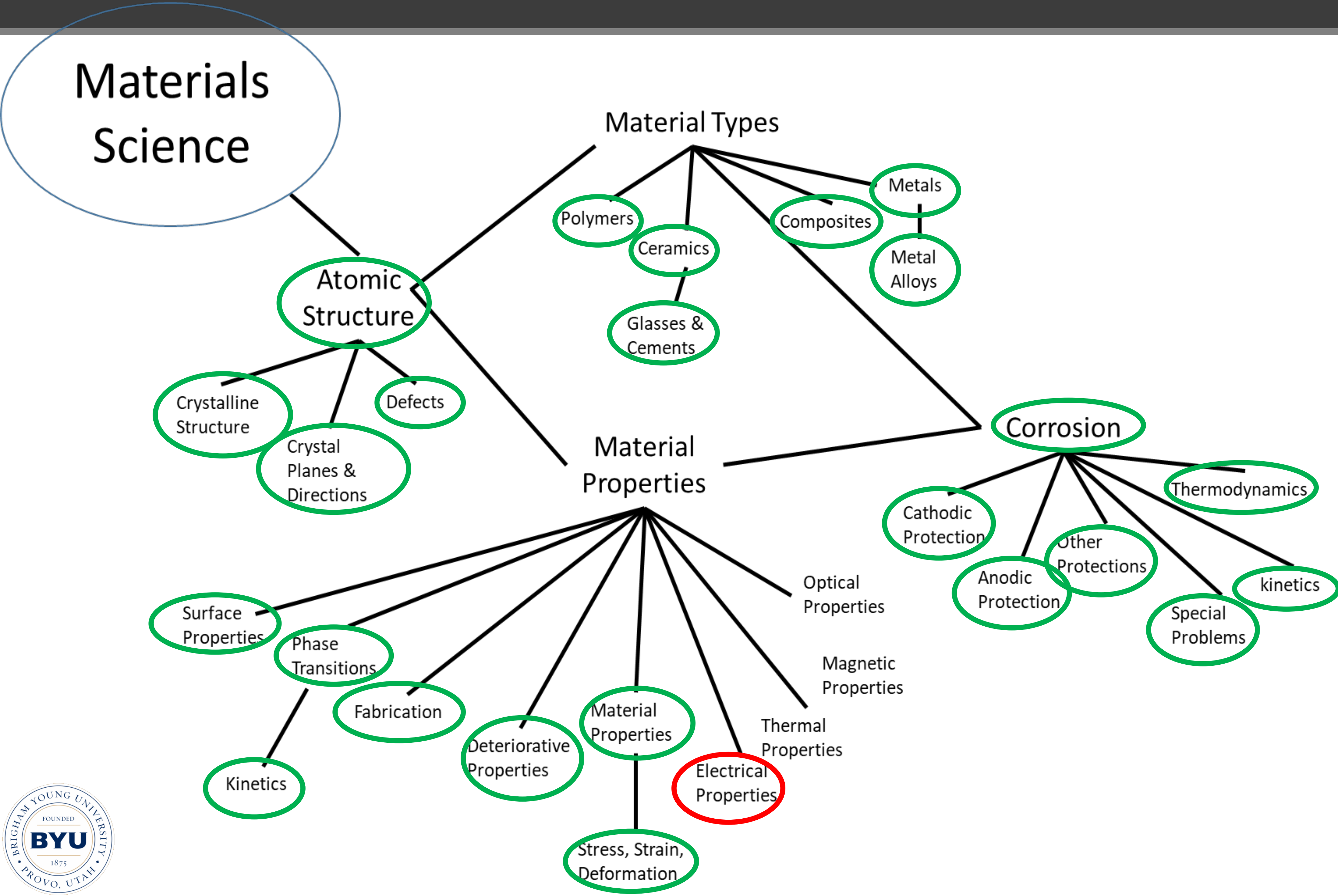
“If you have not chosen the Kingdom of God first, it will in the end make no difference what you have chosen instead.”

-William Law

“This power that he had sought with such a singular focus, Midas realized, was not a blessing, but a curse. This ancient fable could not be more relevant for us in this day, when the media, academia and the Internet promote a “Midas mindset” that “discounts the importance of marriage” and suggests that fulfillment ‘is to be found in a rewarding career, in money, in freedom from the encumbrances of family life.’”

-W. Brad Wilcox

Materials Roadmap



Materials Science

Atomic Structure

Material Types

Polymers

Ceramics

Glasses & Cements

Composites

Metals

Metal Alloys

Crystalline Structure

Defects

Crystal Planes & Directions

Material Properties

Corrosion

Thermodynamics

Cathodic Protection

Other Protections

Anodic Protection

kinetics

Special Problems

Optical Properties

Magnetic Properties

Thermal Properties

Surface Properties

Phase Transitions

Fabrication

Kinetics

Deteriorative Properties

Material Properties

Electrical Properties

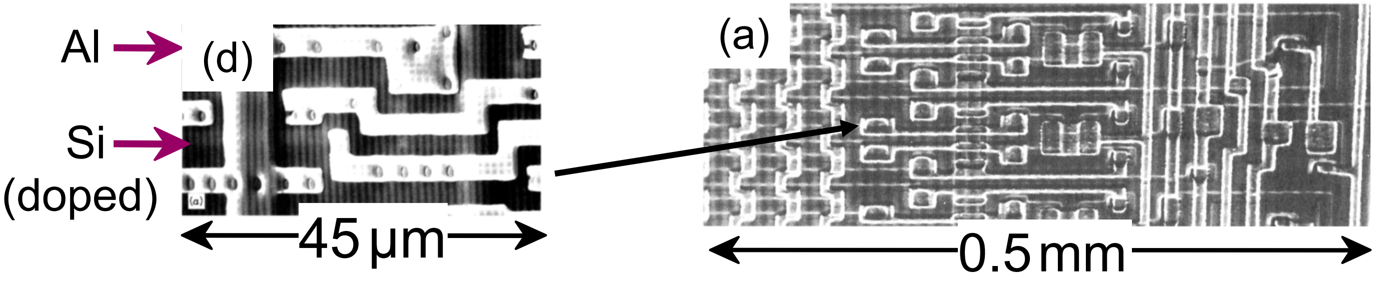
Stress, Strain, Deformation

Big Picture

- Electricity Equations/concepts
- Types of electrical materials
  - Conductors
  - Insulators
  - Semiconductors
- Semiconductor Behavior/Theory
- The “Why” behind each type (band gaps)
- Understand junction behaviors

View of an Integrated Circuit

- Scanning electron micrographs 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.

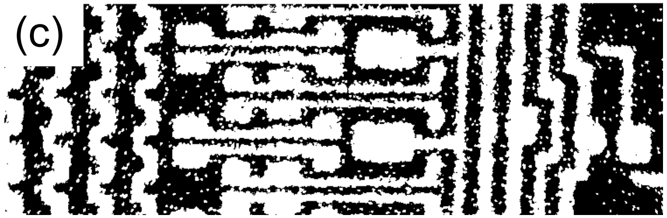


Fig. (d) from Fig. 12.27 (a), *Callister & Rethwisch 3e.* (Courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Figs. (a), (b), (c) from Fig. 18.26, *Callister & Rethwisch 10e.*

Electrical Conduction

- Ohm's Law:

$$V = I R$$

voltage drop (volts = J/C)
C = Coulomb

current (amps = C/s)

resistance (Ohms)

- Resistivity, ρ:
  -- a material property that is independent of sample size and geometry

$$\rho = \frac{RA}{\ell}$$

cross-sectional area of current flow

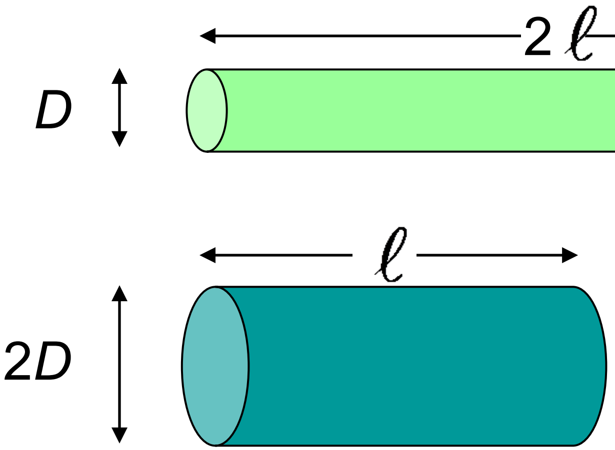
current flow path length

- Conductivity, σ

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

Electrical Properties

- Which will have the greater resistance?



$$R_1 = \frac{2\rho\ell}{\pi\left(\frac{D}{2}\right)^2} = \frac{8\rho\ell}{\pi D^2}$$

$$R_2 = \frac{\rho\ell}{\pi\left(\frac{2D}{2}\right)^2} = \frac{\rho\ell}{\pi D^2} = \frac{R_1}{8}$$

- Analogous to flow of water in a pipe
- Resistance depends on sample geometry and size.

