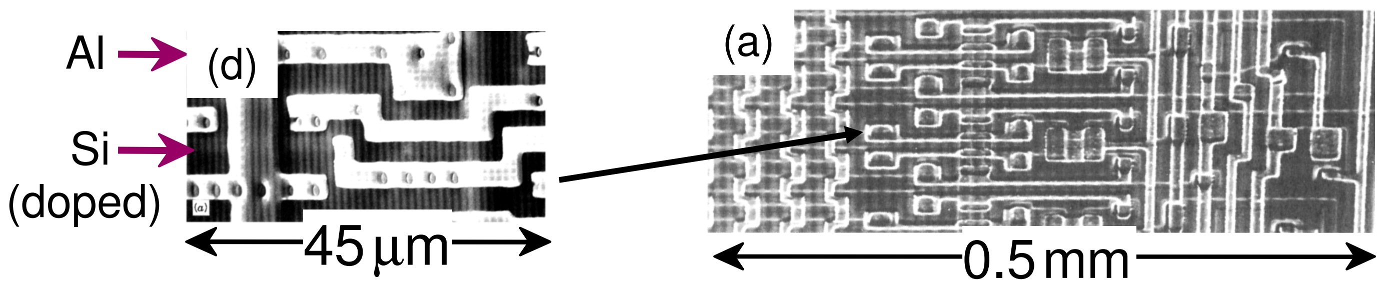
Chapter 18: Electrical Properties

ISSUES TO ADDRESS...

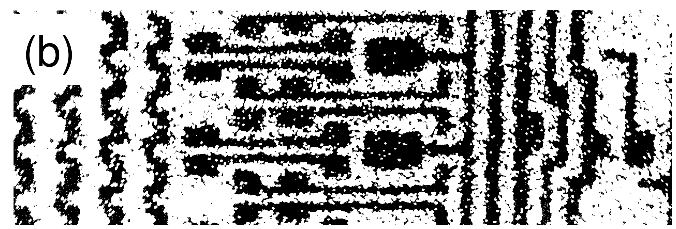
- How are electrical conductance and resistance characterized?
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, *T*, and deformation?
- For semiconductors, how is conductivity affected by impurities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

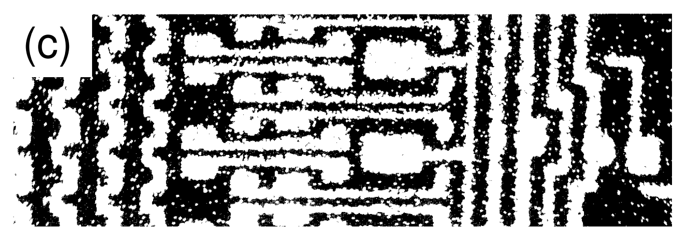


Fig. (d) from Fig. 18.27 (a), *Callister 7e*. (Fig. 18.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

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

Electrical Conduction

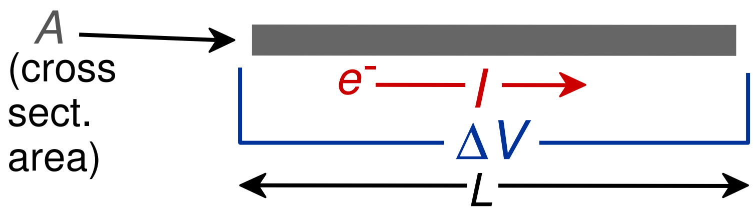
- Ohm's Law:

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

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

current (amps = C/s)

resistance (Ohms)



- 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

resistivity (Ohm-m)

J: current density

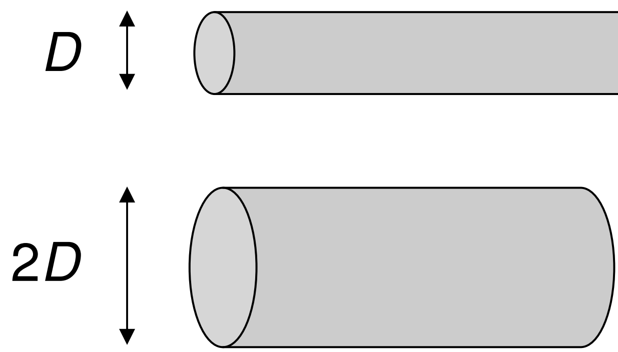
- Resistance:

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

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

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

$$\varepsilon \equiv \text{electric field potential} = V/\ell \quad \text{or} \quad (\Delta V/\Delta \ell)$$

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

Electron flux conductivity voltage gradient

<u>Current carriers</u>

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

Conductivity: Comparison

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

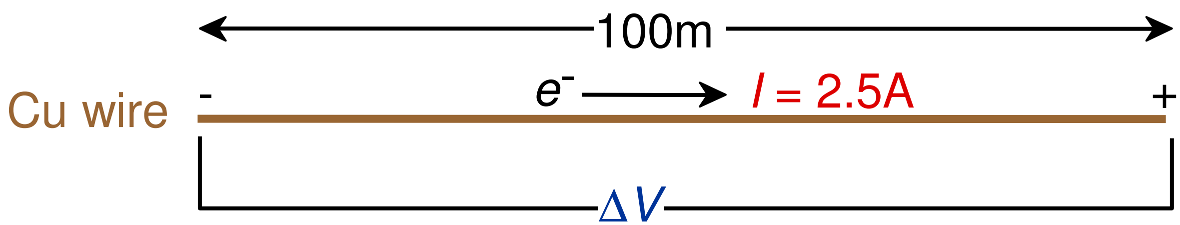
METALS	conductors	CERAMICS	
Silver	6.8×10^{7}	Soda-lime glass	10^{-10}-10^{-11}
Copper	6.0×10^{7}	Concrete	10^{-9}
Iron	1.0×10^{7}	Aluminum oxide	$<10^{-13}$

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*.

