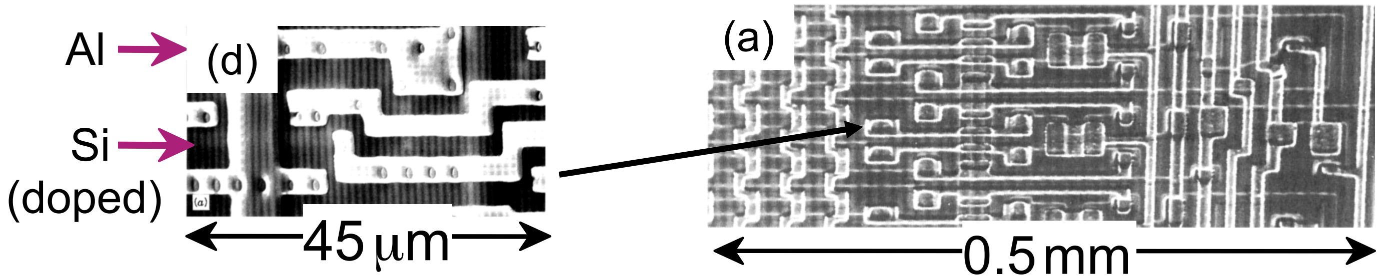
Chapter 18: Electrical Properties

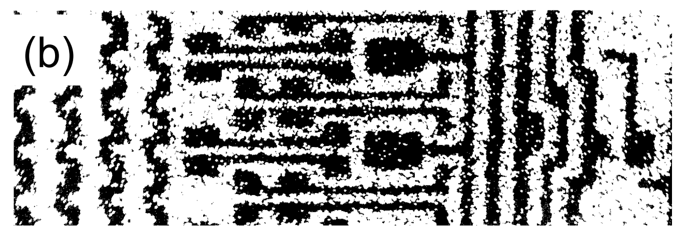
- Why study electrical properties?
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, *T*, and deformation?
- For semiconductors, how is conductivity affected by impurities (doping) and *T*?

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.

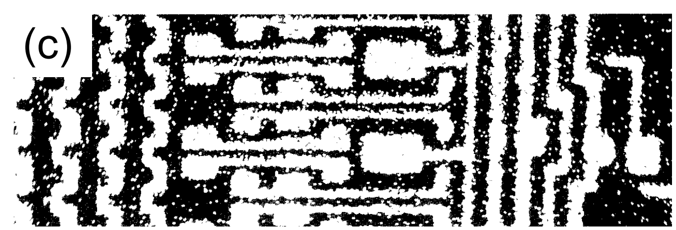


Fig. (d) from Fig. 18.27 (a), *Callister 7e*. (Fig. 18.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

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

Definitions

Further definitions

$$J = \sigma \, \varepsilon$$ <= 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 conductivity voltage gradient

<u>Current carriers</u>

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

Electrical Conduction

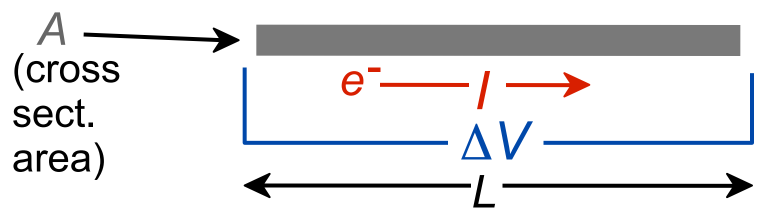
- Ohm's Law:

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

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 → $\frac{I}{A}$

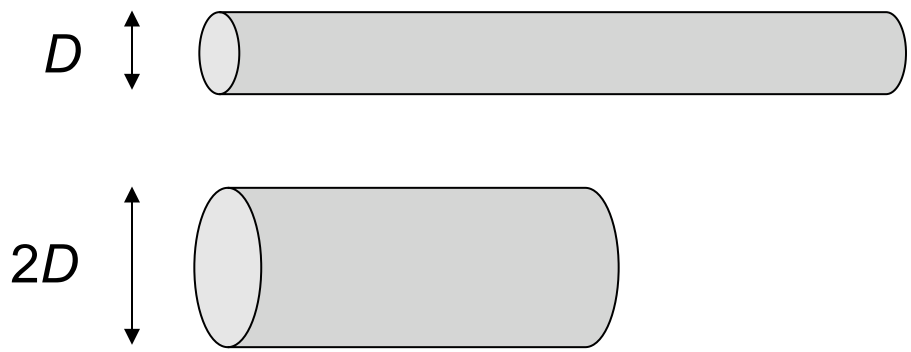
- Resistance:

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

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.