Definitions

Further definitions

$\boxed{J = \sigma \mathcal{E}}$ <= another way to state Ohm’s law

$J \equiv$ current density $= \dfrac{\text{current}}{\text{surface area}} = \dfrac{I}{A}$ like a flux

$\mathcal{E} \equiv$ electric field potential $= V/\ell$

$$\underbrace{J}_{\text{Electron flux}} = \underbrace{\sigma}_{\text{conductivity}} (\underbrace{V/\ell}_{\text{voltage gradient}})$$

Conductivity: Comparison

- Room temperature values (Ohm-m)$^{-1}$ = (Ω - m)$^{-1}$

METALS	conductors
Silver	6.8×10^{7}
Copper	6.0×10^{7}
Iron	1.0×10^{7}

CERAMICS	
Soda-lime glass	10^{-10}-10^{-11}
Concrete	10^{-9}
Aluminum oxide	$<10^{-13}$

SEMICONDUCTORS	
Silicon	4×10^{-4}
Germanium	2×10^{0}
GaAs	10^{-6}

semiconductors

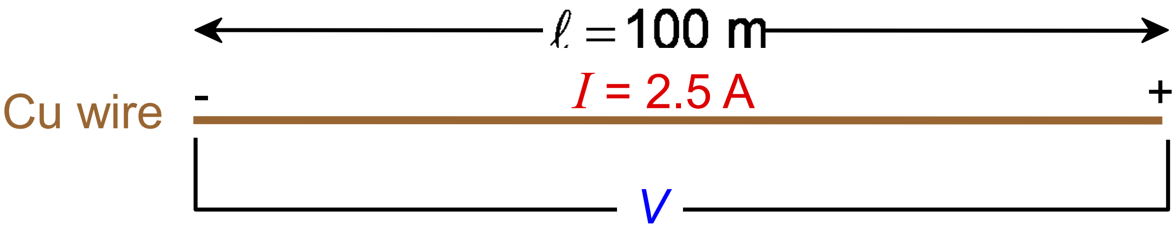
POLYMERS	
Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}-10^{-17}

insulators

Selected values from Tables 18.1, 18.3, and 18.4, *Callister & Rethwisch 10e.*

Example: Conductivity Problem

What is the minimum diameter (*D*) of the wire so that *V* < 1.5 V?