Example: Conductivity Problem

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



100m

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

< 1.5V

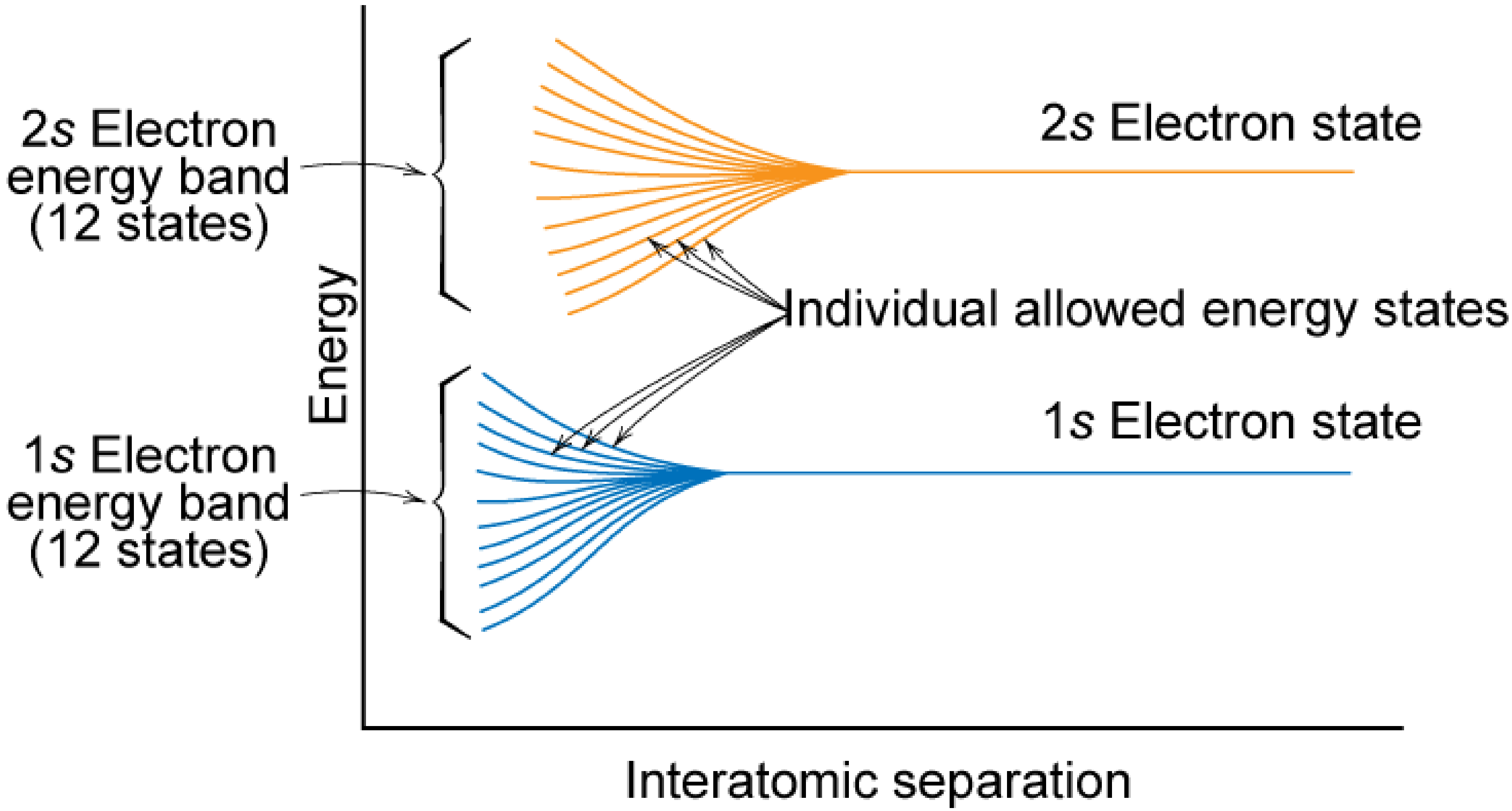
2.5A

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

6.07×10^7 (Ohm-m)$^{-1}$

