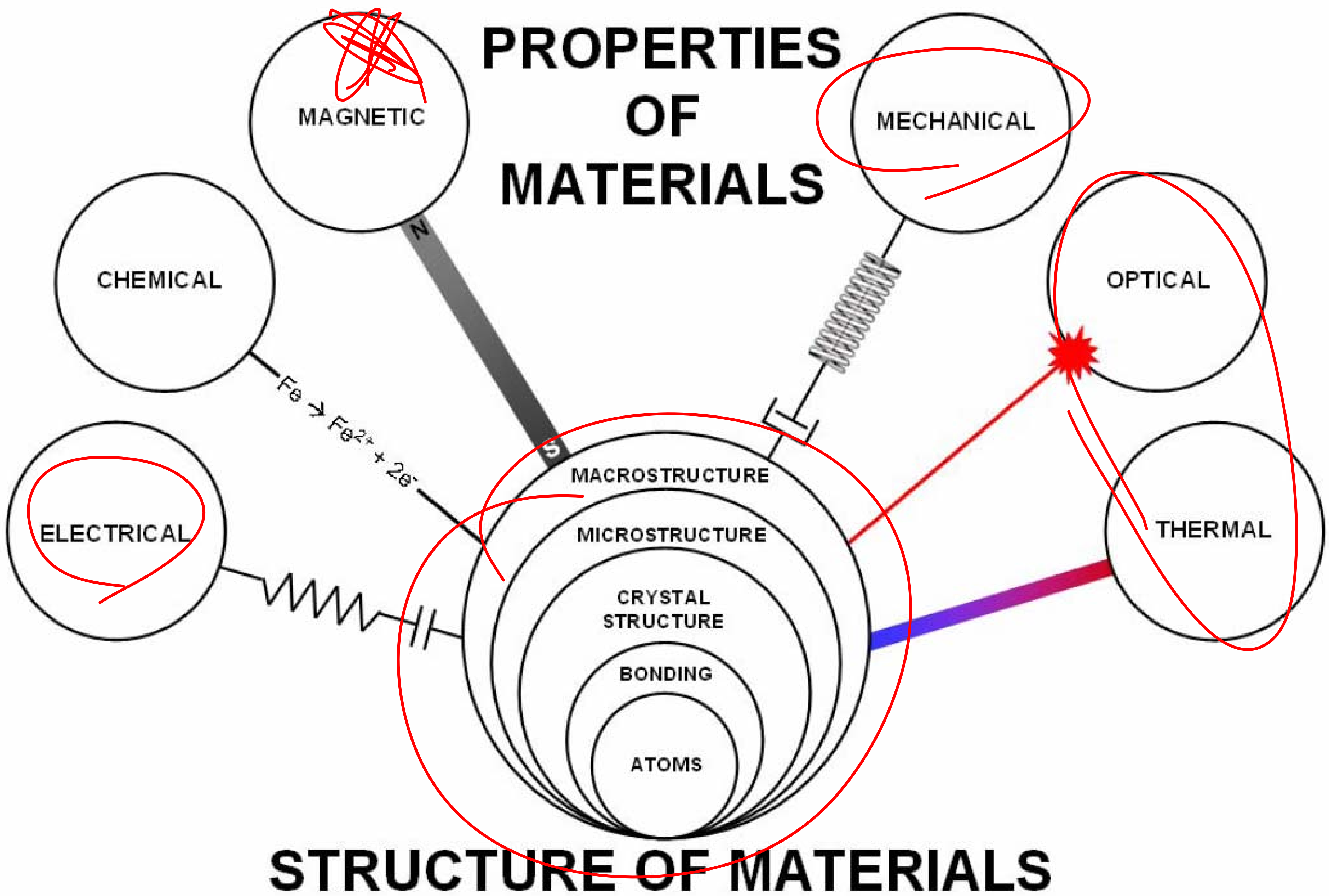


PROPERTIES
OF
MATERIALS
MAGNETIC
MECHANICAL
CHEMICAL
OPTICAL
ELECTRICAL
THERMAL
N
S
Fe → Fe2+ + 2e-
MACROSTRUCTURE
MICROSTRUCTURE
CRYSTAL
STRUCTURE
BONDING
ATOMS
STRUCTURE OF MATERIALS

28-02-07	Mechanical Properties I	6.1-6.12	NO QUIZ
05-03-07	Mechanical Properties II	6.1-6.12, 7.1-7.13	
07-03-07	Mechanical Properties III	7.1-7.13	WebCT Quiz
12-03-07	Mechanical Properties IV	8.1-8.15	
14-03-07	Mechanical Properties V	8.1-8.15	Tutorial Quizzes
19-03-07	Electrical Properties I	18.1-18.12	
21-03-07	Electrical Properties II	18.12-18.25	~~Tutorial Quizzes~~
26-03-07	***CANCELLED - Election Day***		
28-03-07	Ceramics, Plastics, Polymers		Tutorial Quizzes & WebCT Quiz
02-04-07	Thermal Properties	19.1-19.5 (Web)	
04-04-07	Optical Properties	21.1-21.14 (Web)	Tutorial Quizzes
09-04-07	***CANCELLED – Easter Monday***		
11-04-07	*Review of Properties*		

Chapter 18: Electrical Properties

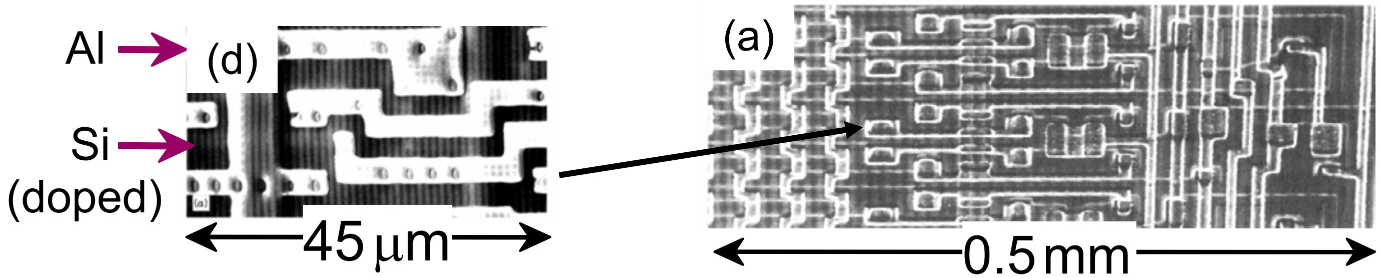
We will cover 18.1 – 18.13 and 18.15 – 18.23

TODAY

- 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.

insulators

Fig. (d) from Fig. 18.27 (a), *Callister 7e*. (Fig. 18.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Fig. (a), (b), (c) from Fig. 18.0, *Callister 7e*.

Electrical Conduction

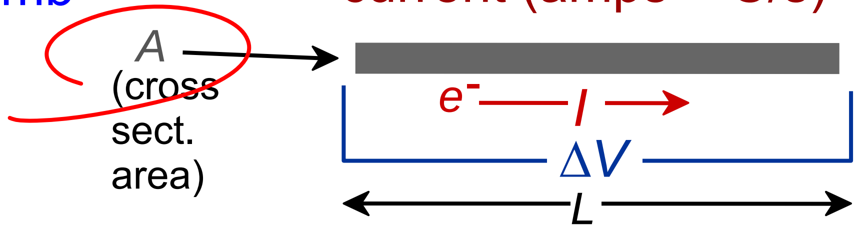
- Ohm's Law:

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

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

current (amps = C/s) → I

resistance (Ohms) → R



- Resistivity, ρ and Conductivity, σ:
  -- geometry-independent forms of Ohm's Law
  -- Resistivity is a material property & is independent of sample

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

E: electric field intensity → $\frac{\Delta V}{L}$

resistivity (Ohm-m) → ρ

J: current density → $\frac{I}{A}$

area

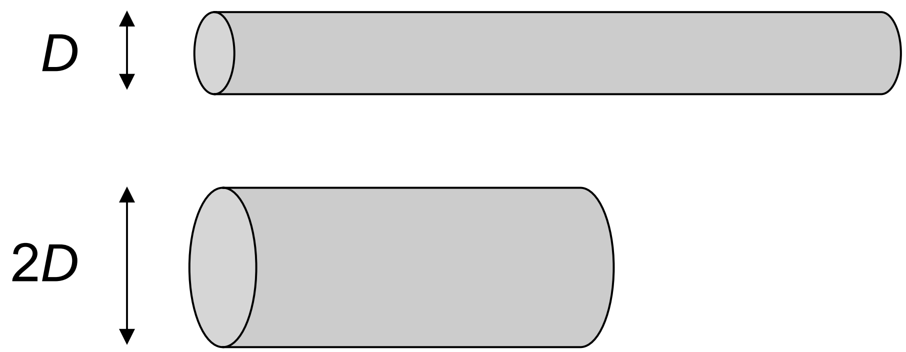
- Resistance:

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

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

Electrical Properties

- Which will conduct more electricity?



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

- Analogous to flow of water in a pipe
- So resistance depends on sample geometry, etc.