$\ell = 100$ m

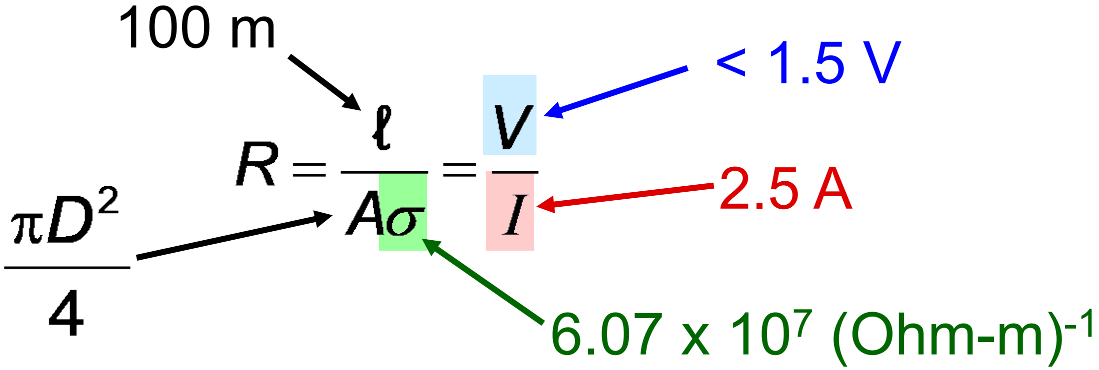
Cu wire

-

I = 2.5 A

+

V



$$R = \frac{\ell}{A\sigma} = \frac{V}{I}$$

100 m

$\frac{\pi D^2}{4}$

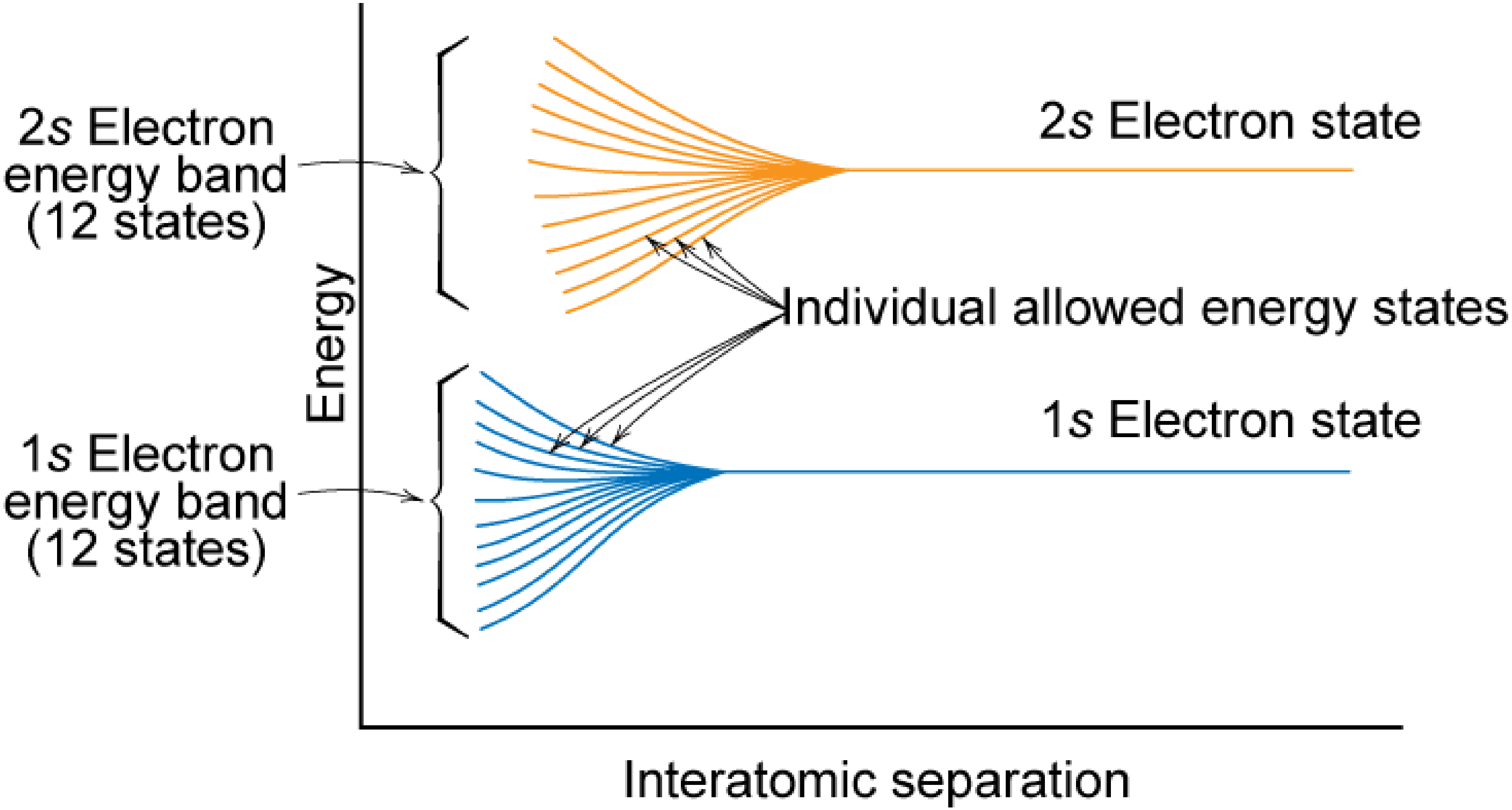
< 1.5 V

2.5 A

6.07 x 10^7 (Ohm-m)$^{-1}$

Solve to get *D* > 1.87 mm

Electron Energy Band Structures



Adapted from Fig. 18.2, *Callister & Rethwisch 10e.*

Band Structure Representation

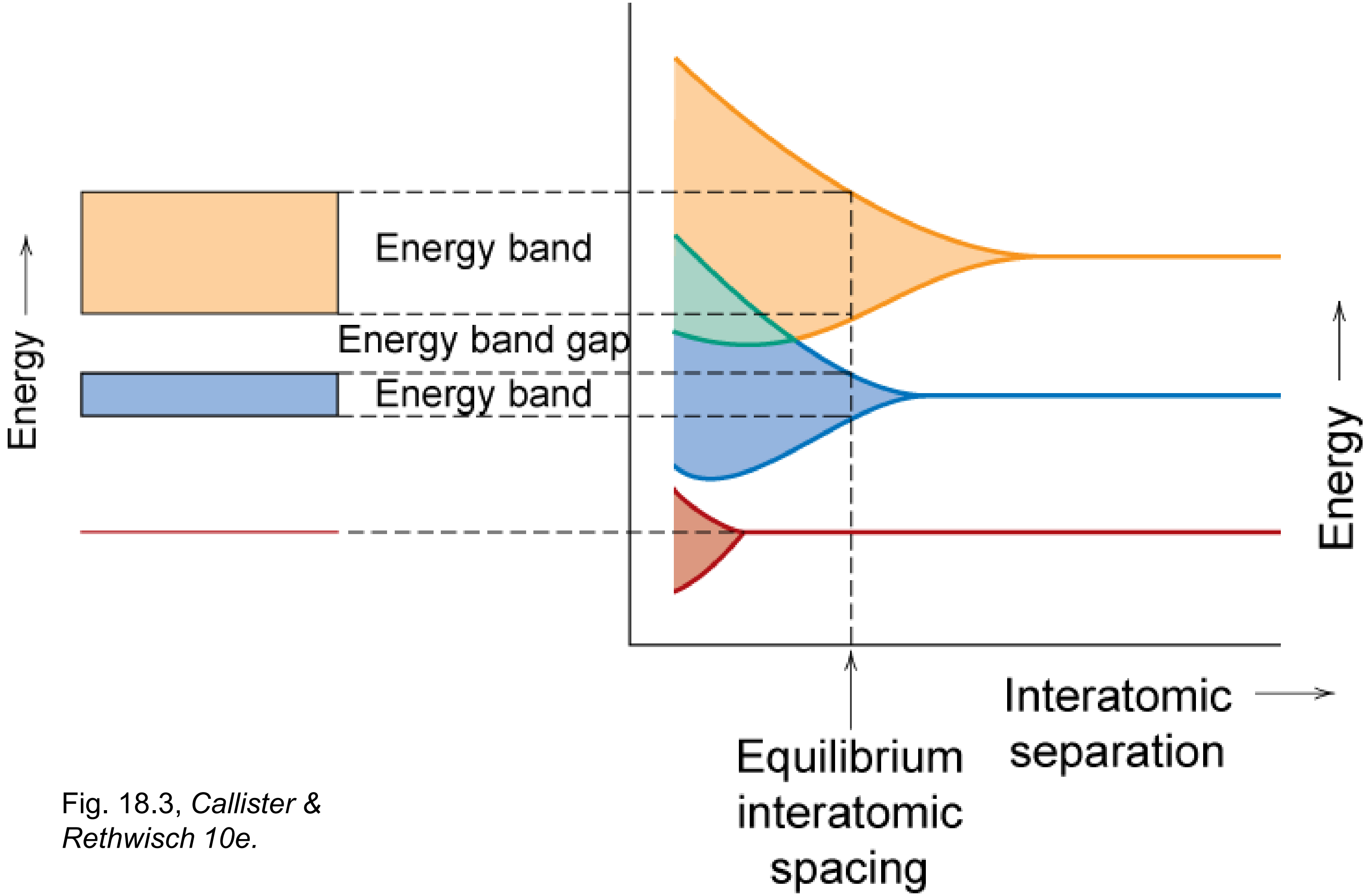


Fig. 18.3, *Callister & Rethwisch 10e.*

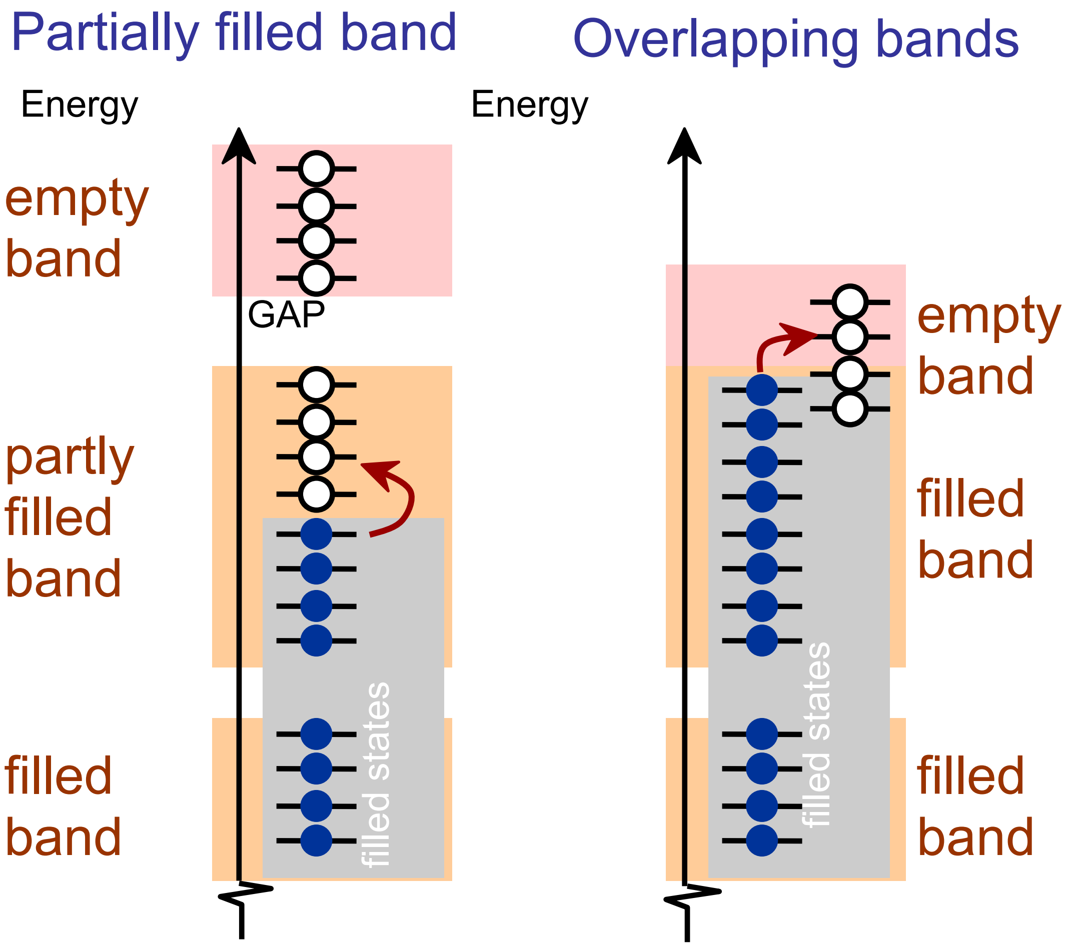
Conduction & Electron Transport

- Metals (Conductors):

-- for metals empty energy states are adjacent to filled states.

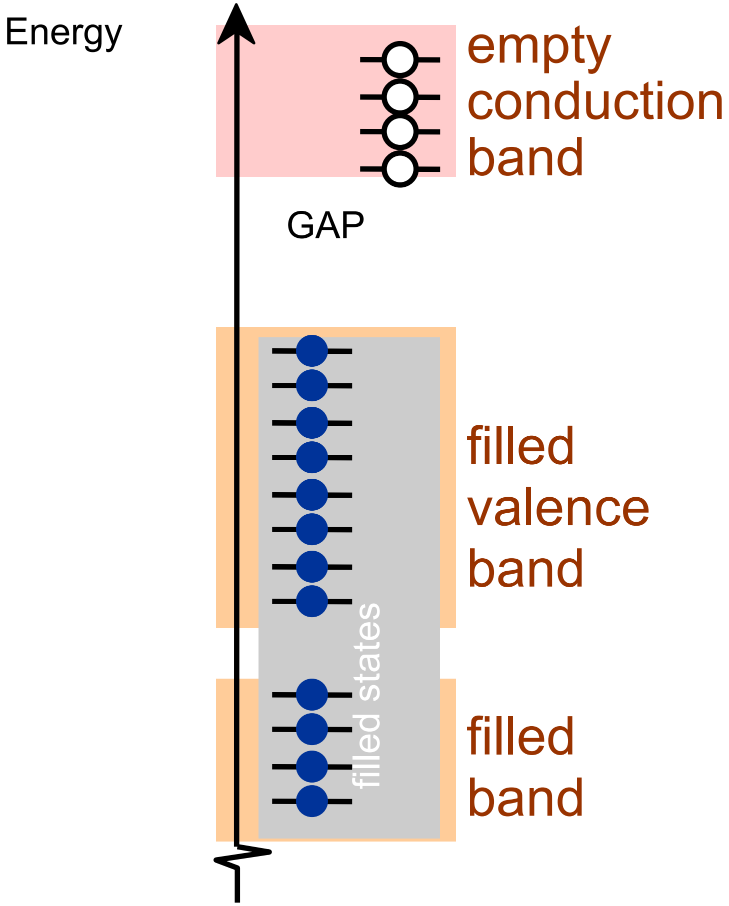
-- thermal energy excites electrons into empty higher energy states.