Solve to get $D > 1.87$ mm

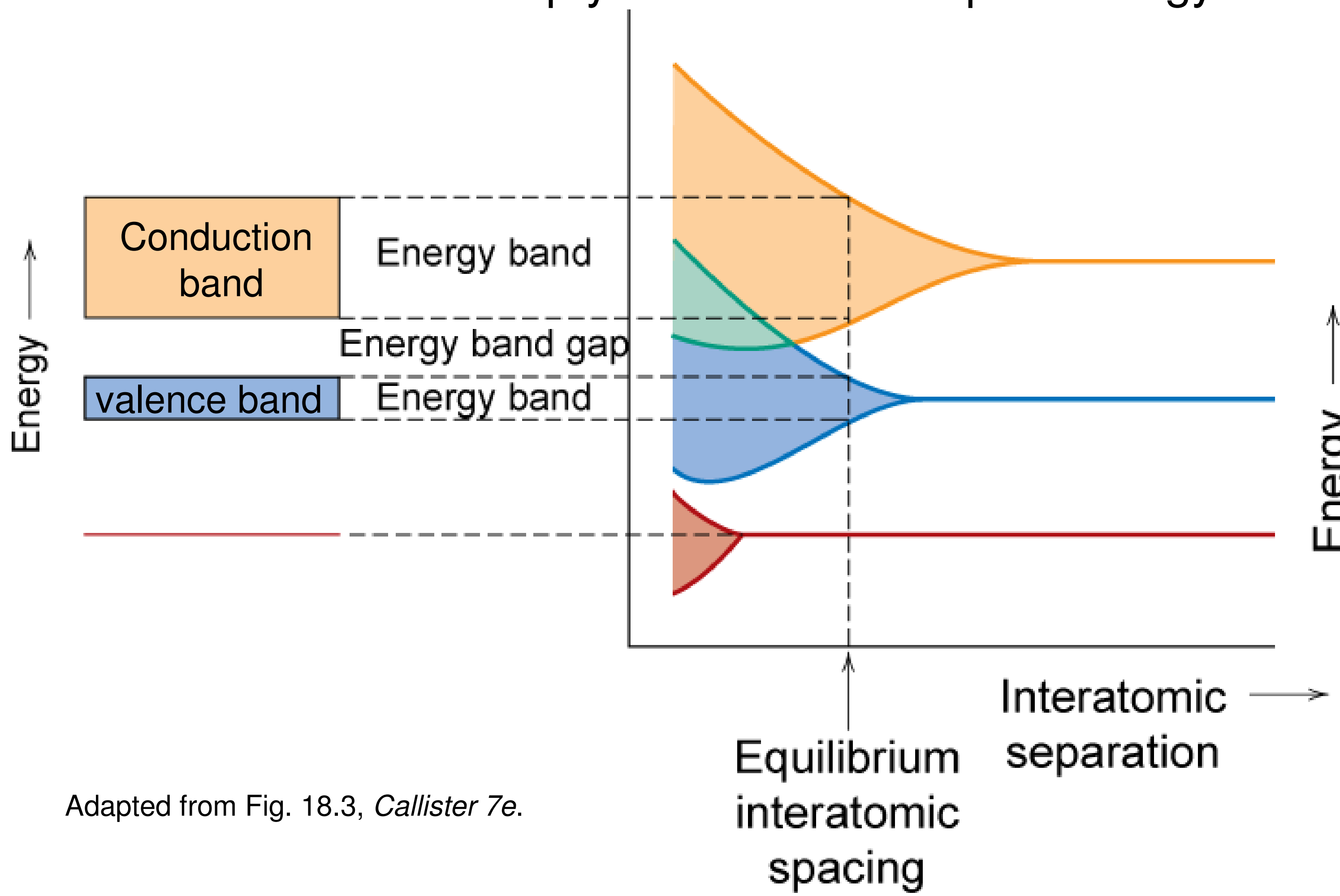
Electronic Band Structures



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

Band Structure

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

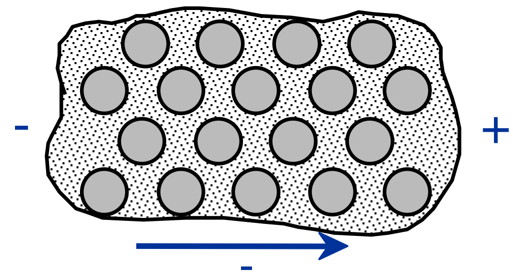


Adapted from Fig. 18.3, *Callister 7e*.