Definitions

Further definitions

$$\boxed{J = \sigma\,\varepsilon}$$ <= another way to state Ohm's law

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

$\varepsilon \equiv$ electric field potential $= V/\ell$ or $(\Delta V/\Delta\ell)$

$$J = \sigma\,(\Delta V/\Delta\ell)$$

Electron flux (J) conductivity (σ) voltage gradient ($\Delta V/\Delta\ell$)

<u>Current carriers</u>

- electrons in most solids
- ions can also carry (particularly in liquid solutions)

Conductivity: Comparison

- Room *T* values $(\text{Ohm-m})^{-1} = (\Omega - \text{m})^{-1}$

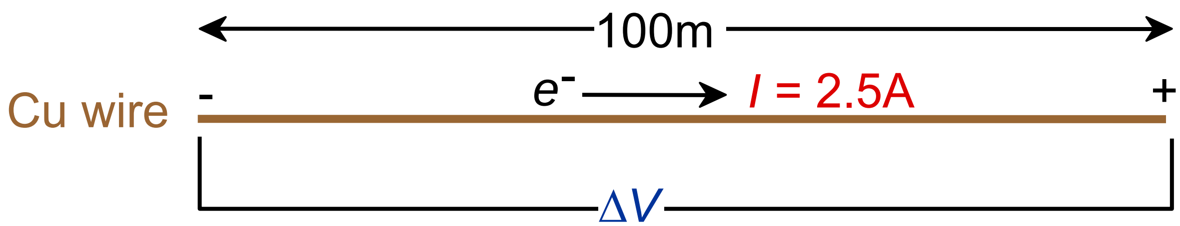
METALS	conductors	CERAMICS	
Silver	6.8×10^{7}	Soda-lime glass	10^{-10}-10^{-11}
Copper	6.0×10^{7}	Concrete	10^{-9}
Iron	1.0×10^{7}	Aluminum oxide	$<10^{-13}$

SEMICONDUCTORS		POLYMERS	
Silicon	4×10^{-4}	Polystyrene	$<10^{-14}$
Germanium	2×10^{0}	Polyethylene	10^{-15}-10^{-17}
GaAs	10^{-6}		
	semiconductors		insulators

Selected values from Tables 18.1, 18.3, and 18.4, *Callister 7e*.

Example: Conductivity Problem

What is the minimum diameter (D) of a Cu wire so that $\Delta V < 1.5$ V?



$$R = \frac{L}{A\sigma} = \frac{\Delta V}{I}$$

- L = 100m
- $A = \frac{\pi D^2}{4}$
- σ = 6.07×10^7 (Ohm-m)$^{-1}$
- ΔV < 1.5V
- I = 2.5A

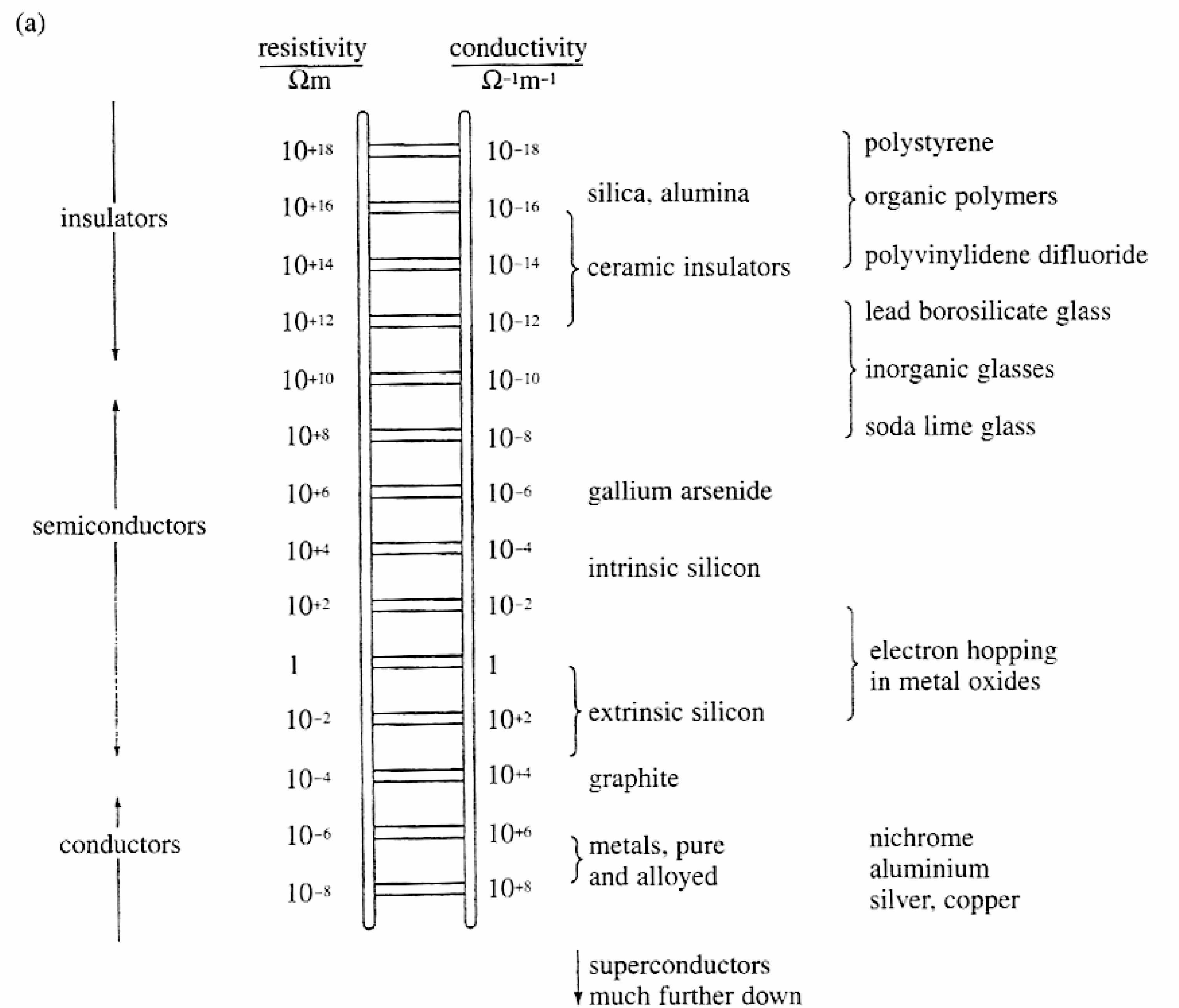
Solve to get $D > 1.87$ mm

Callister 18.17

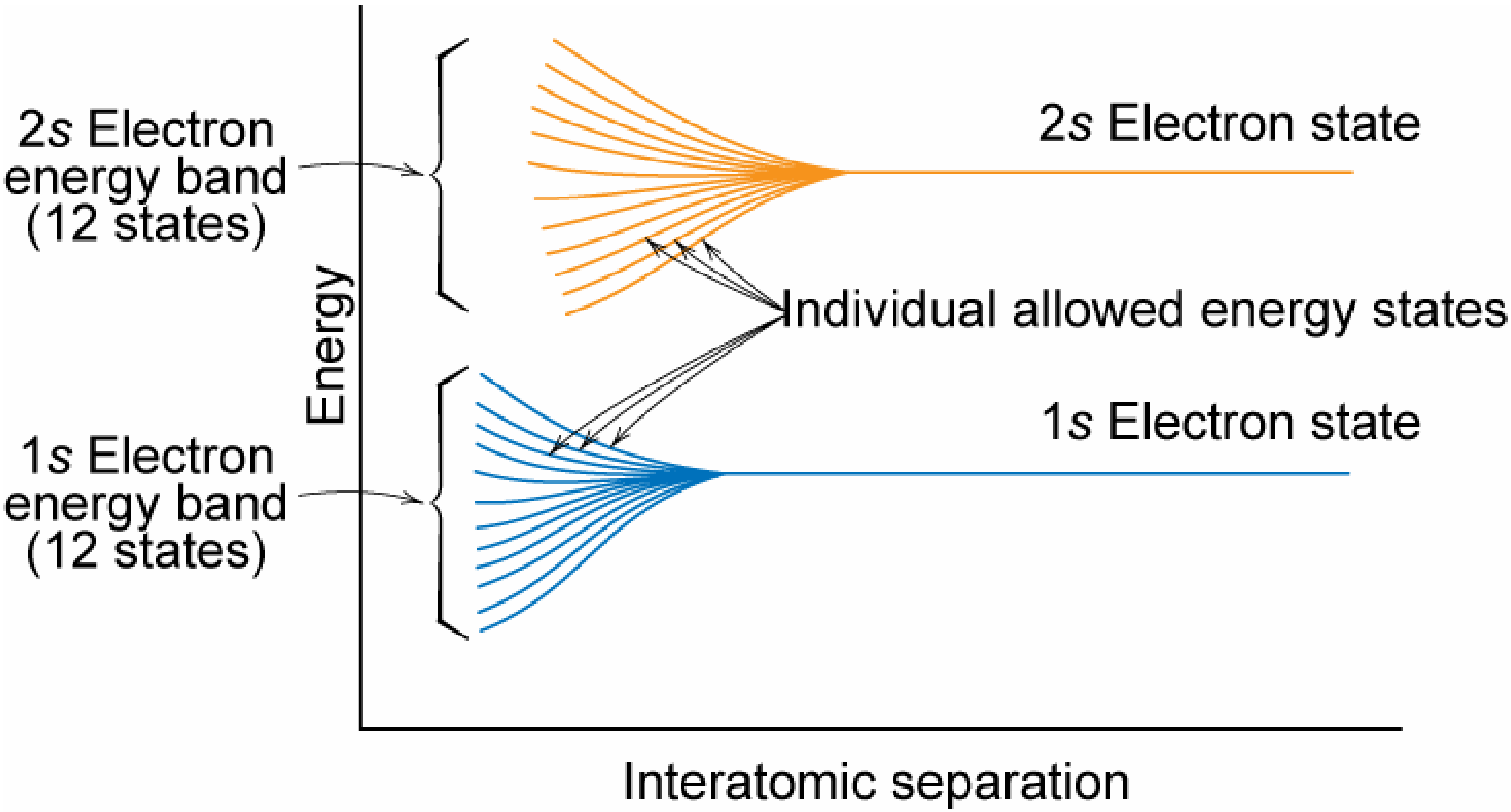
- **A cylindrical metal wire 3 mm in diameter is required to carry a current of 12 A with a minimum of 0.01 V drop per foot (300 mm) of wire. Which of the metals and alloys listed in Table 18.1 are possible candidates?**