-- two types of band structures for metals
  - partially filled band
  - empty band that overlaps filled band



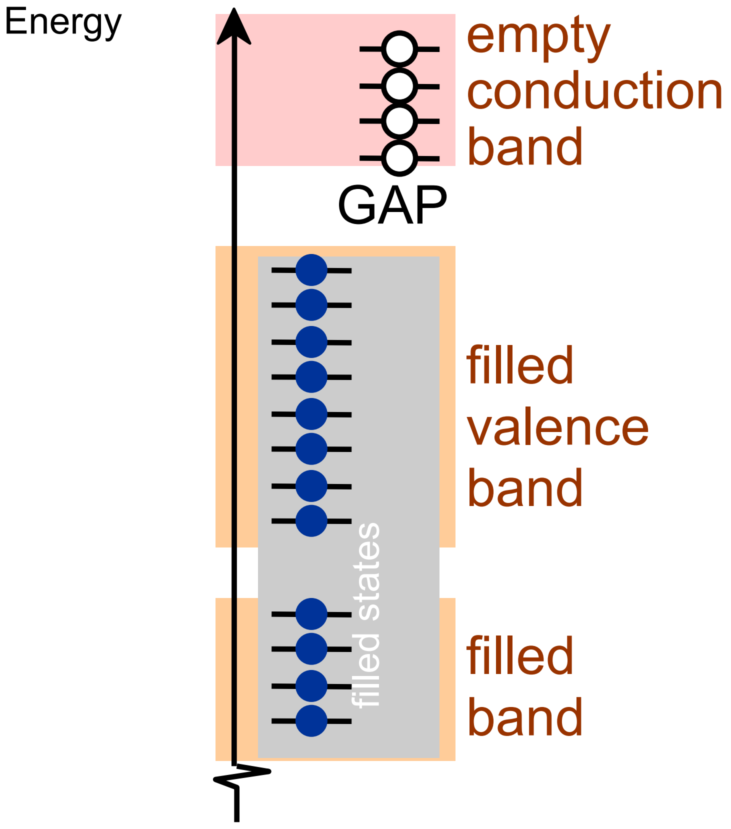
Energy Band Structures: Insulators

- Wide band gap (> 2 eV)
- Few electrons excited across band gap

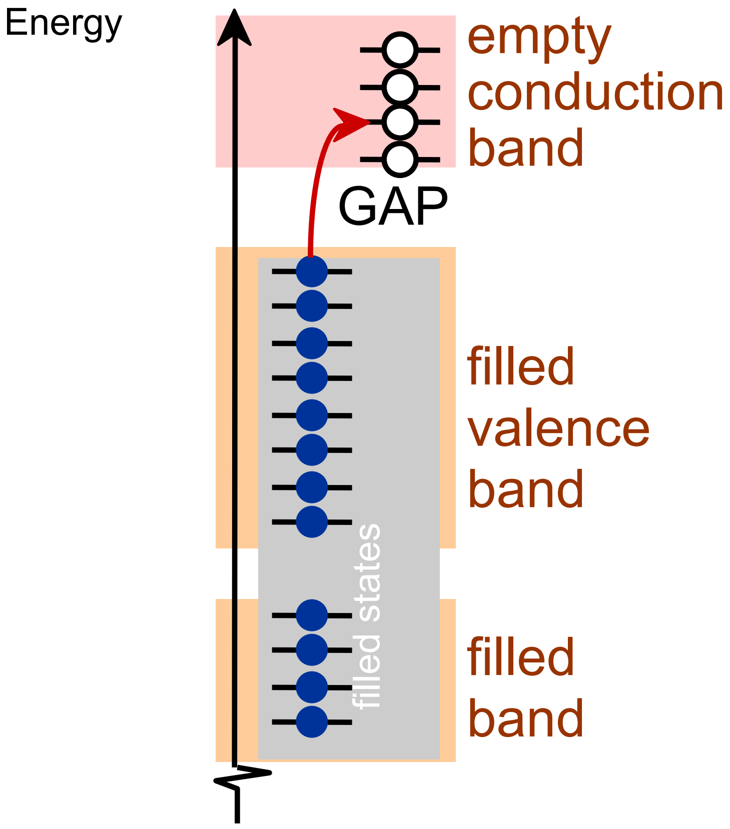


Energy Band Structures: Semiconductors

- Narrow band gap (< 2 eV)
- Electrons with enough energy excited across band gap



Low temperature
(low electron energy)



High temperature
(high electron energy)

Metals: Influence of Temperature and Impurities on Resistivity

- Presence of imperfections increases resistivity
  - -- grain boundaries
  - -- dislocations
  - -- impurity atoms
  - -- vacancies

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

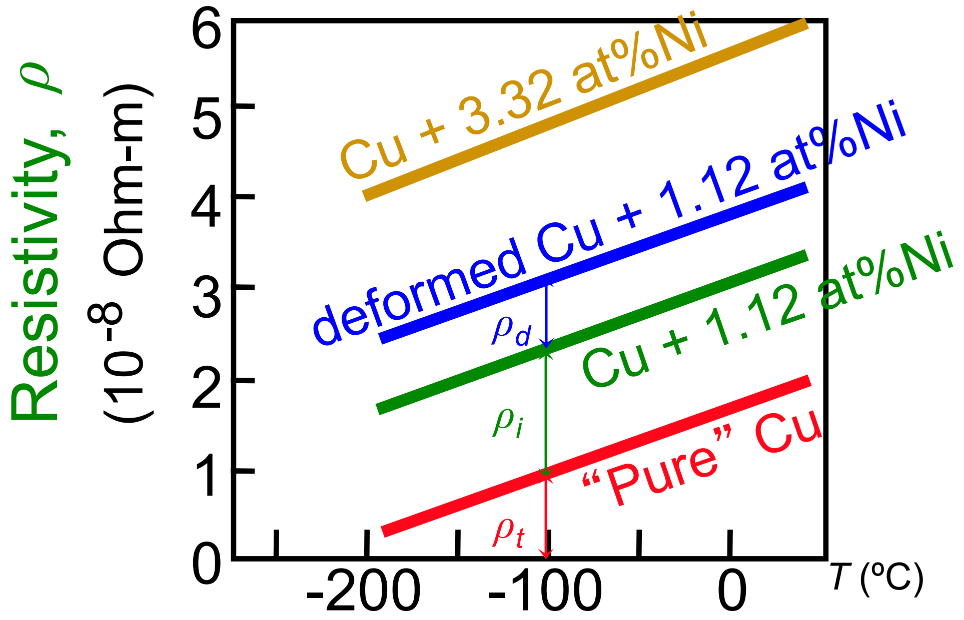


Fig. 18.8, *Callister & Rethwisch 10e.* (Based on data taken from J. O. Linde, *Ann. Physik*, 5, 1932, p. 219.)

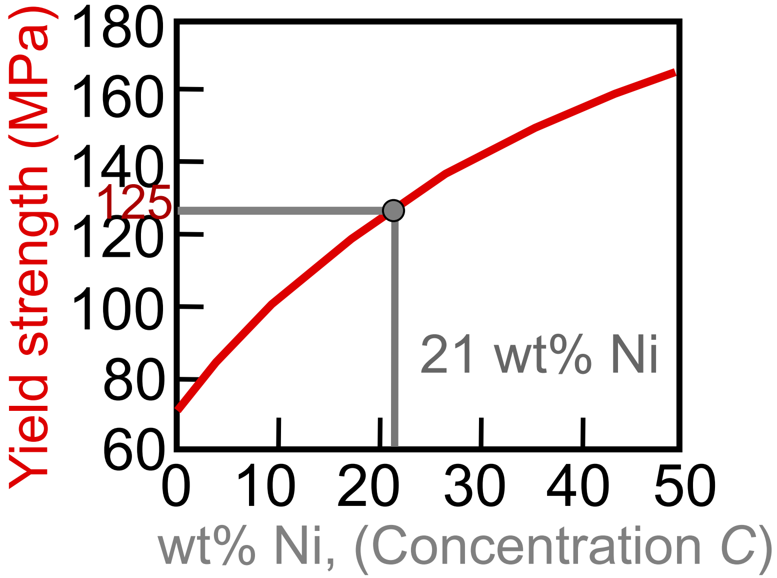
- Resistivity increases with:
  - -- temperature
  - -- wt% impurity
  - -- %*CW*

$$\rho = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{deformation}}$$

Estimating Conductivity

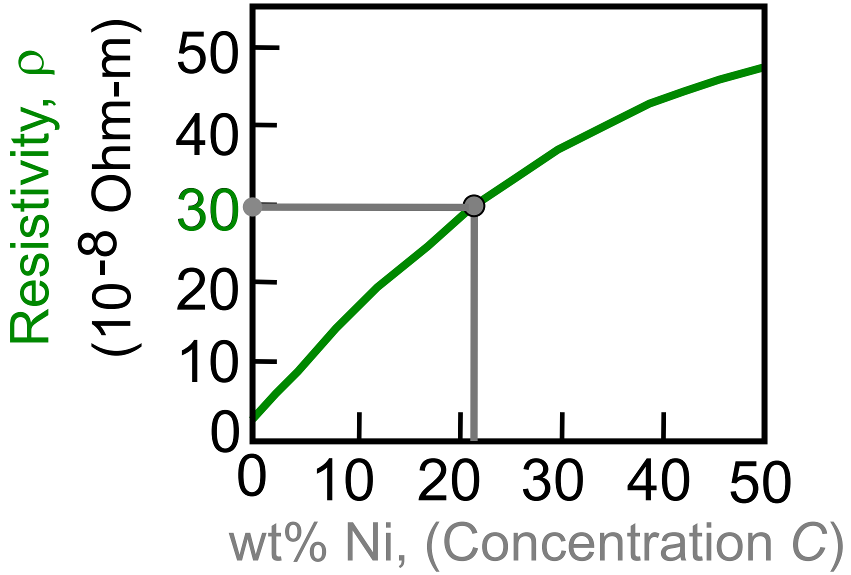
- Question:

-- Estimate the electrical conductivity σ of a Cu-Ni alloy that has a yield strength of 125 MPa.