Conduction & Electron Transport

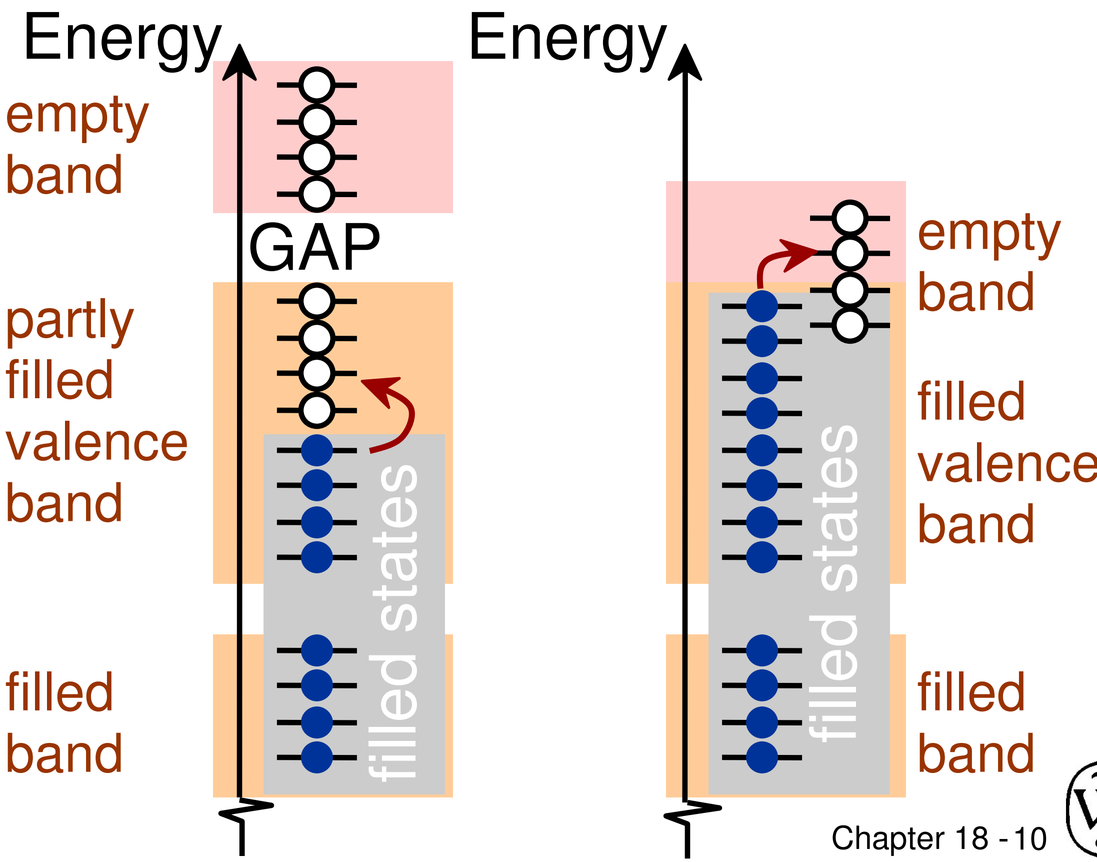
- Metals (Conductors):

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



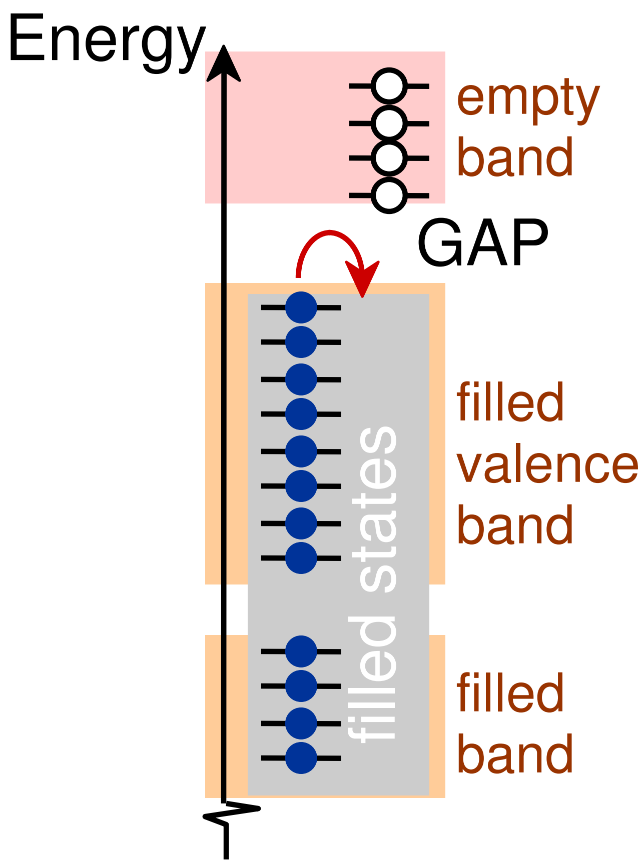
- Energy States:

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

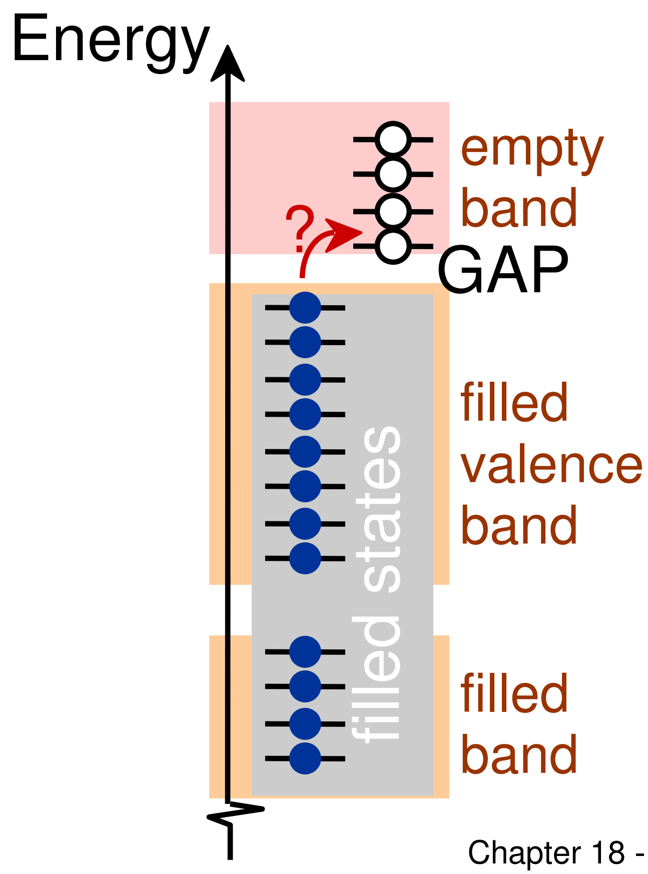


Energy States: Insulators & Semiconductors

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

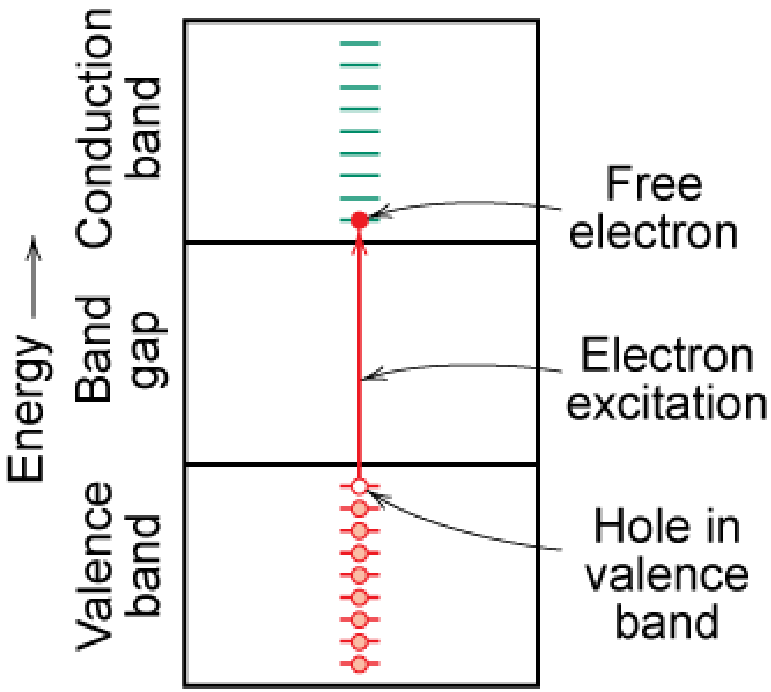


- Semiconductors:
  -- Higher energy states separated by smaller gap (< 2 eV).



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

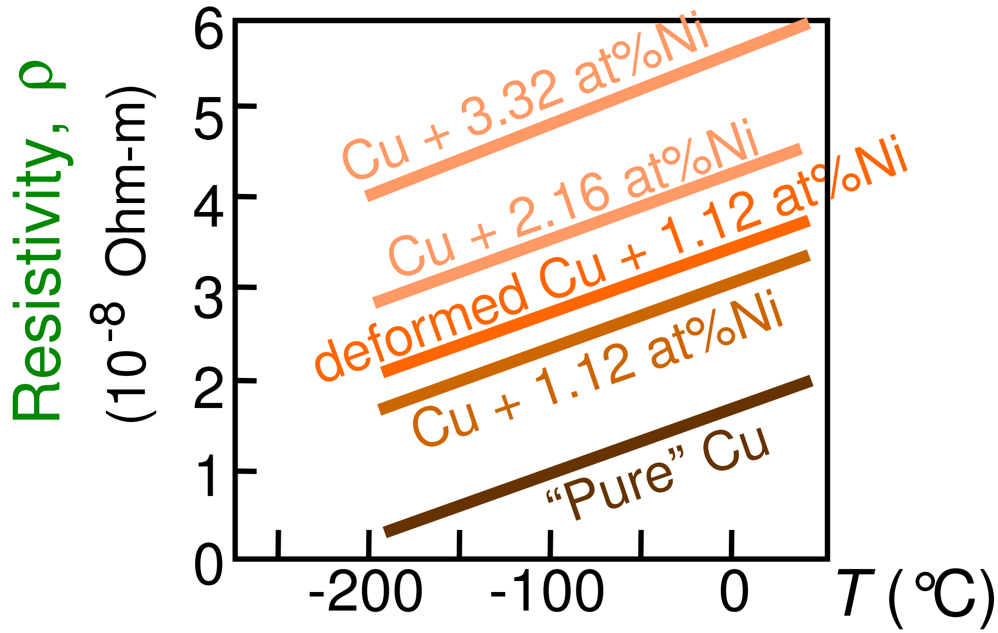
$\therefore \quad \sigma\uparrow$ as $T\uparrow$

Electrons scattered by impurities, grain boundaries, etc.

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.