Table 18.1 Room-Temperature Electrical Conductivities for Nine Common Metals and Alloys

Metal	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$
Silver	6.8×10^7
Copper	6.0×10^7
Gold	4.3×10^7
Aluminum	3.8×10^7
Brass (70Cu–30Zn)	1.6×10^7
Iron	1.0×10^7
Platinum	0.94×10^7
Plain carbon steel	0.6×10^7
Stainless steel	0.2×10^7


(a)
resistivity Ωm
conductivity Ω-1m-1
insulators
semiconductors
conductors
10+18
10+16
10+14
10+12
10+10
10+8
10+6
10+4
10+2
1
10-2
10-4
10-6
10-8
10-18
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
10+2
10+4
10+6
10+8
silica, alumina
ceramic insulators
gallium arsenide
intrinsic silicon
extrinsic silicon
graphite
metals, pure
and alloyed
superconductors
much further down
polystyrene
organic polymers
polyvinylidene difluoride
lead borosilicate glass
inorganic glasses
soda lime glass
electron hopping
in metal oxides
nichrome
aluminium
silver, copper

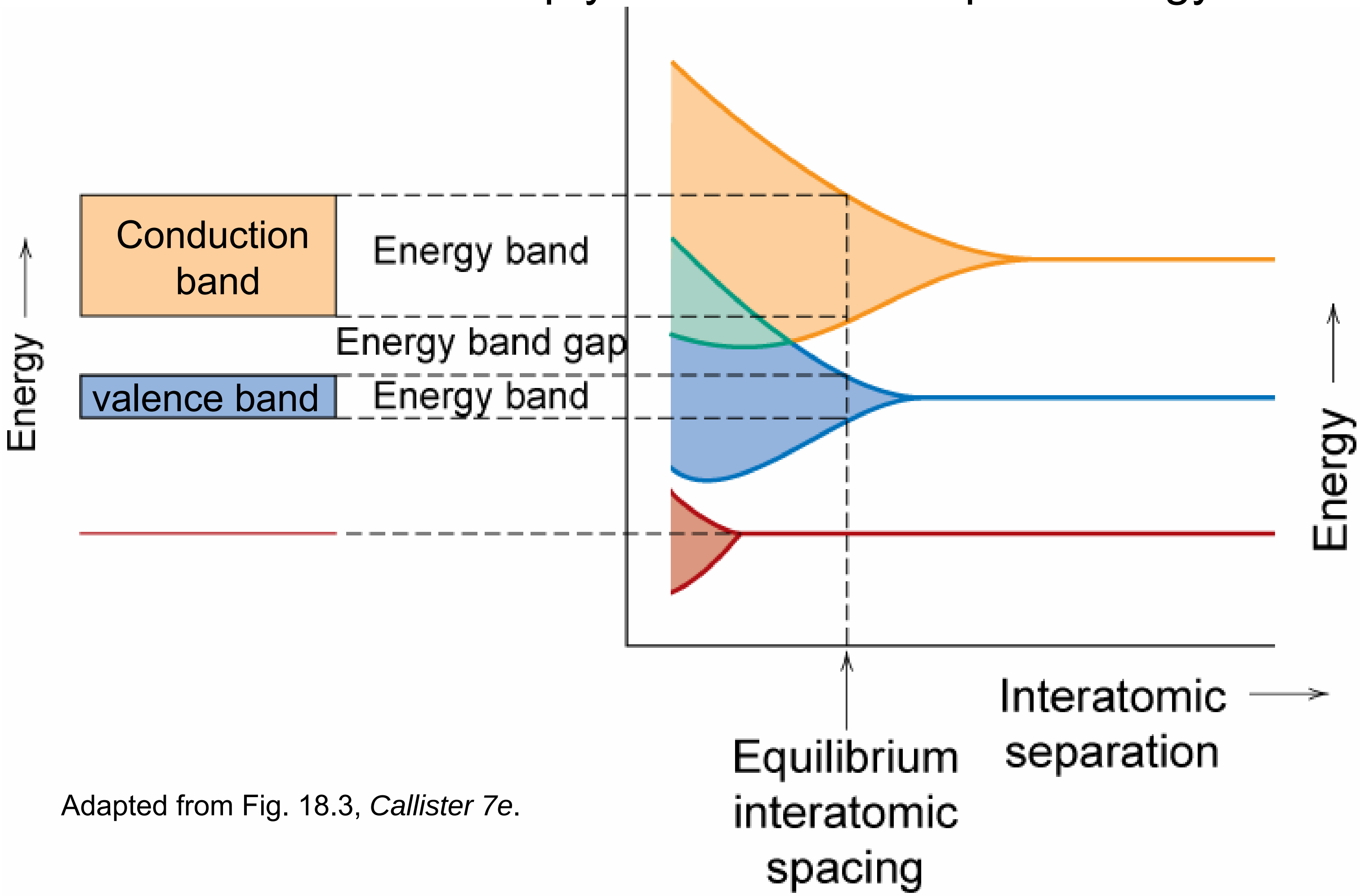
Electronic Band Structures



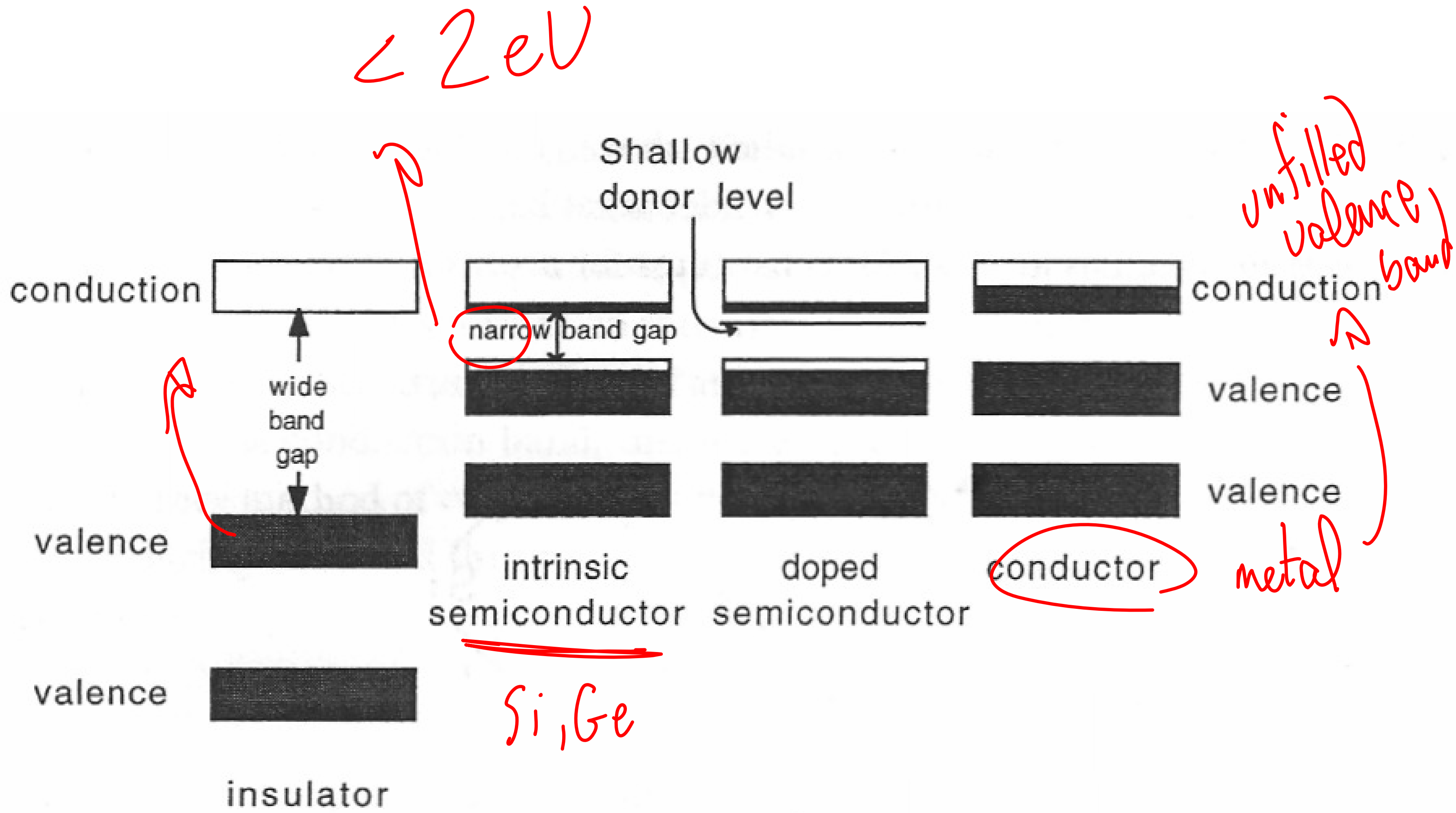
Adapted from Fig. 18.2, *Callister 7e*.