Adapted from Fig. 7.16(b), *Callister & Rethwisch 10e.*

Adapted from Fig. 18.9, *Callister & Rethwisch 10e.*



From step 1:

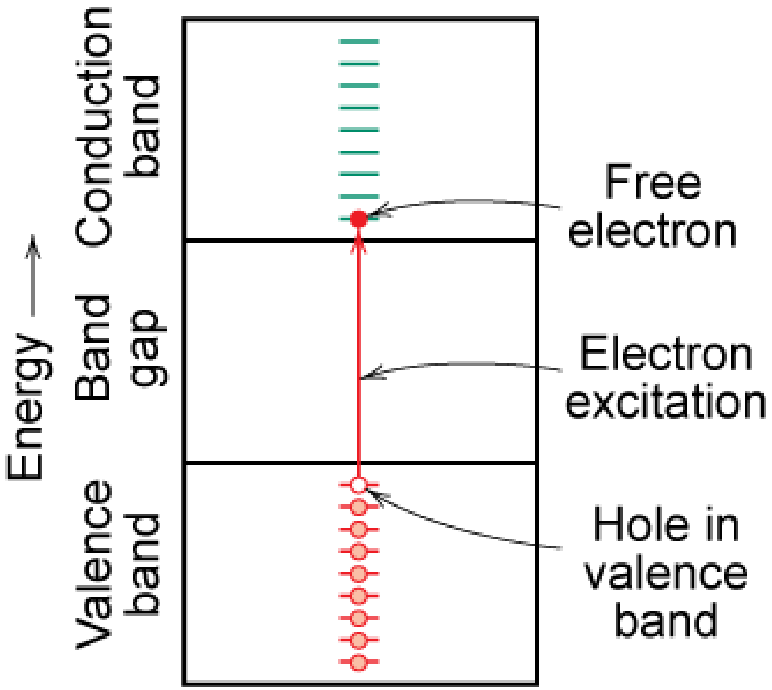
C_{Ni} = 21 wt% Ni

$$\rho = 30 \text{ x } 10^{-8} \text{ Ohm} - \text{m}$$

$$\sigma = \frac{1}{\rho} = 3.3 \text{ x } 10^{6} \text{ (Ohm} - \text{m)}^{-1}$$

Charge Carriers in Insulators and Semiconductors

Fig. 18.6 (b), *Callister & Rethwisch 10e.*



Two types of electronic charge carriers:

Free Electron

- negative charge
- in conduction band

Hole

- positive charge
- vacant electron state in the valence band

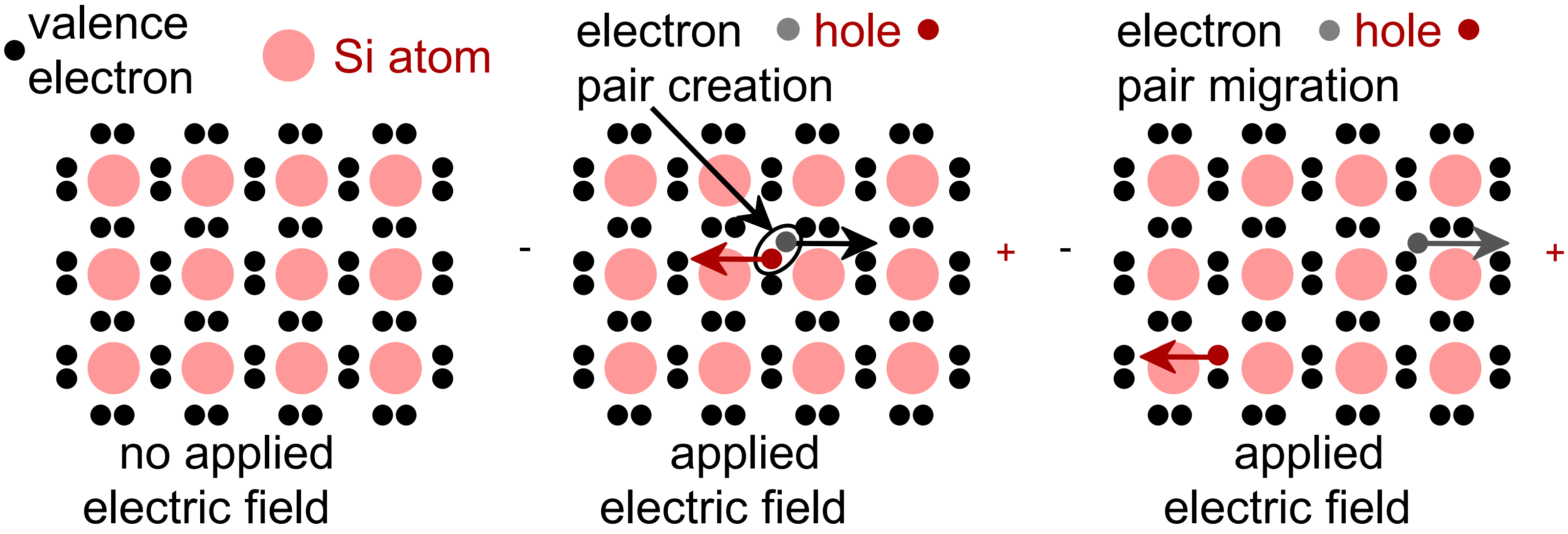
Move at different speeds - drift velocities

Intrinsic Semiconductors

- Pure material semiconductors: e.g., silicon & germanium
  - Group IVA materials
- Compound semiconductors
  - III-V compounds
    - Ex: GaAs & InSb
  - II-VI compounds
    - Ex: CdS & ZnTe
  - The wider the electronegativity difference between the elements the wider the energy gap.

Intrinsic Semiconduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



Adapted from Fig. 18.10, *Callister & Rethwisch 10e.*

- Electrical Conductivity given by:

holes/m^3

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

hole mobility

electrons/m^3

electron mobility

Number of Charge Carriers

Intrinsic Conductivity

$$\boxed{\sigma = n|e|\mu_e + p|e|\mu_h}$$

- for intrinsic semiconductor $n = p = n_i$

$$\therefore \qquad \sigma = n_i|e|(\mu_e + \mu_h)$$

- Ex: GaAs

$$n_i = \frac{\sigma}{|e|\left(\mu_e + \mu_h\right)} = \frac{10^{-6}(\Omega \cdot \mathrm{m})^{-1}}{(1.6 \times 10^{-19}\,\mathrm{C})(0.85 + 0.45\ \mathrm{m}^2/\mathrm{V}\cdot\mathrm{s})}$$

For GaAs $n_i = 4.8 \times 10^{24}\ \mathrm{m}^{-3}$

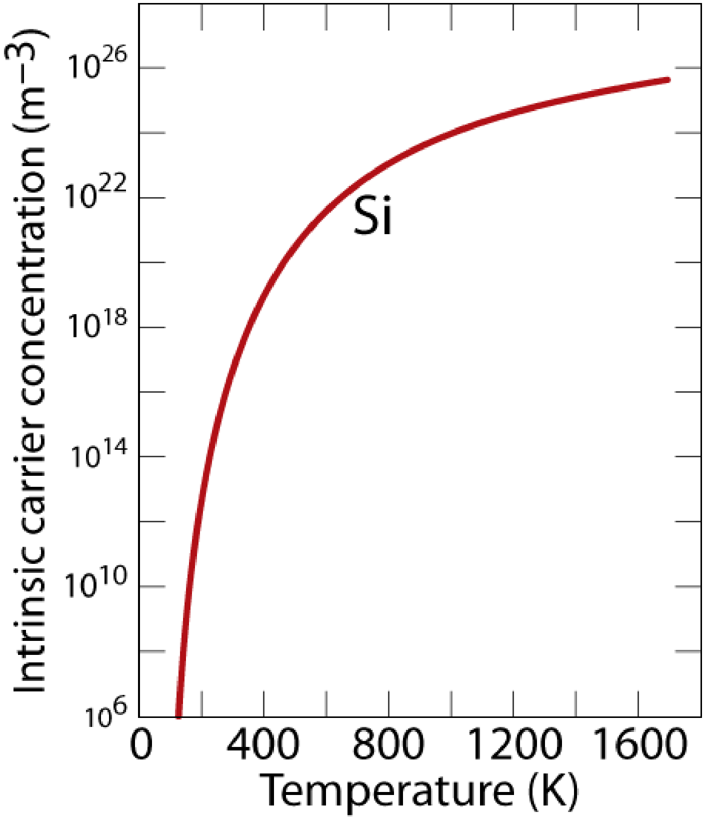
For Si $n_i = 1.3 \times 10^{16}\ \mathrm{m}^{-3}$