Conductivity: Comparison

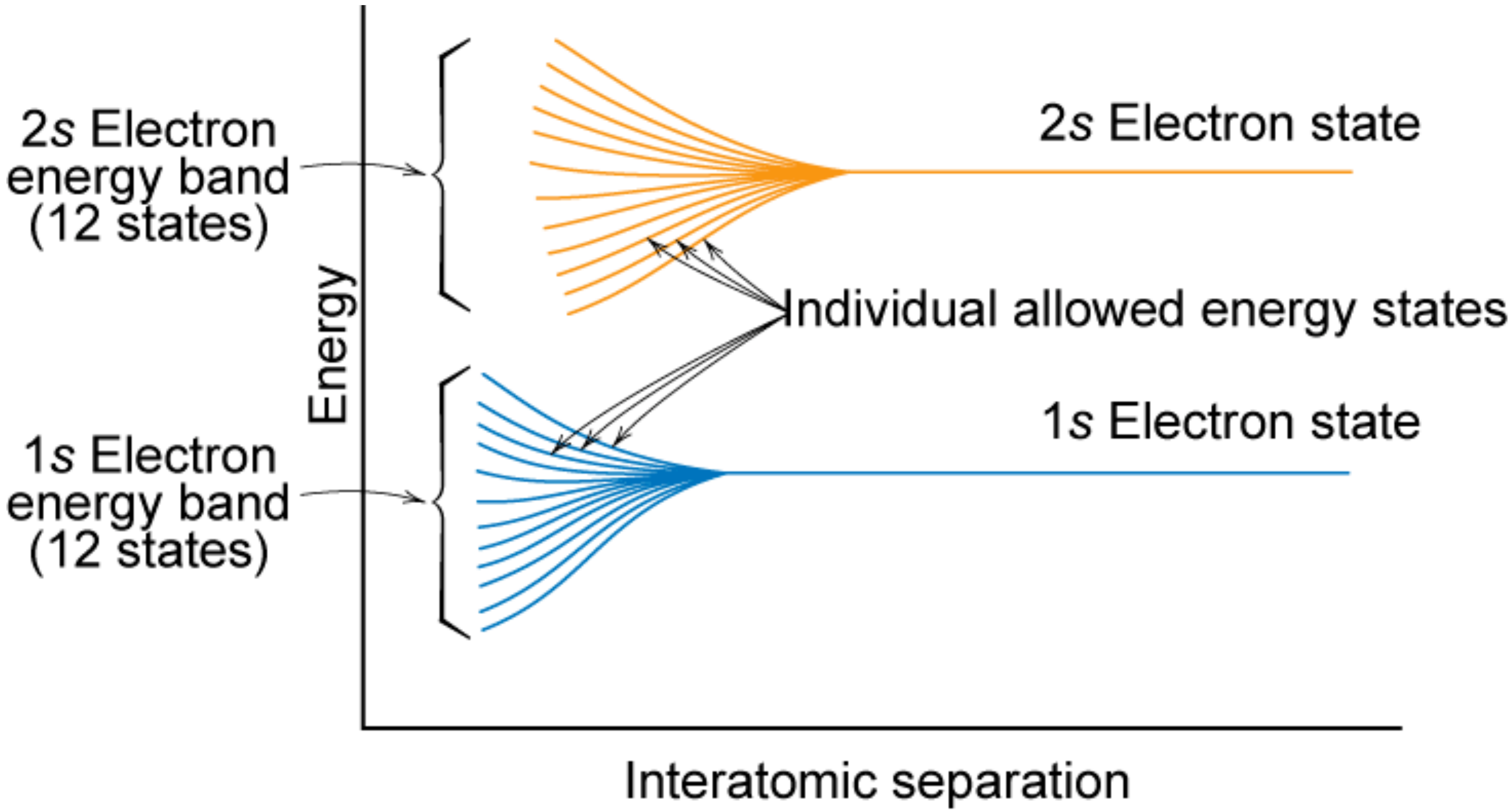
- Room *T* values (Ohm-m)$^{-1}$ = $(\Omega$ - m$)^{-1}$

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*.