Band Structure

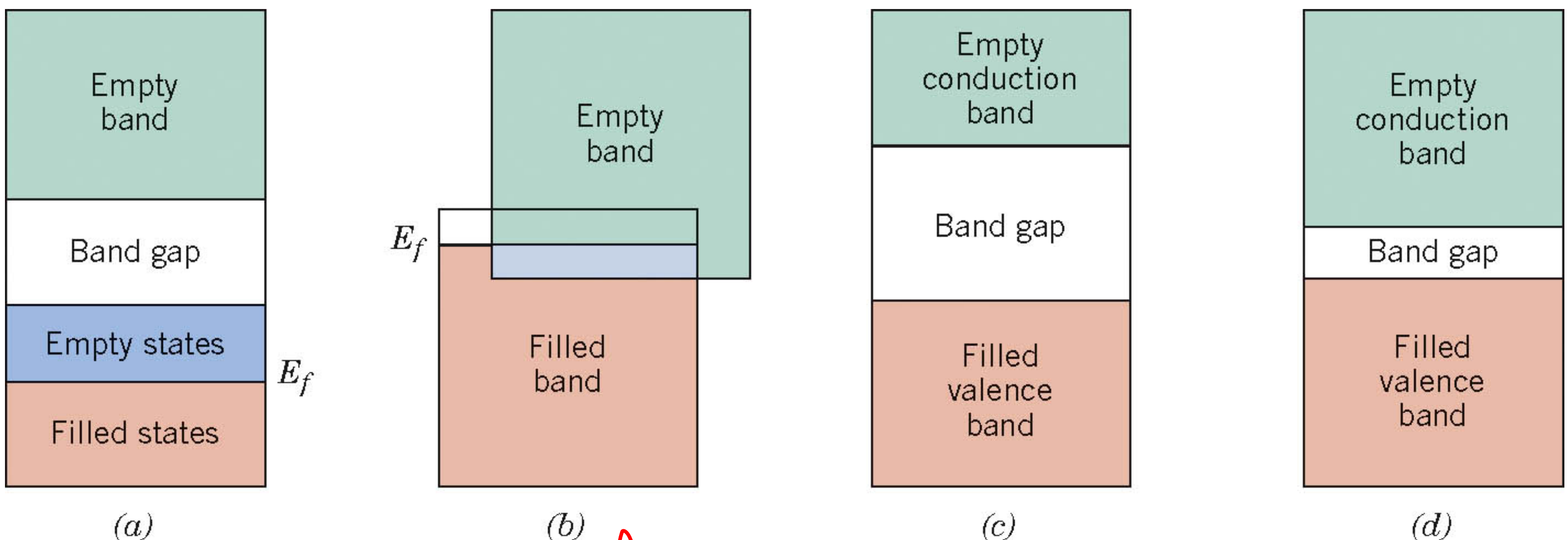
- Valence band – filled – highest occupied energy levels
- Conduction band – empty – lowest unoccupied energy levels



Adapted from Fig. 18.3, *Callister 7e*.



< 2eV
Shallow donor level
conduction
narrow band gap
wide band gap
valence
valence
conduction
valence
valence
intrinsic semiconductor
doped semiconductor
conductor
unfilled valence band
metal
Si, Ge
insulator



conductor metal Cu

metal Mg

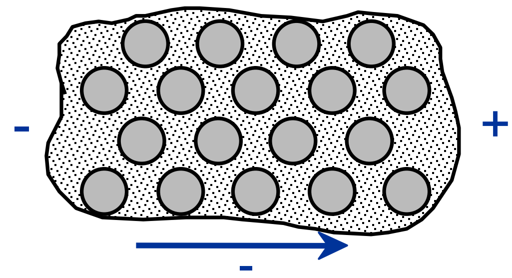
insulator

semi conductor

Conduction & Electron Transport

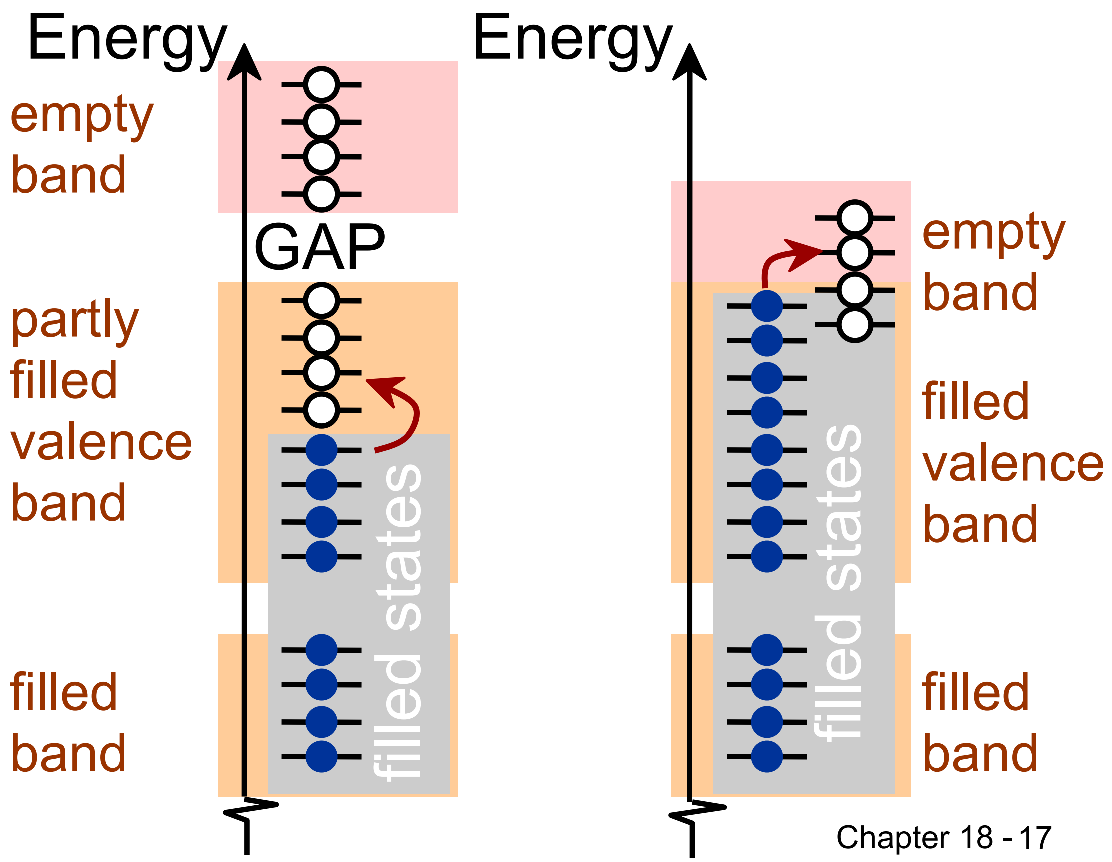
- Metals (Conductors):

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



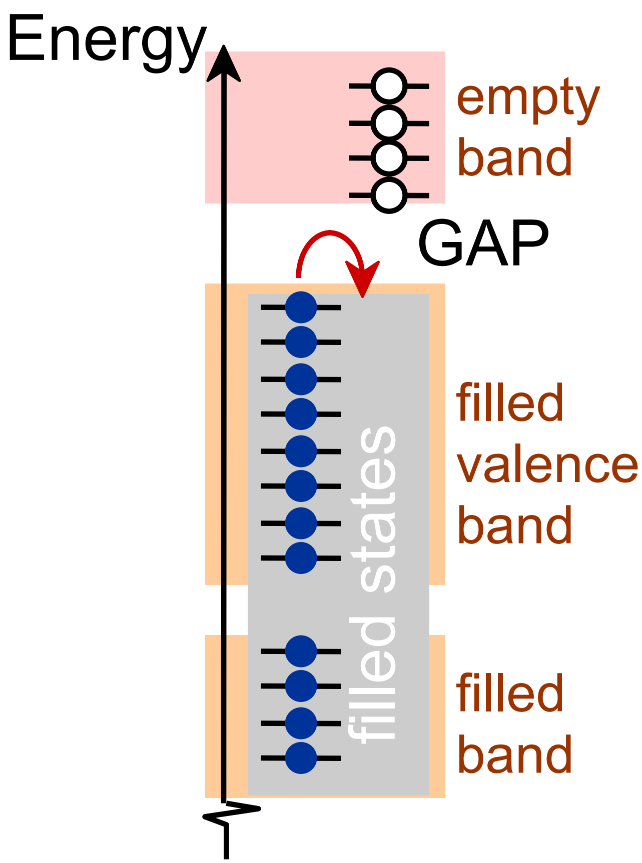
- Energy States:

-- for metals nearby energy states are accessible by thermal fluctuations.

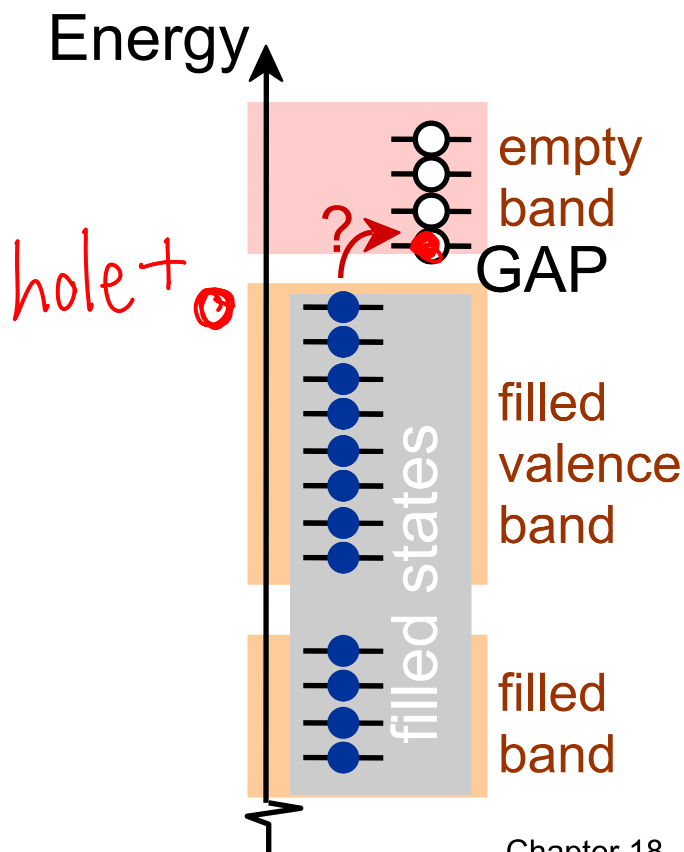


Energy States: Insulators & Semiconductors

- Insulators:
  -- Higher energy states not accessible due to gap (> 2 eV).