Intrinsic Semiconductors: Conductivity vs T

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

$$\sigma = n_i |e| (\mu_e + \mu_h)$$

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



Adapted from Fig. 18.15, *Callister & Rethwisch 10e.*

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

Selected values from Table 18.3, *Callister & Rethwisch 10e.*

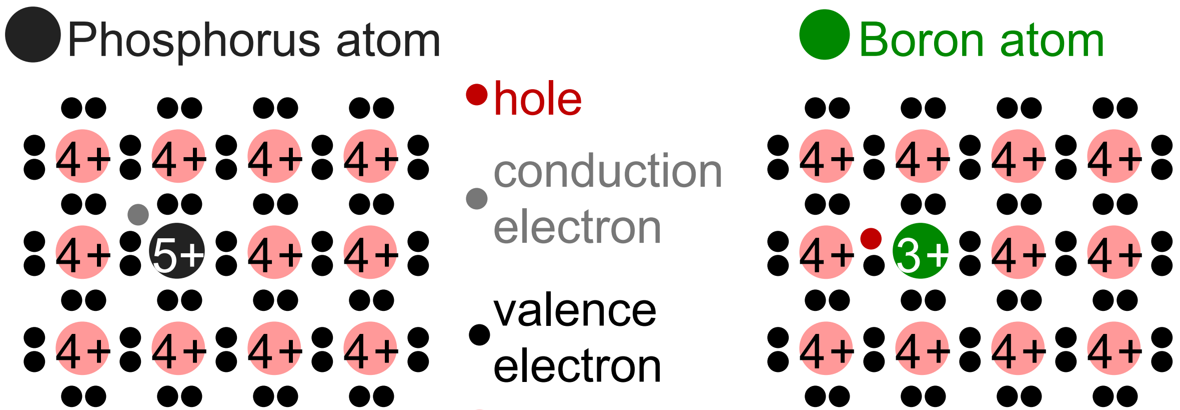
Intrinsic vs Extrinsic Conduction

- Intrinsic:
  -- case for pure Si
  -- # electrons = # holes ($n = p$)
- Extrinsic:
  -- electrical behavior is determined by presence of impurities that introduce excess electrons or holes
  -- $n \neq p$

- n-type Extrinsic: ($n >> p$)
- p-type Extrinsic: ($p >> n$)

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

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



no applied electric field

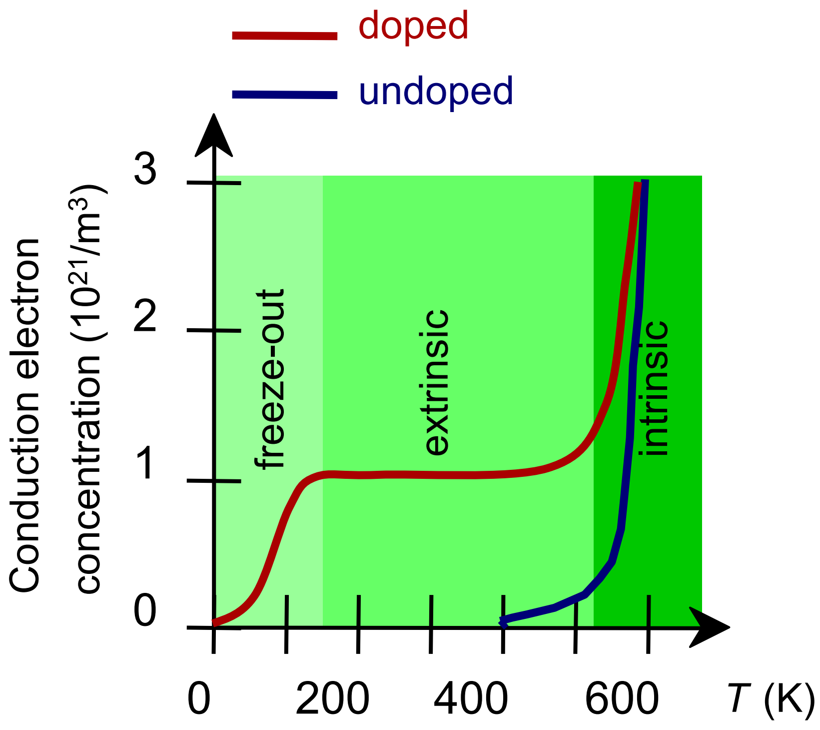
no applied electric field

Adapted from Figs. 18.11(a) & 18.13(a), *Callister & Rethwisch 10e.*

Extrinsic Semiconductors: Conductivity vs. Temperature

- Data for Doped Silicon:
  - -- σ increases with 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* < 100 K: "freeze-out", thermal energy insufficient to excite electrons.
  - -- for 150 K < *T* < 450 K: "extrinsic"
  - -- for *T* >> 450 K: "intrinsic"

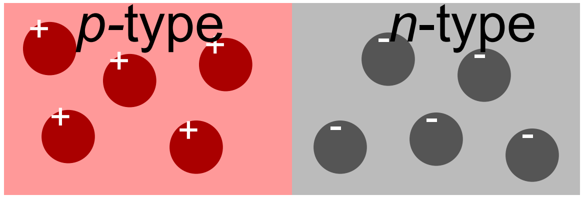


Adapted from Fig. 18.16, *Callister & Rethwisch 10e.* (From S. M. Sze, *Semiconductor Devices, Physics and Technology.* Copyright © 1985 by Bell Telephone Laboratories, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

p-n Rectifying Junction

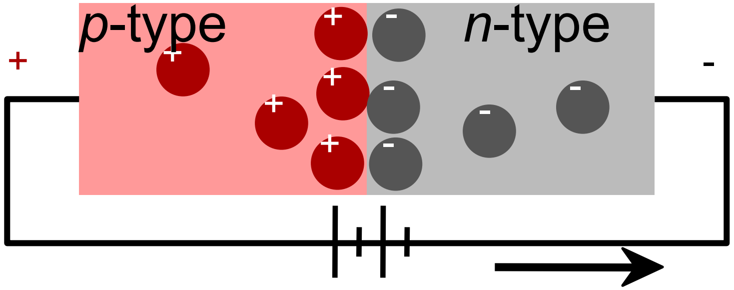
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current).
- Processing: diffuse P into one side of a B-doped crystal.

-- No applied potential: no net current flow.

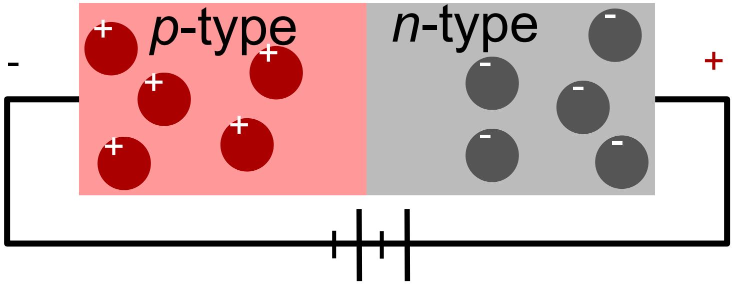


Adapted from Fig. 18.20, *Callister & Rethwisch 10e.*

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



-- Reverse bias: carriers flow away from *p-n* junction; junction region depleted of carriers; little current flow.