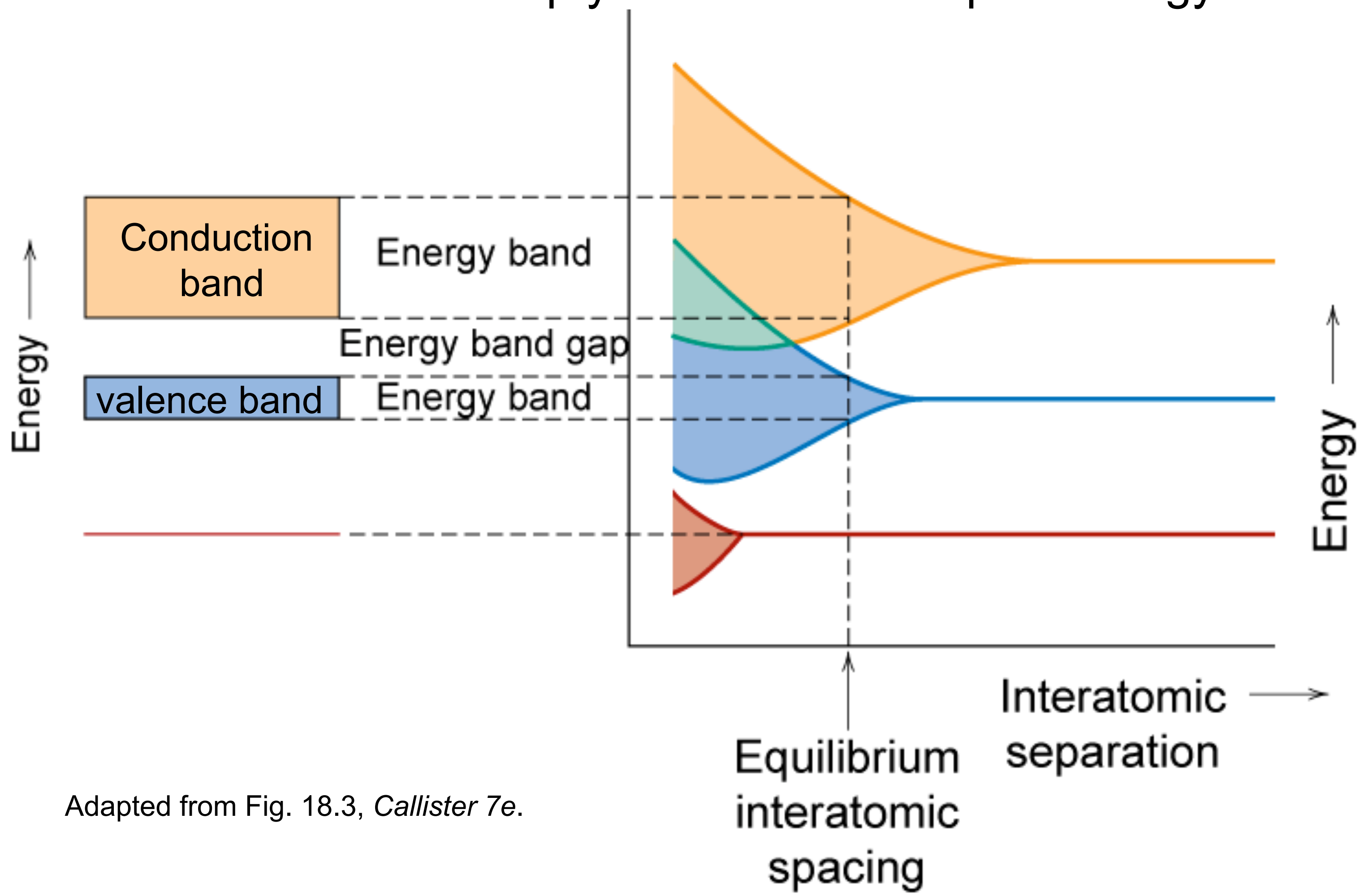
Electronic Band Structures



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

Band Structure