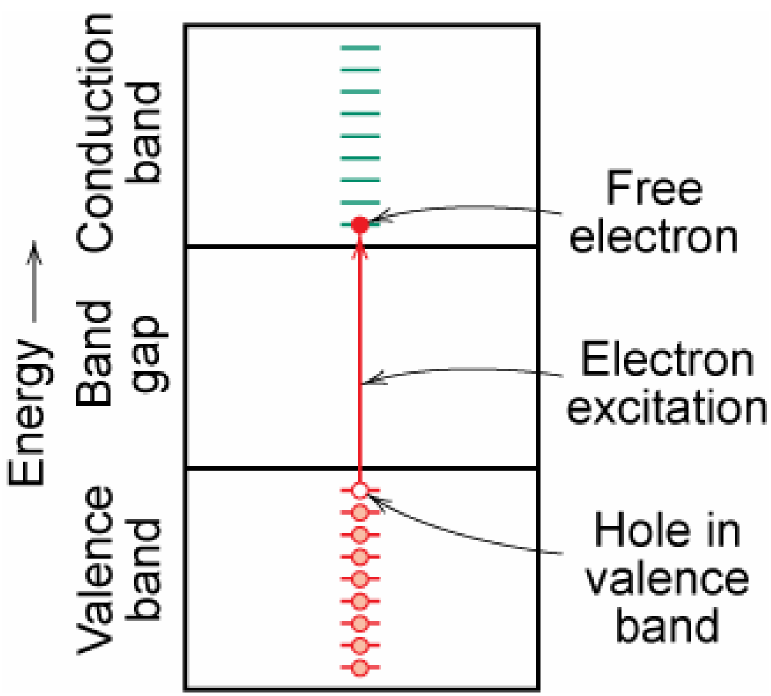


- Semiconductors:
  -- Higher energy states separated by smaller gap (< 2 eV).



Charge Carriers

Adapted from Fig. 18.6 (b), *Callister 7e*.



Two charge carrying mechanisms

Electron – negative charge

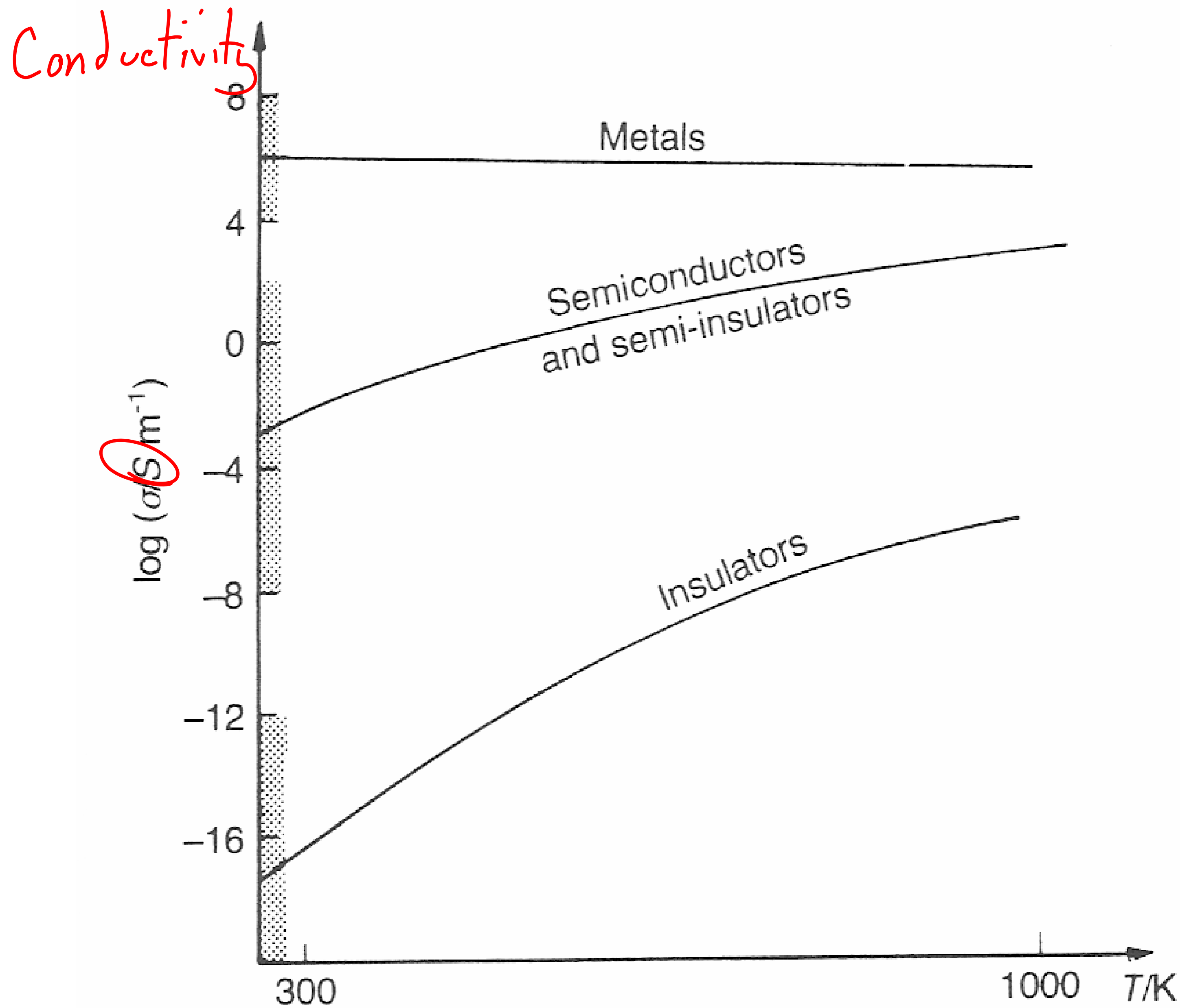
Hole – equal & opposite positive charge

Move at different speeds - drift velocity

Higher temp. promotes more electrons into the conduction band

∴ $\sigma\uparrow$ as $T\uparrow$

Electrons scattered by impurities, grain boundaries, etc.


Conductivity
log (σ/S m⁻¹)
8
4
0
−4
−8
−12
−16
Metals
Semiconductors
and semi-insulators
Insulators
300
1000
T/K