Properties of Rectifying Junction

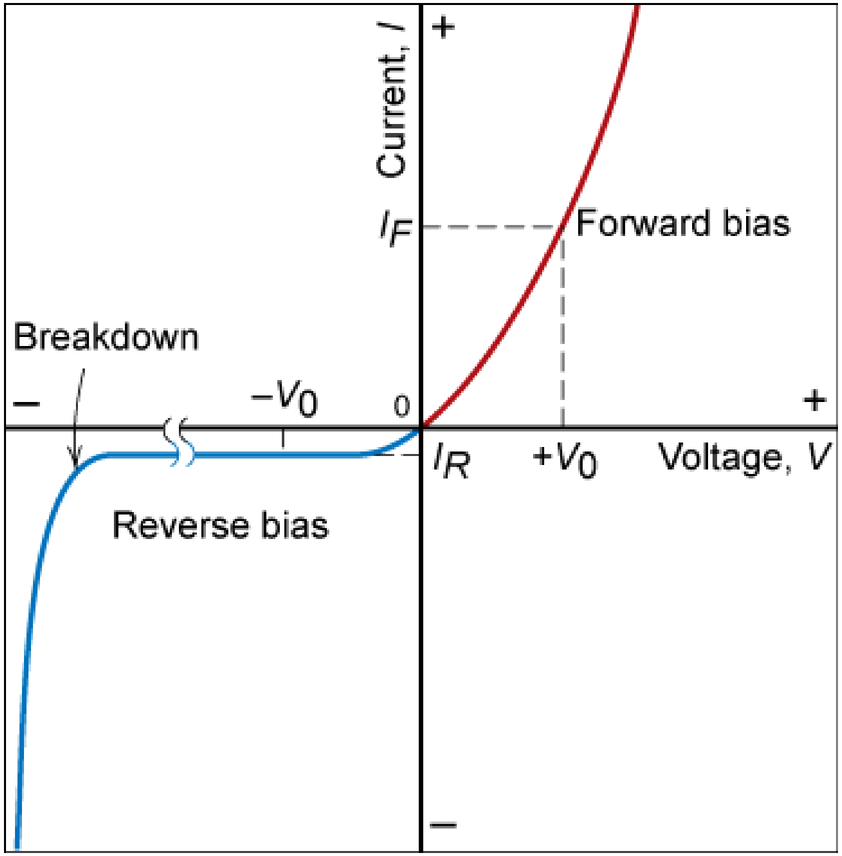


Fig. 18.21, *Callister & Rethwisch 10e.*

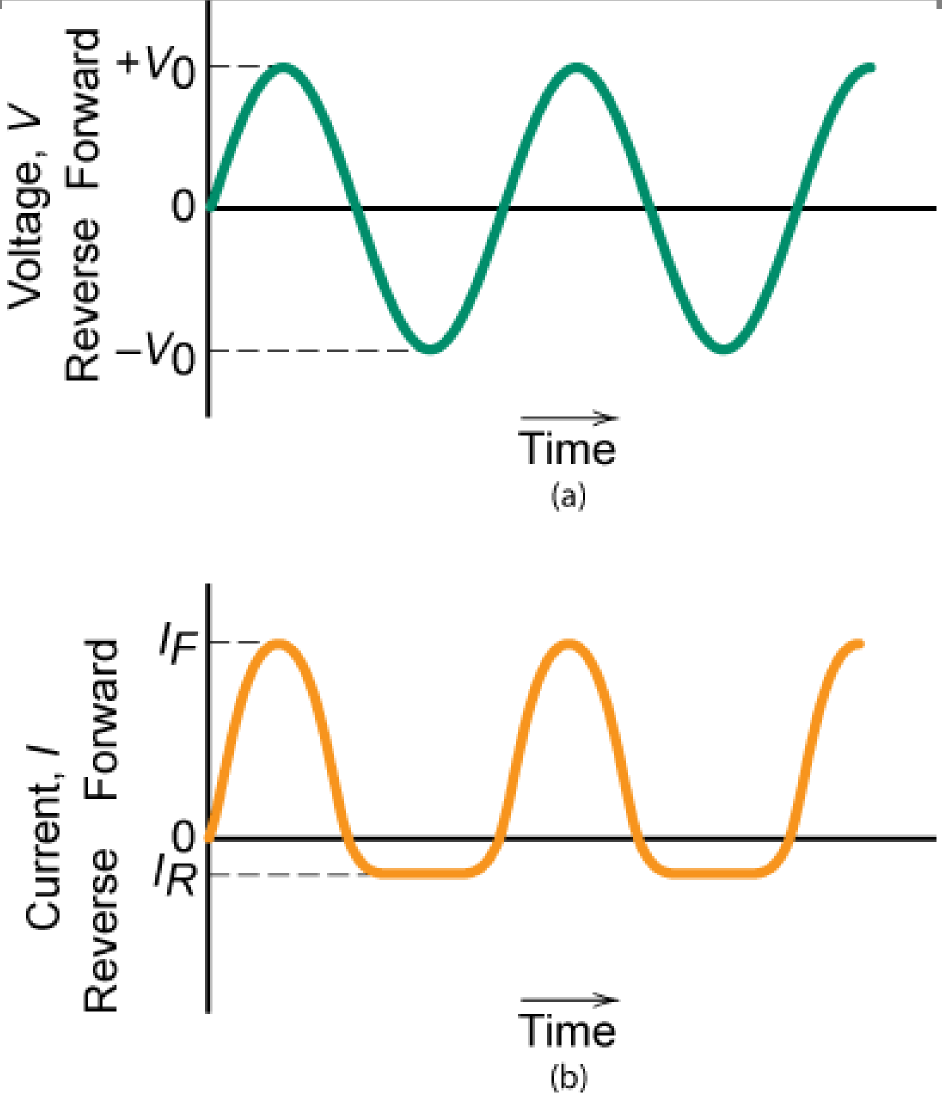


Fig. 18.22, *Callister & Rethwisch 10e.*

Junction Transistor

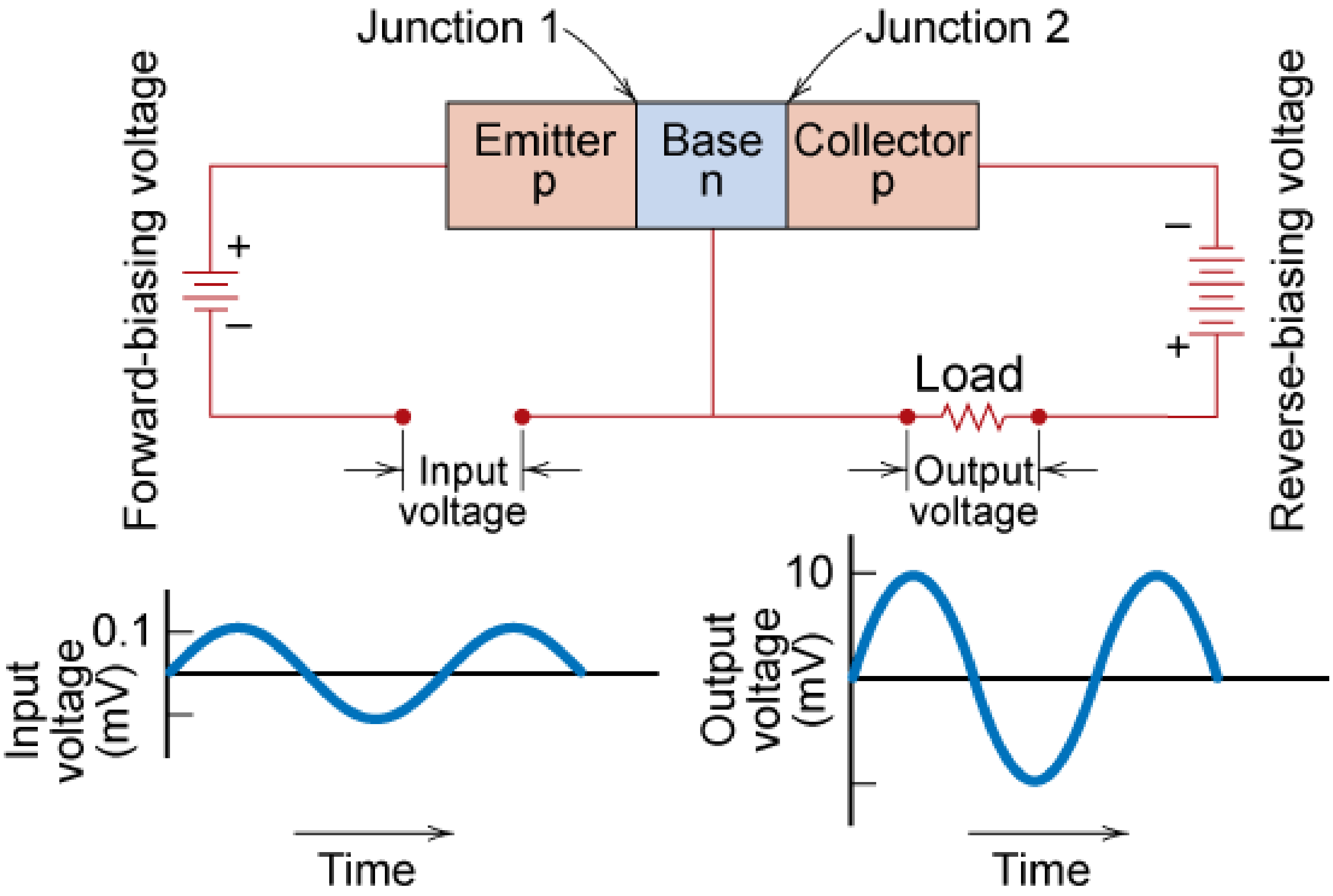


Fig. 18.23, *Callister & Rethwisch 10e.*

MOSFET Transistor Integrated Circuit Device

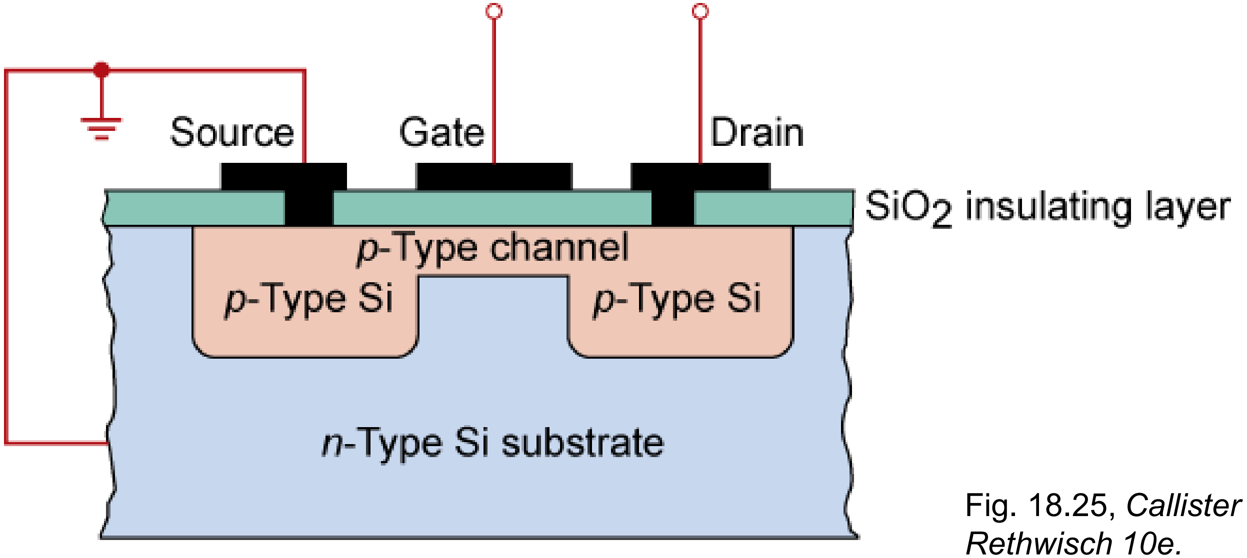


Fig. 18.25, *Callister & Rethwisch 10e.*

- MOSFET (metal oxide semiconductor field effect transistor)
- Integrated circuits - state of the art ca. 50 nm line width
  - ~ 1,000,000,000 components on chip