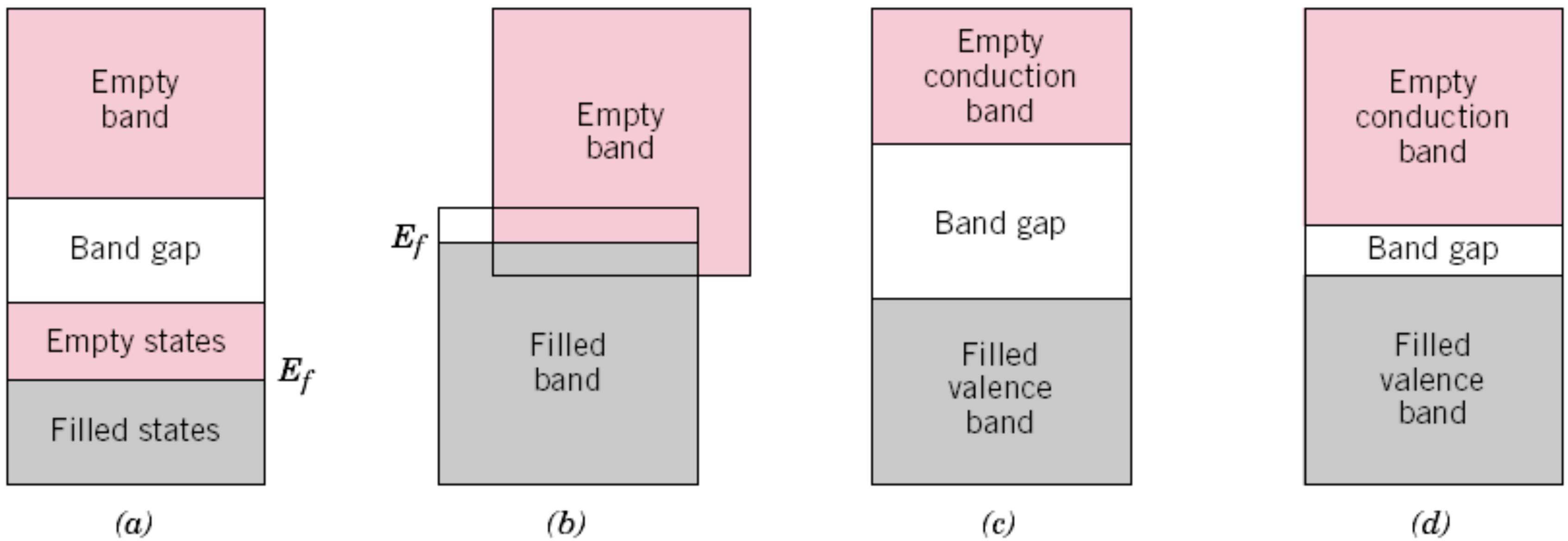
- Valence band – filled – highest occupied energy levels
- Conduction band – empty – lowest unoccupied energy levels