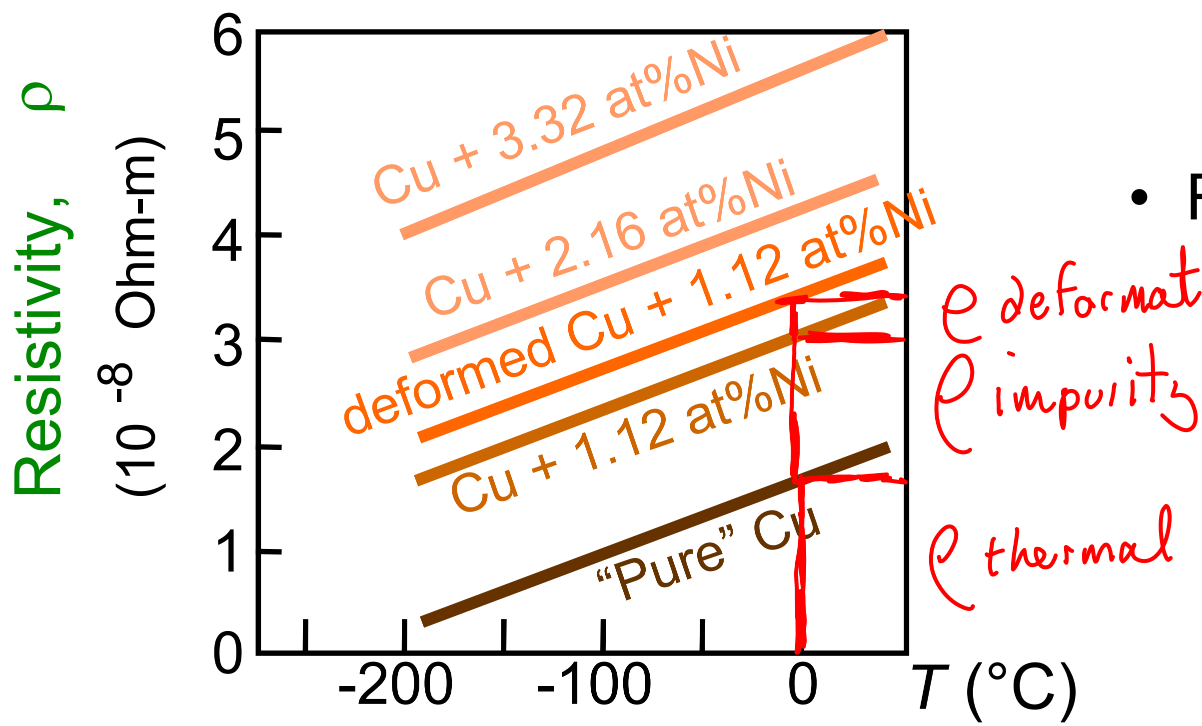
Metals: Resistivity vs T, Impurities

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

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

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

defects

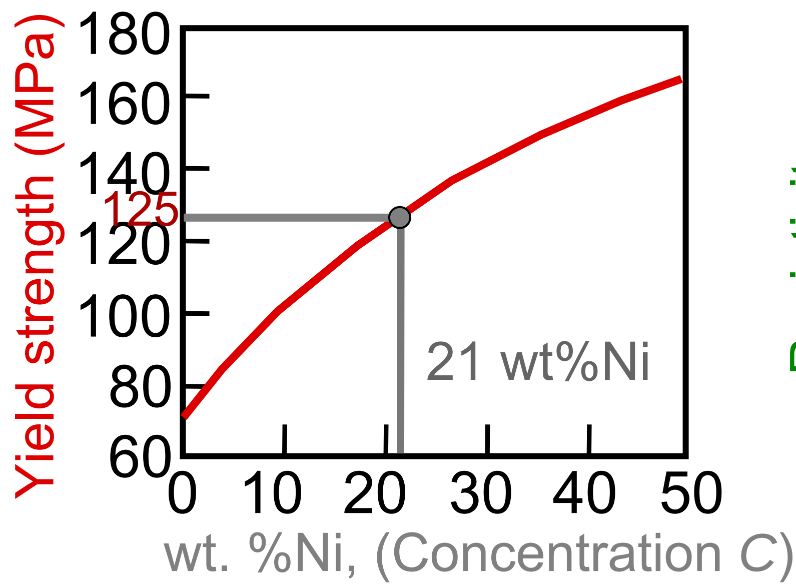


- Resistivity increases with:
  - -- temperature ✓
  - -- wt% impurity ✓
  - -- %CW → deformation

Adapted from Fig. 18.8, *Callister 7e*. (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.)

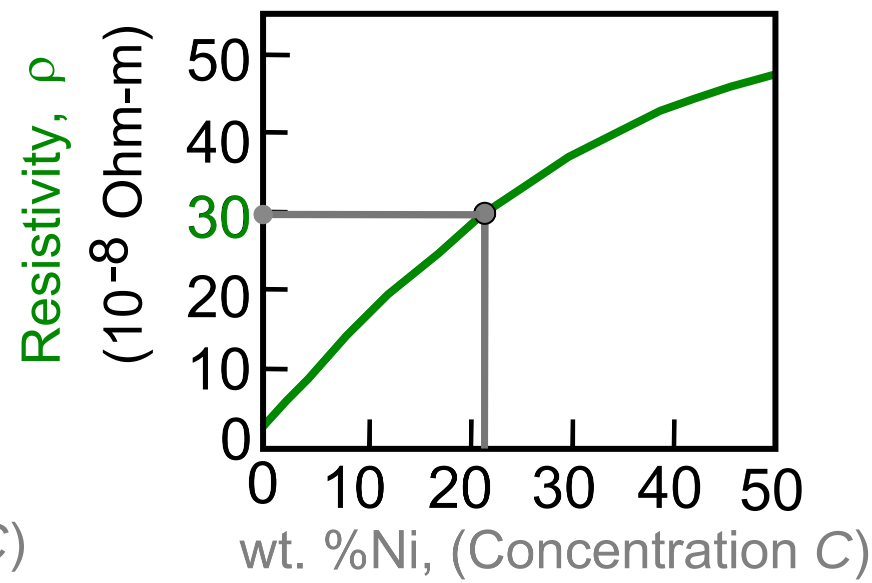
Estimating Conductivity

- 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 7e*.

Adapted from Fig. 18.9, *Callister 7e*.



From step 1:

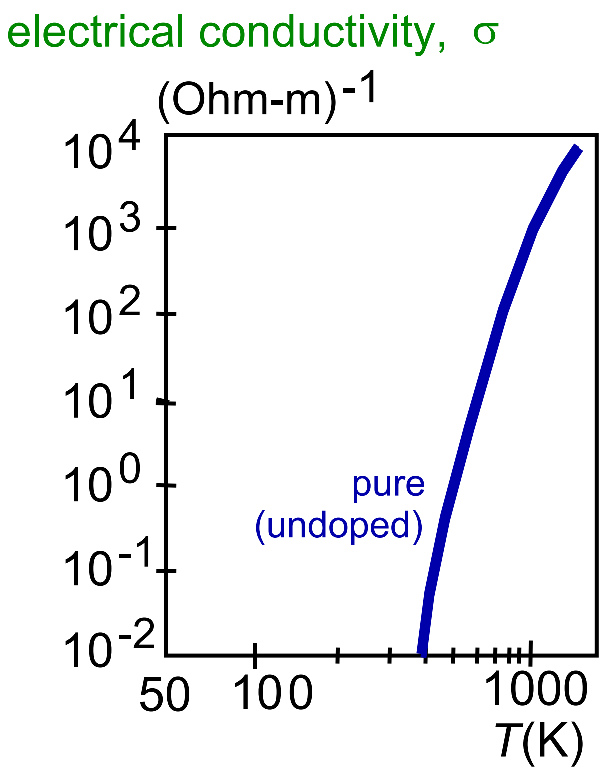
C_{Ni} = 21 wt%Ni

$$\rho = 30x10^{-8}\mathrm{Ohm-m}$$

$$\sigma = \frac{1}{\rho} = 3.3x10^{6}(\mathrm{Ohm-m})^{-1}$$

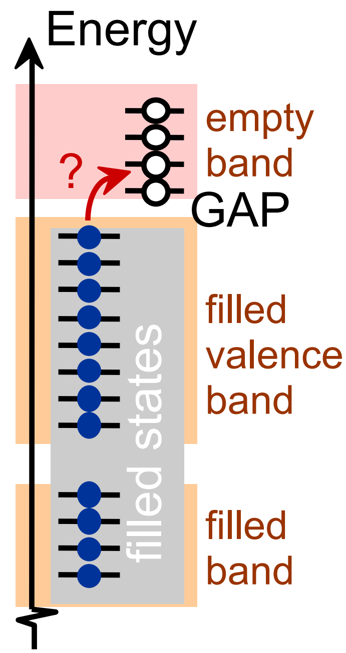
Pure Semiconductors: Conductivity vs T

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



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

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



electrons can cross gap at higher *T*

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

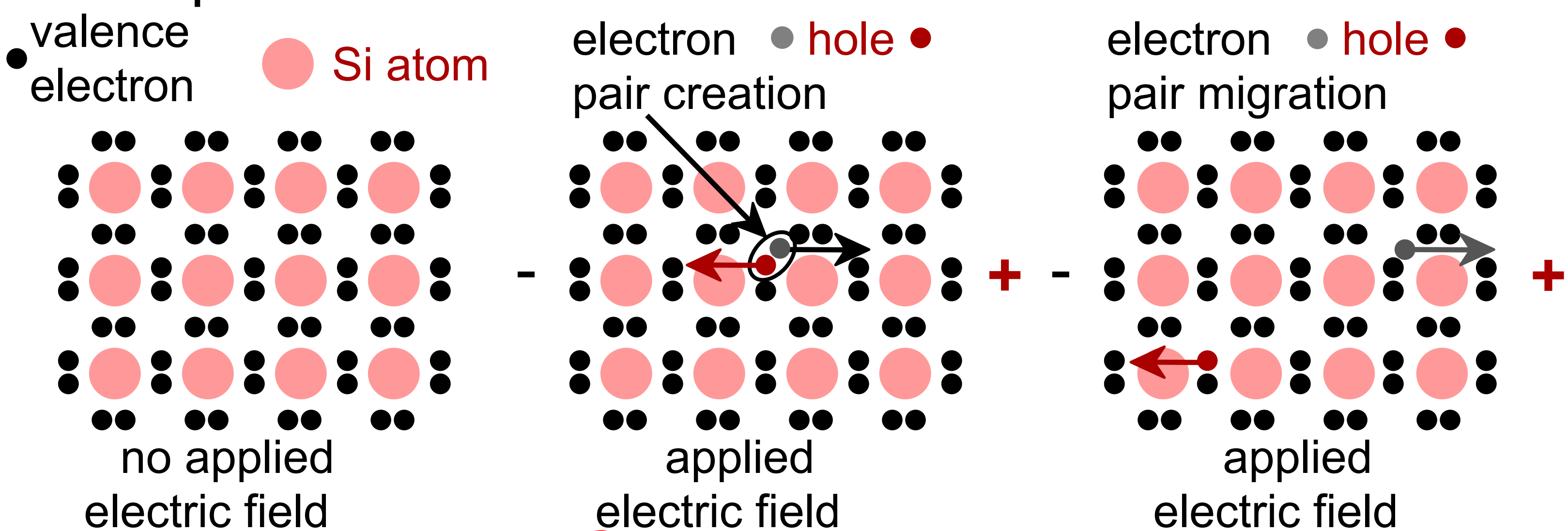
Selected values from Table 18.3, *Callister 7e*.

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.

Conduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



Adapted from Fig. 18.11, *Callister 7e*.