  - chips formed one layer at a time

Ferroelectric Ceramics

- Experience spontaneous polarization

$BaTiO_3$ -- ferroelectric below its Curie temperature (120° C)

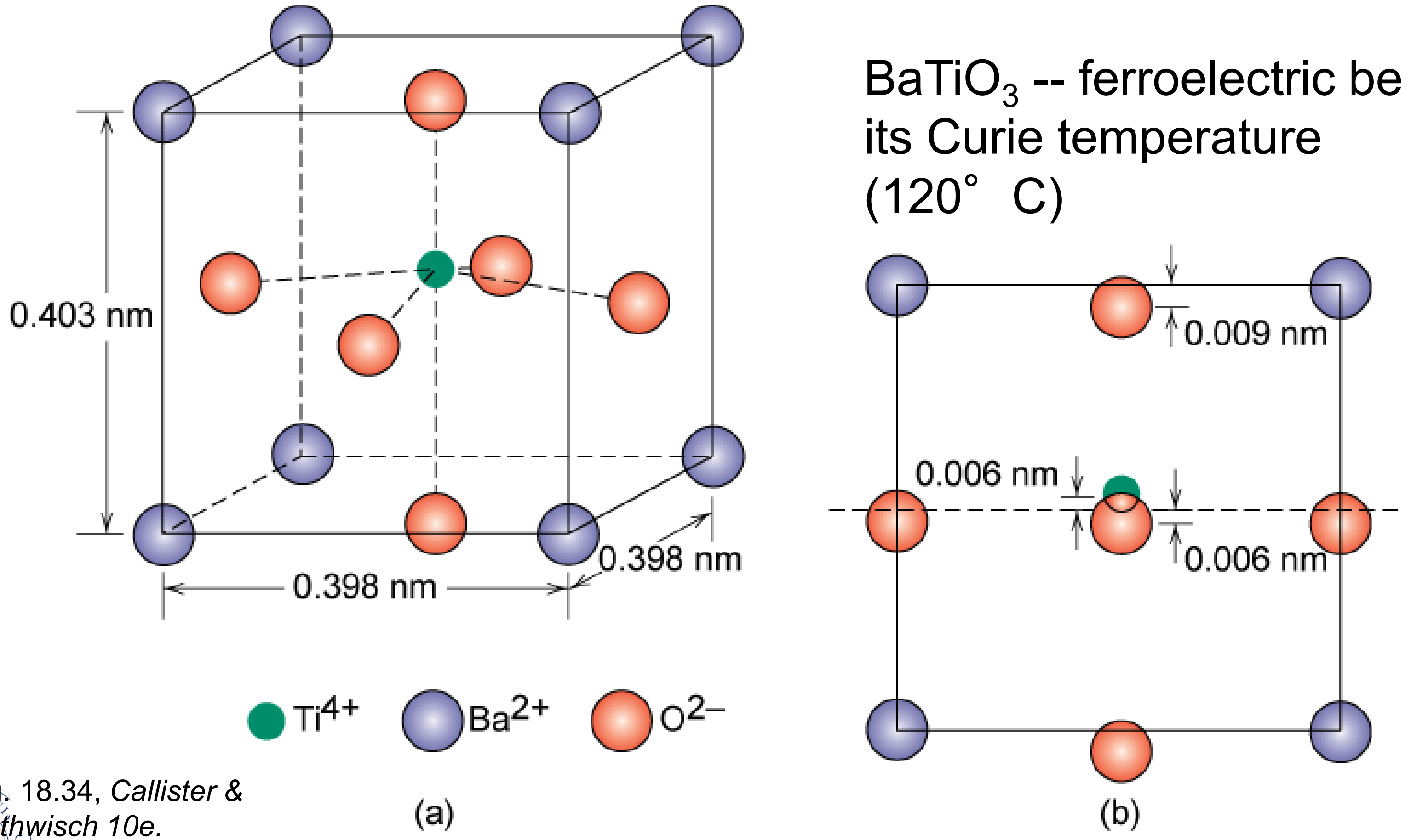
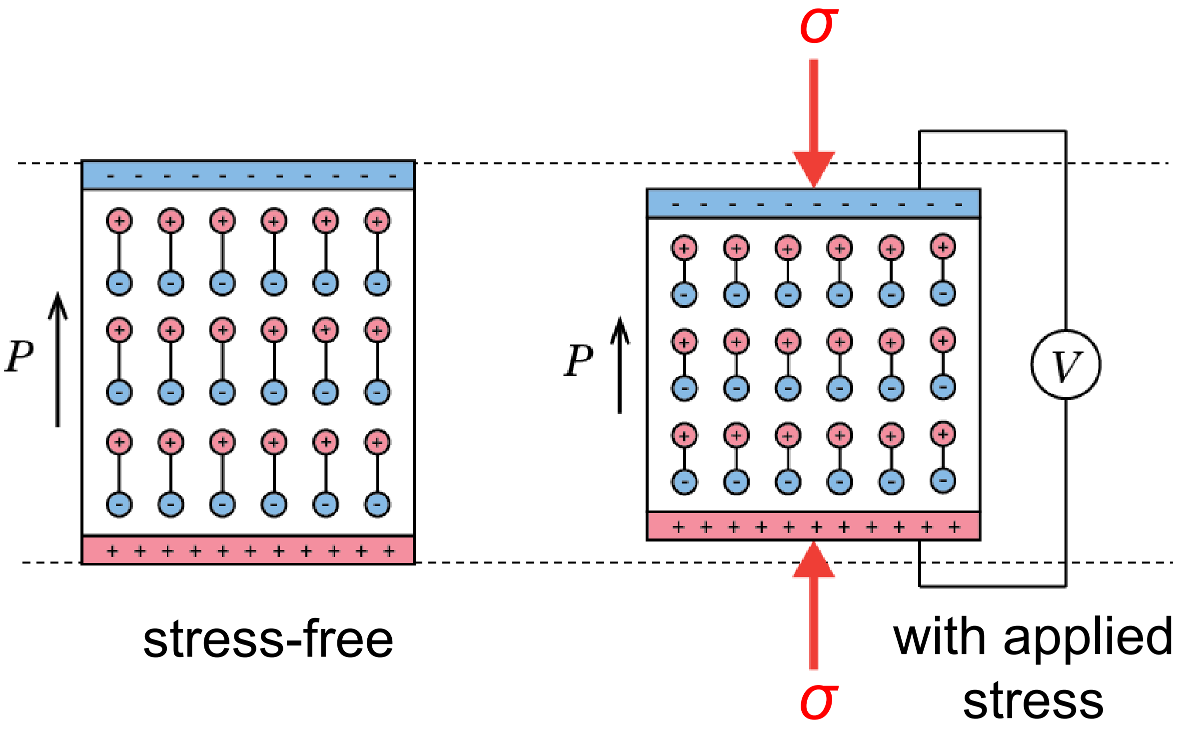


Fig. 18.34, *Callister & Rethwisch 10e.*

Piezoelectric Materials

Piezoelectricity

- application of stress induces voltage
- application of voltage induces dimensional change



Adapted from Fig. 18.35, *Callister & Rethwisch 10e.* (From L. H. Van Vlack, A Textbook of Materials Technology, Addison-Wesley, 1973. Reproduced with permission of the estate of Lawrence H. Van Vlack.)