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

Various possible electron band structures

- Fermi energy E_f: the energy corresponding to the highest filled state at 0 K

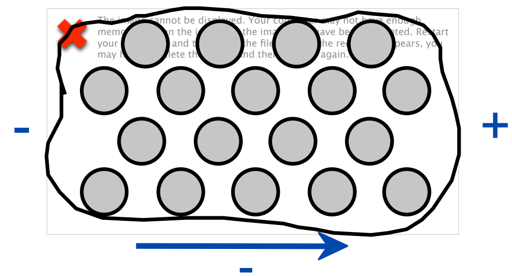


Metal (Cu) **Metal (Mg)** **Insulator** **Semiconductor**

Conduction & Electron Transport

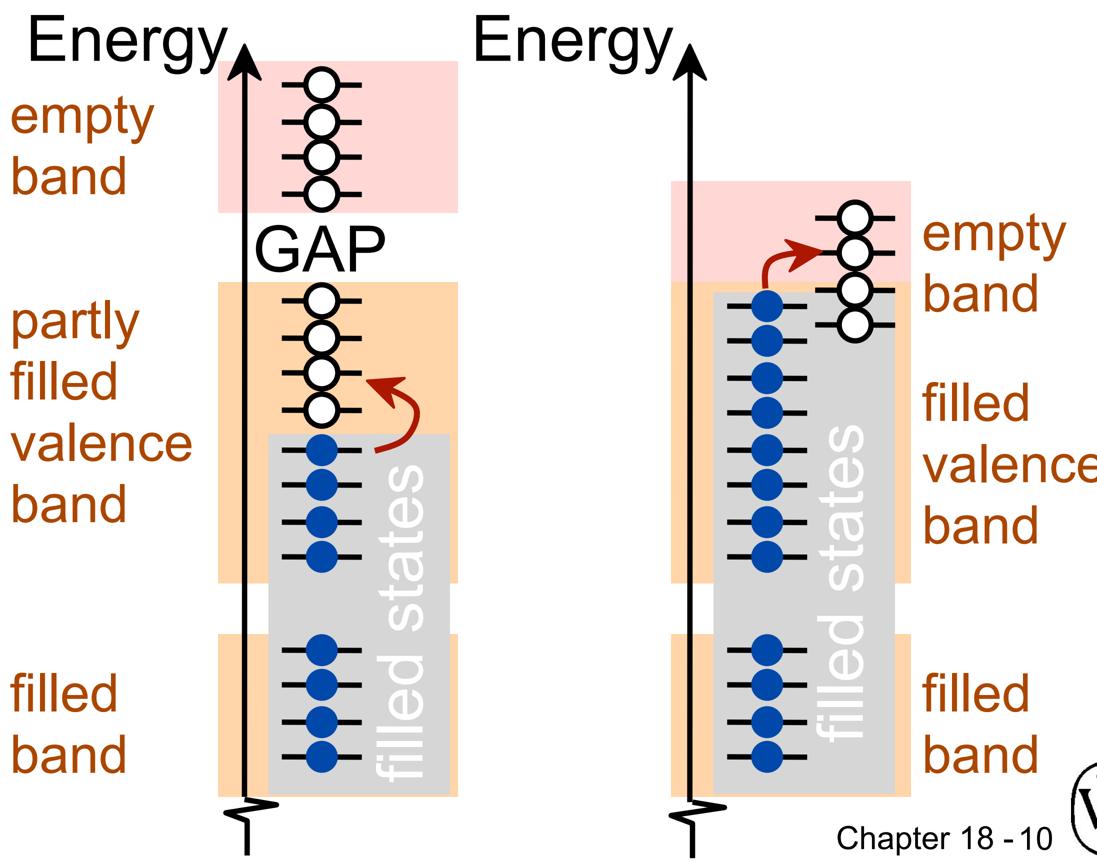
- Metals (Conductors):

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



- Energy States:

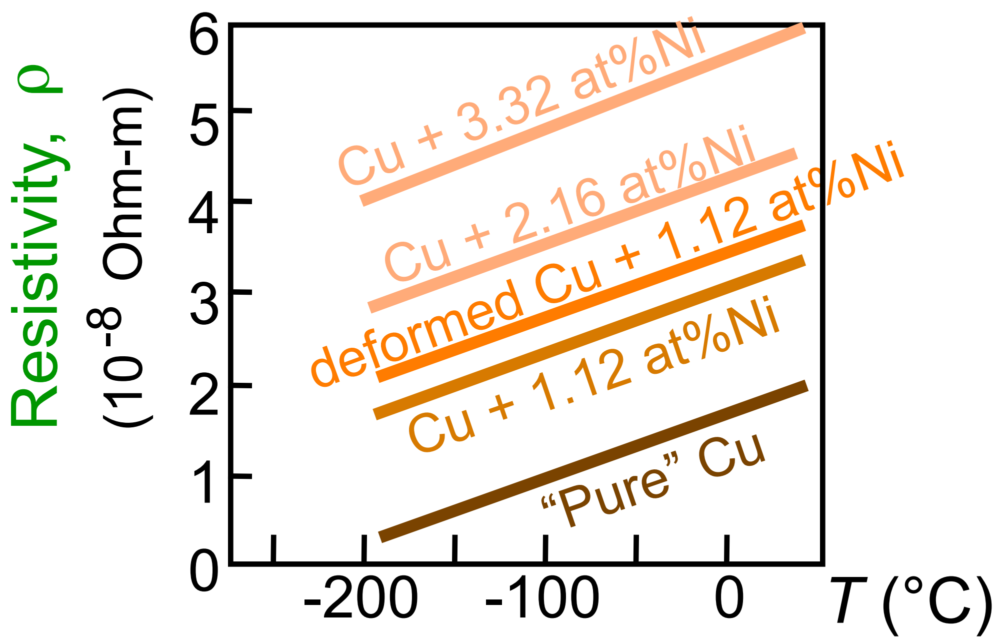
-- for metals nearby energy states are accessible by thermal fluctuations.



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.