- Electrical Conductivity given by:

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

n: # electrons/m^3

μ_e: electron mobility

p: # holes/m^3

μ_h: hole mobility

Number of Charge Carriers

Intrinsic Conductivity

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

n

Table 18.3

- for intrinsic semiconductor $n = p$

$$\therefore \qquad \sigma = n|e|(\mu_e + \mu_n)$$

- Ex: GaAs

$$n = \frac{\sigma}{|e|(\mu_e + \mu_n)} = \frac{10^{-6}(\Omega\cdot\text{m})^{-1}}{(1.6x10^{-19}\,\text{C})(0.85 + 0.45\ \text{m}^2/\text{V}\cdot\text{s})}$$

For GaAs $\qquad n = 4.8 \times 10^{24}\ \text{m}^{-3}$

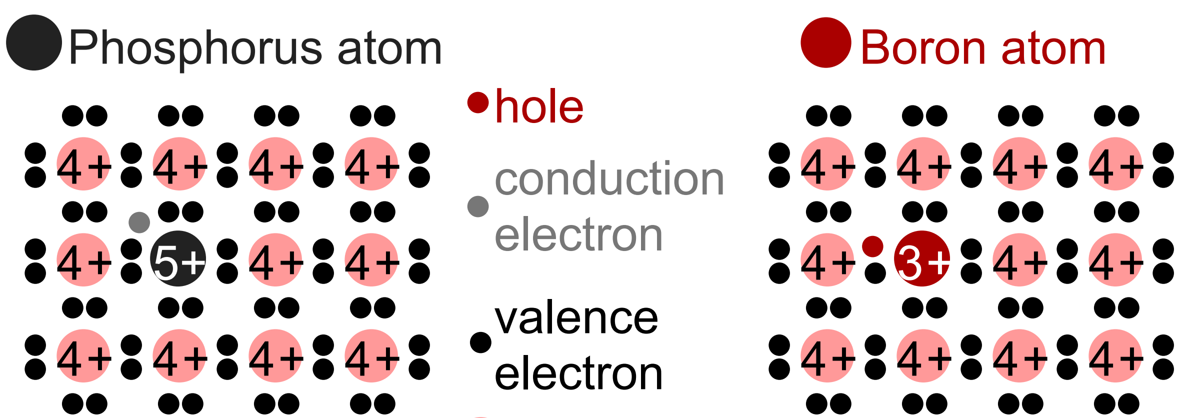
For Si $\qquad n = 1.3 \times 10^{16}\ \text{m}^{-3}$

Intrinsic vs Extrinsic Conduction

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

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

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



no applied electric field

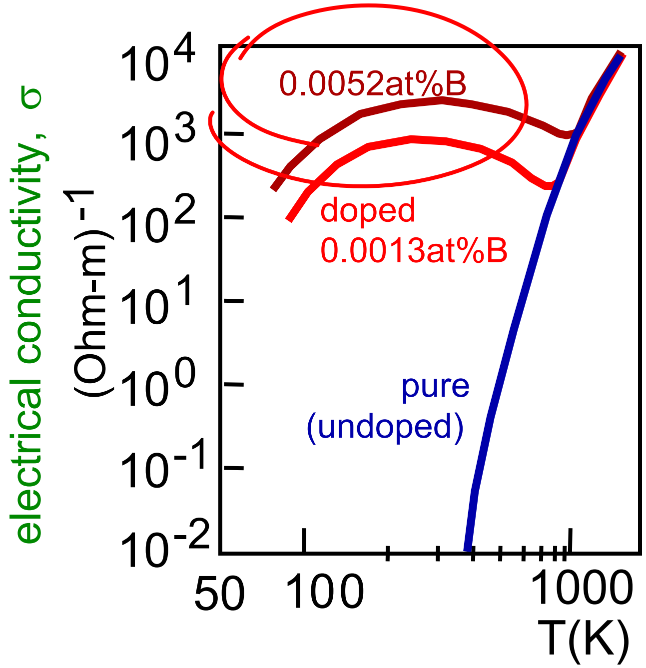
no applied electric field

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

Adapted from Figs. 18.12(a) & 18.14(a), *Callister 7e*.

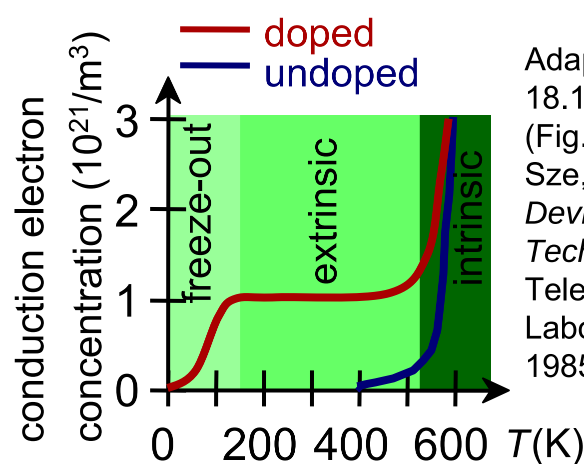
Doped Semiconductor: Conductivity vs. T

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



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

- 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"



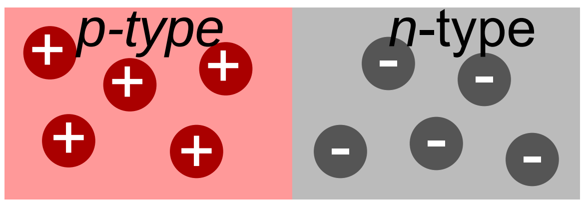
Adapted from Fig. 18.17, *Callister 7e*. (Fig. 18.17 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

p-n Rectifying Junction

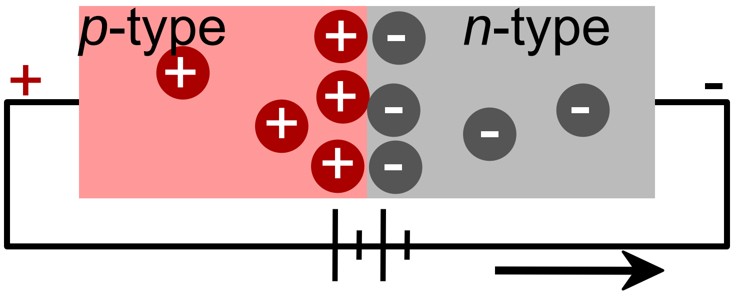
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.
- Processing: diffuse P into one side of a B-doped crystal.
- Results:

Adapted from Fig. 18.21, *Callister 7e*.

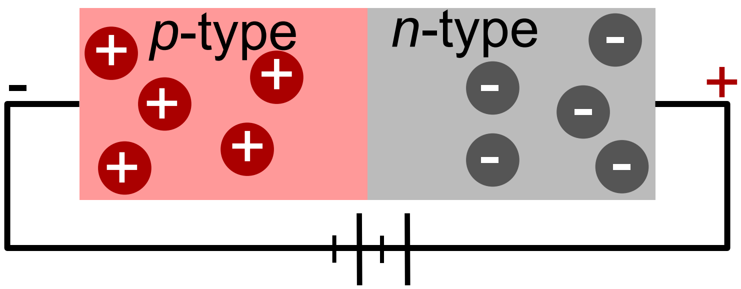
--No applied potential: no net current flow.



--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.



Properties of Rectifying Junction

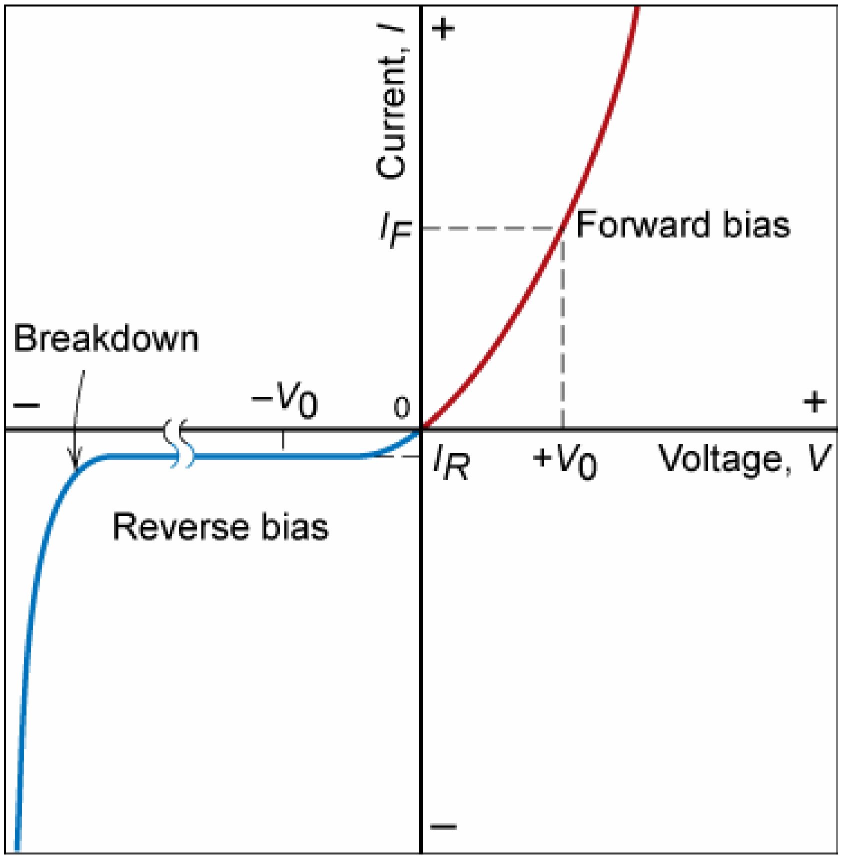


Fig. 18.22, *Callister 7e*.