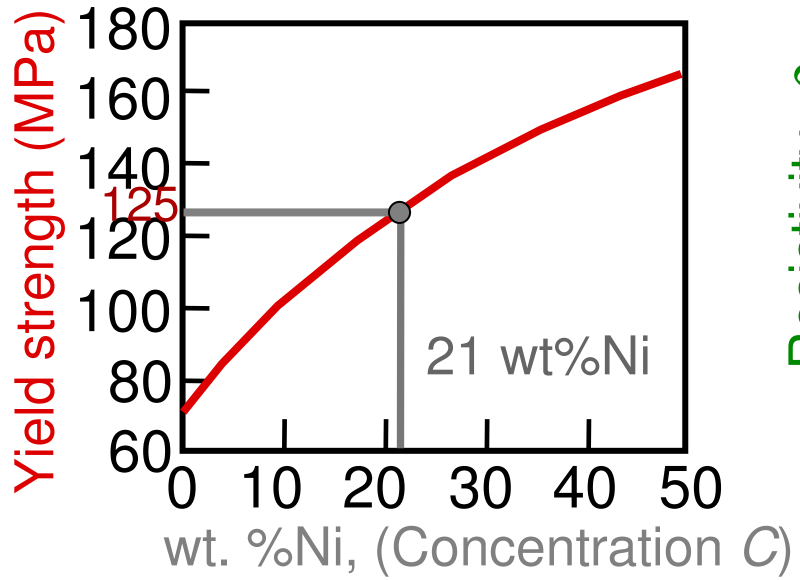
Adapted from Fig. 18.8, *Callister 7e*. (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* **5**, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

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

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

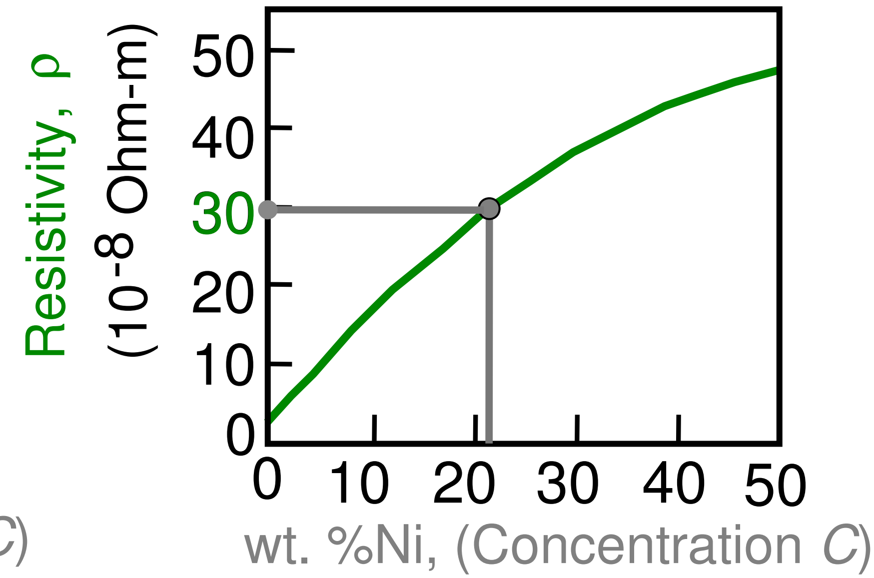
Estimating Conductivity

- 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:

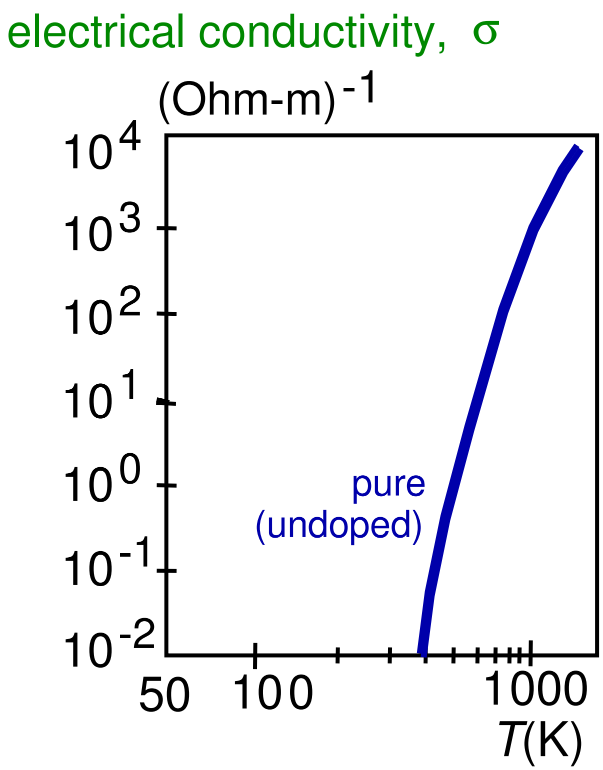
$C_{Ni} = 21$ wt%Ni

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

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

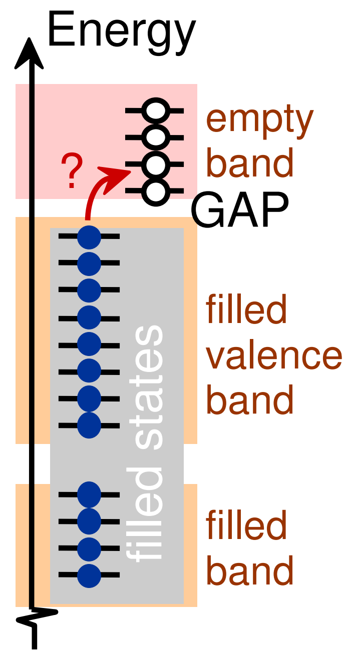
Pure Semiconductors: Conductivity vs T

- 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.)