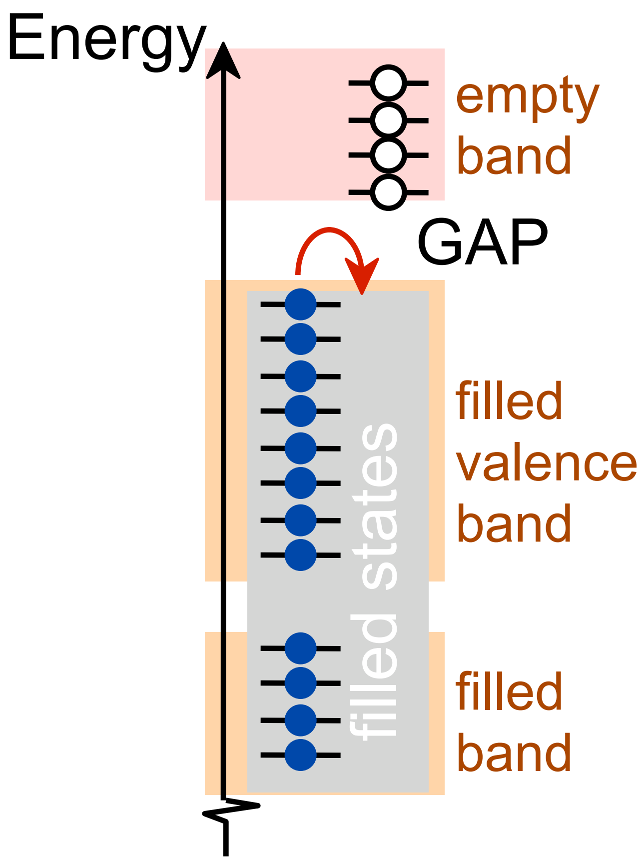
Adapted from Fig. 18.8, *Callister 7e*. (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* **5**, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

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

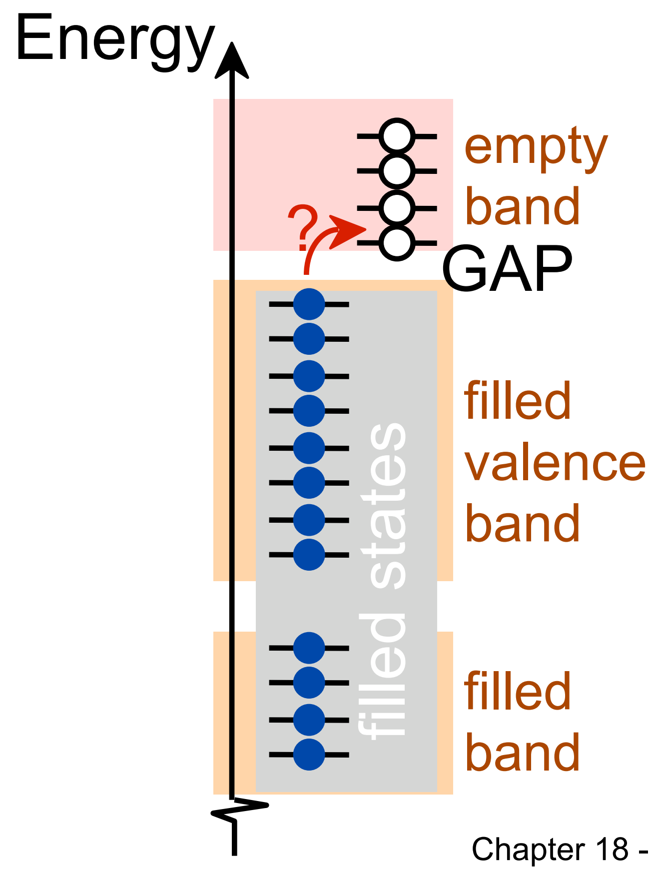
$$\rho = \rho_{thermal} + \rho_{impurity} + \rho_{deformation}$$