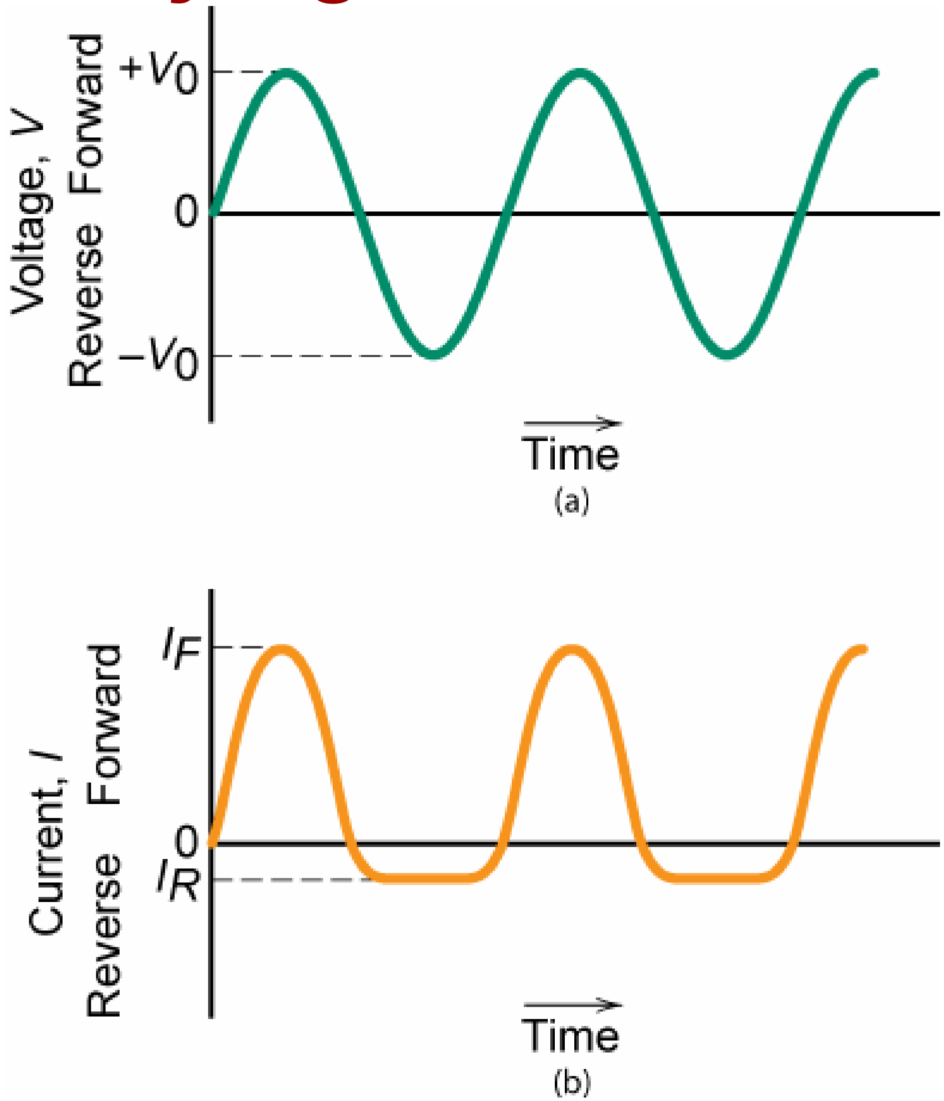


Fig. 18.23, *Callister 7e*.

Junction Transistor

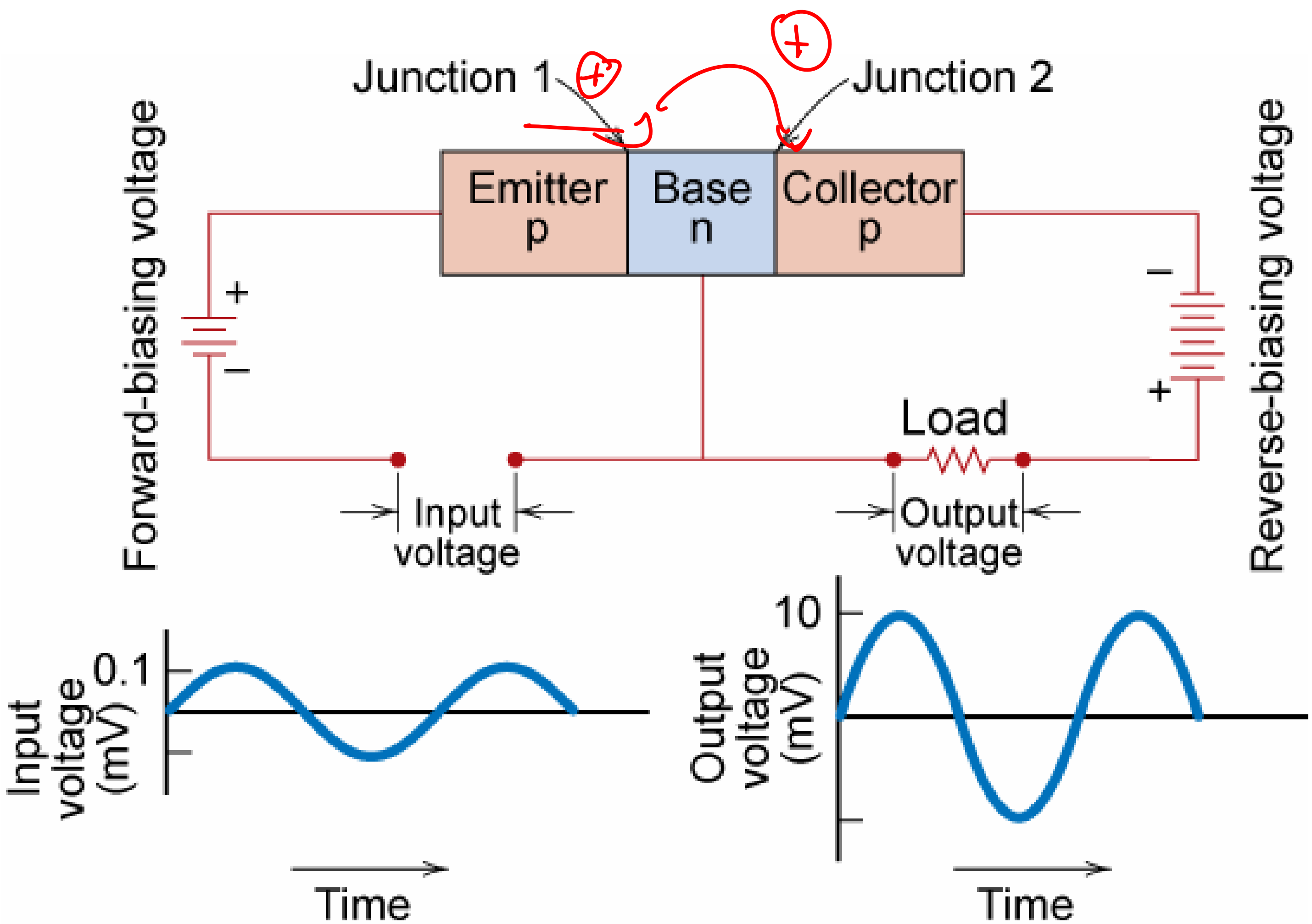


Fig. 18.24, *Callister 7e*.

Integrated Circuit Devices

- MOSFET (metal oxide semiconductor field effect transistor)

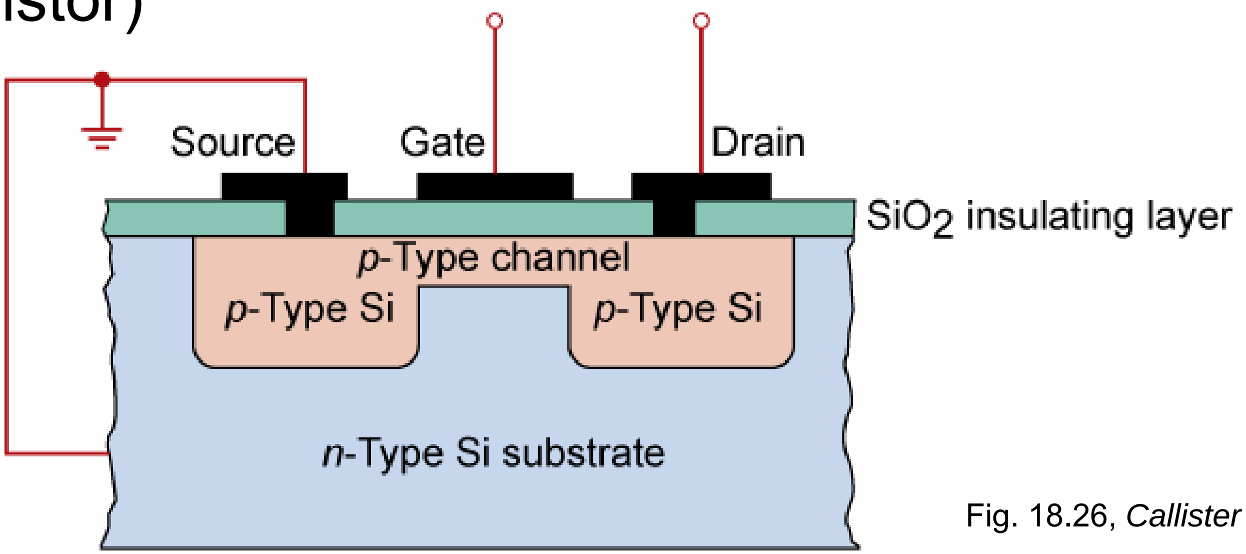


Fig. 18.26, *Callister 6e*.

- Integrated circuits - state of the art ca. 50 nm line width
  - 1 Mbyte cache on board
  - > 100,000,000 components on chip
  - chip formed layer by layer
    - Al is the "wire"

Cu is used a lot now

Summary

$e^{\left(-\frac{E_G}{kT}\right)}$

- Electrical conductivity and resistivity are:
  - -- material parameters.
  - -- geometry independent.
- Electrical resistance is:
  - -- a geometry and material dependent parameter.
- Conductors, semiconductors, and insulators...
  - -- differ in accessibility of 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).

Next time, Insulators (traditionally)

- Ceramics
  - Some structure
  - Capacitance, Dielectric properties
  - Ionic conduction
- Polymers
  - A bit on structure
  - Conducting polymers