Energy States: Insulators & Semiconductors

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

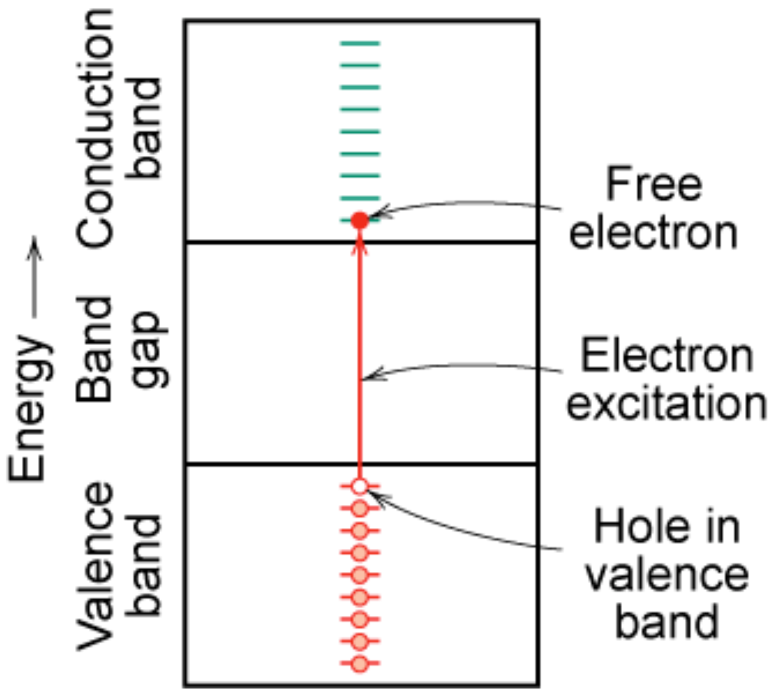


- Semiconductors:
  -- Higher energy states separated by smaller gap (< 2 eV).



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

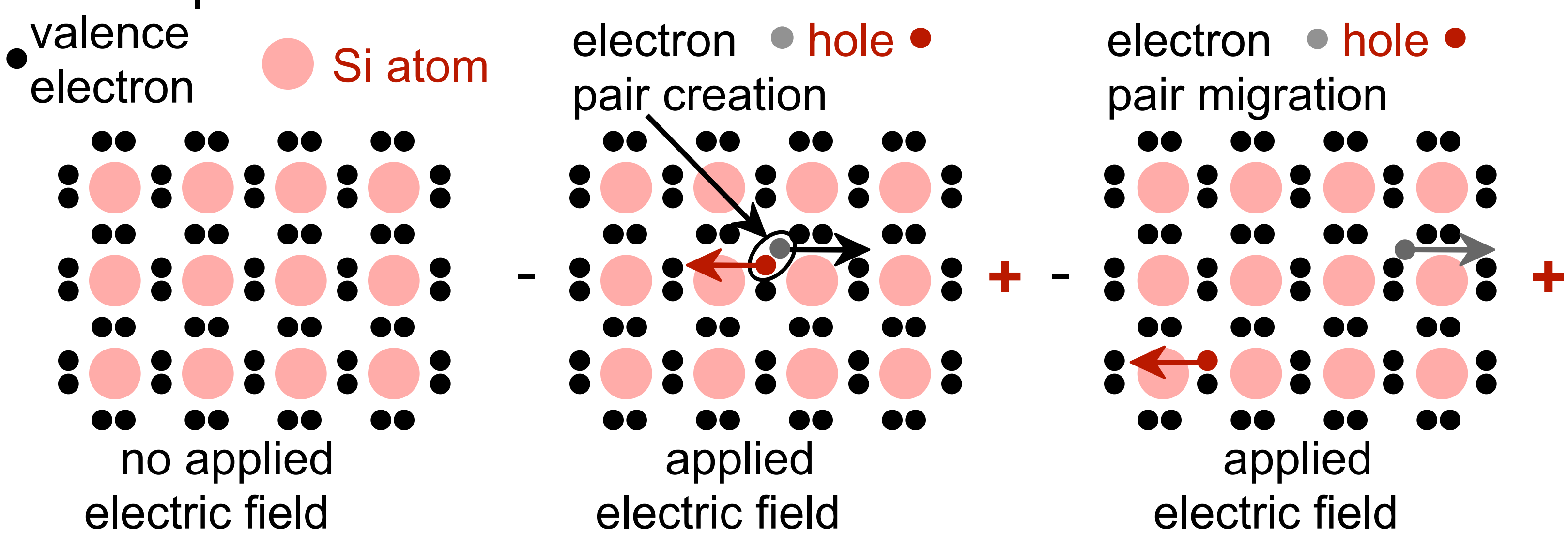
Higher temp. promotes more electrons into the conduction band

$\therefore \quad \sigma\uparrow$ as $T\uparrow$

Electrons scattered by impurities, grain boundaries, etc.

Conduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



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

- Electrical Conductivity given by:

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

electrons/m^3 (n)

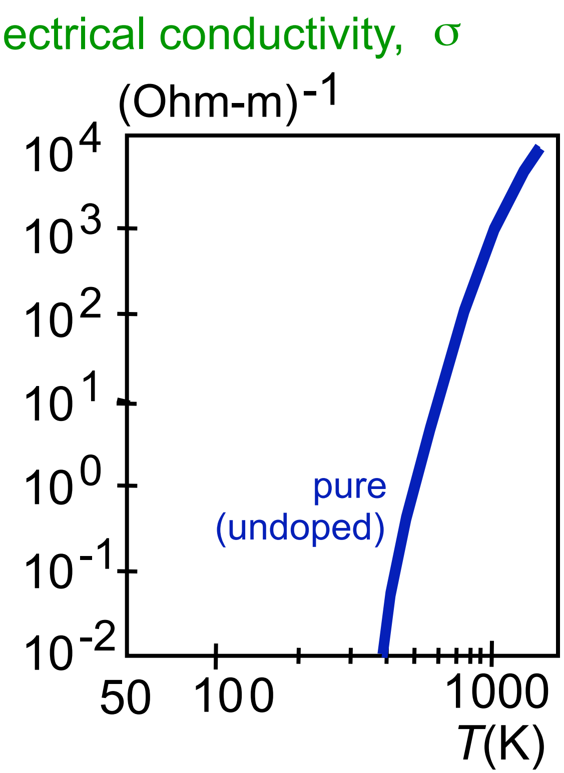
electron mobility (μ_e)

holes/m^3 (p)

hole mobility (μ_h)

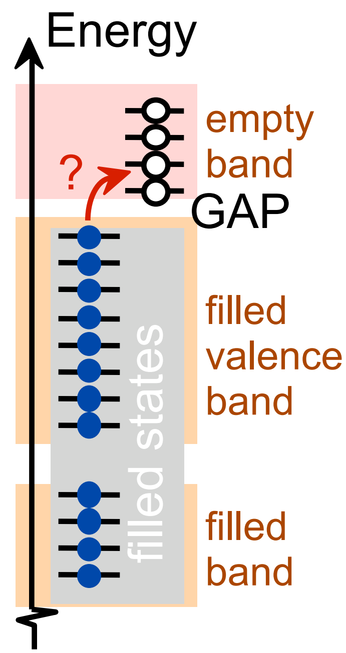
Pure Semiconductors: Conductivity vs T

- 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

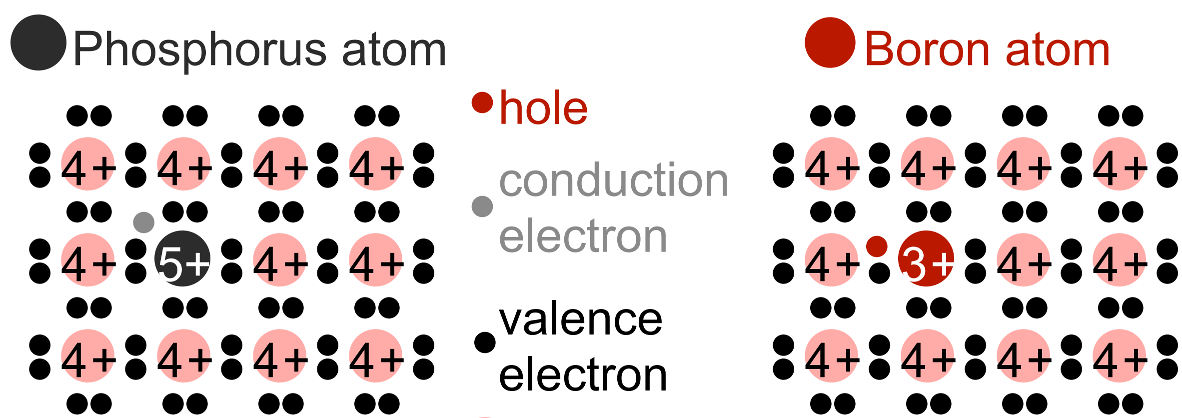
Selected values from Table 18.3, *Callister 7e*.

Intrinsic 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.*

Summary

- 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.