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



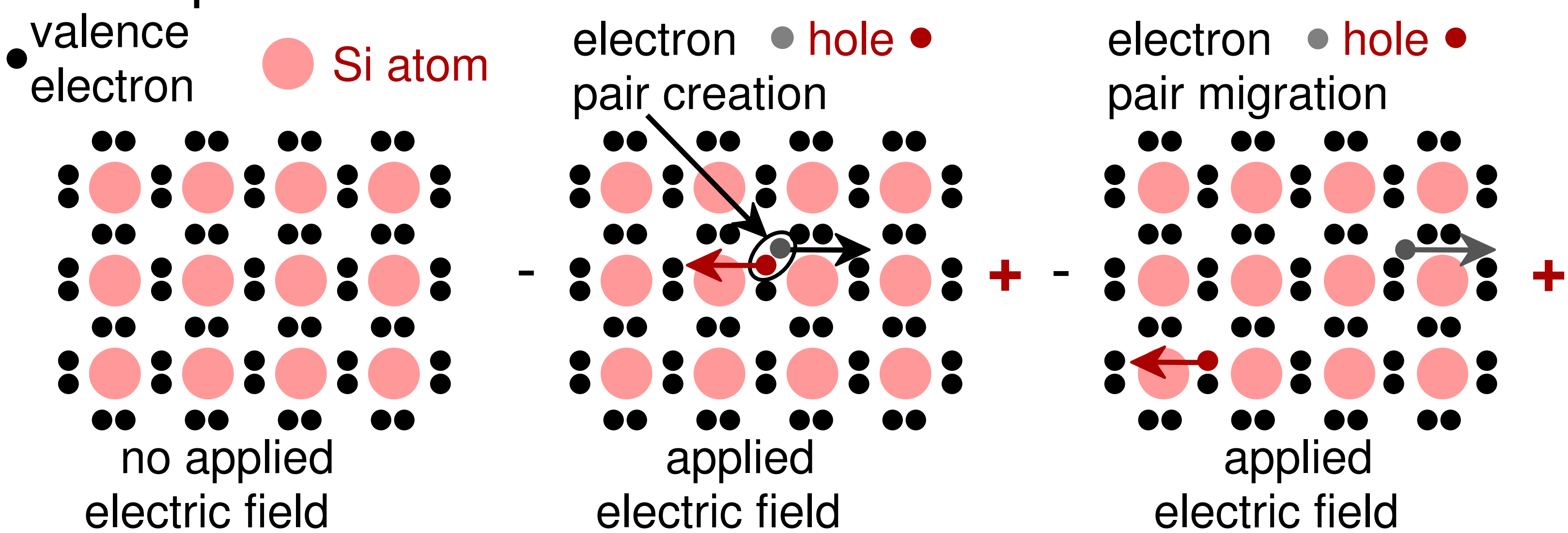
electrons can cross gap at higher T

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

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

Conduction in Terms of Electron and Hole Migration

- Concept of electrons and holes:



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

- Electrical Conductivity given by:

holes/m^3

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

hole mobility

electrons/m^3

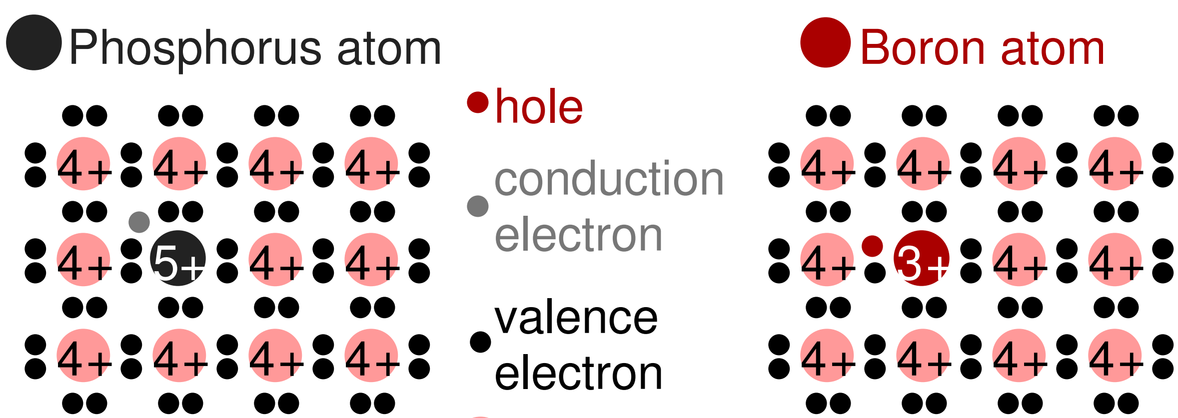
electron mobility

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

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

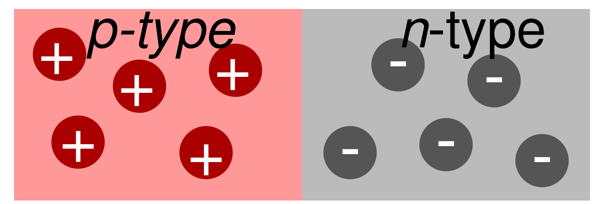
Adapted from Figs. 18.12(a) & 18.14(a), *Callister 7e.*

p-n Rectifying Junction

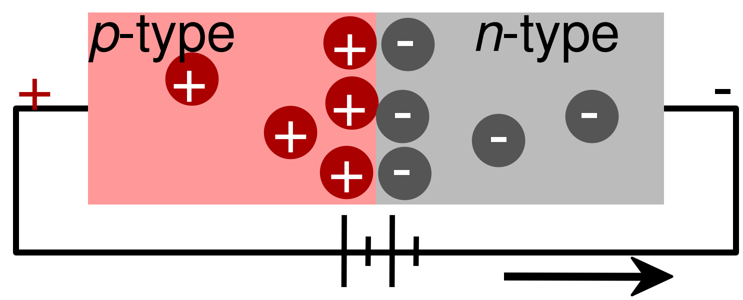
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.
- Processing: diffuse P into one side of a B-doped crystal.
- Results:

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

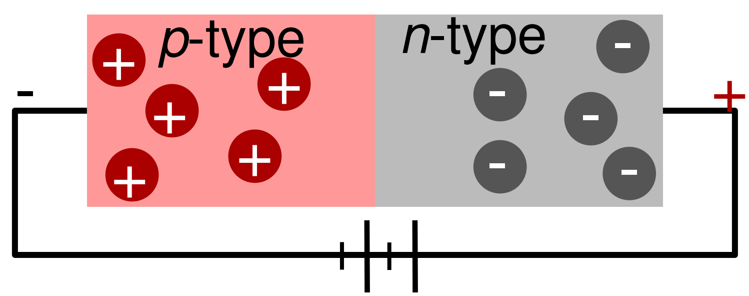
--No applied potential: no net current flow.



--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.

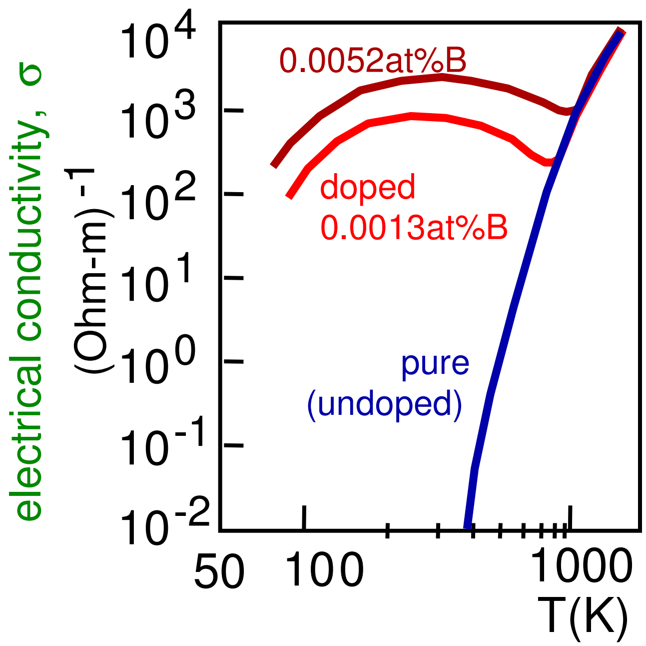


Intrinsic Semiconductors

- 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.

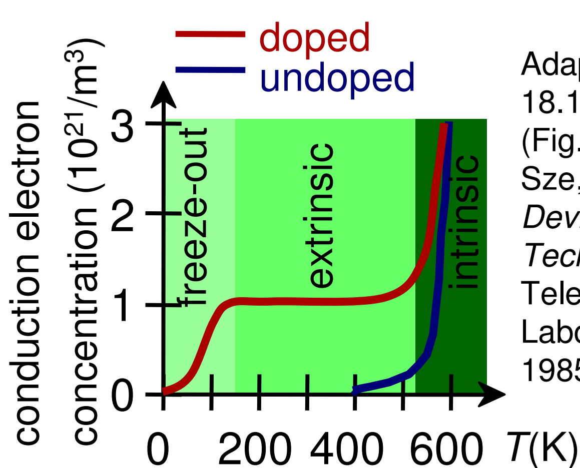
Doped Semiconductor: Conductivity vs. T

- 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.)

Number of Charge Carriers

Intrinsic Conductivity

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

- for intrinsic semiconductor $n = p$

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

- Ex: GaAs

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

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

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

Properties of Rectifying Junction

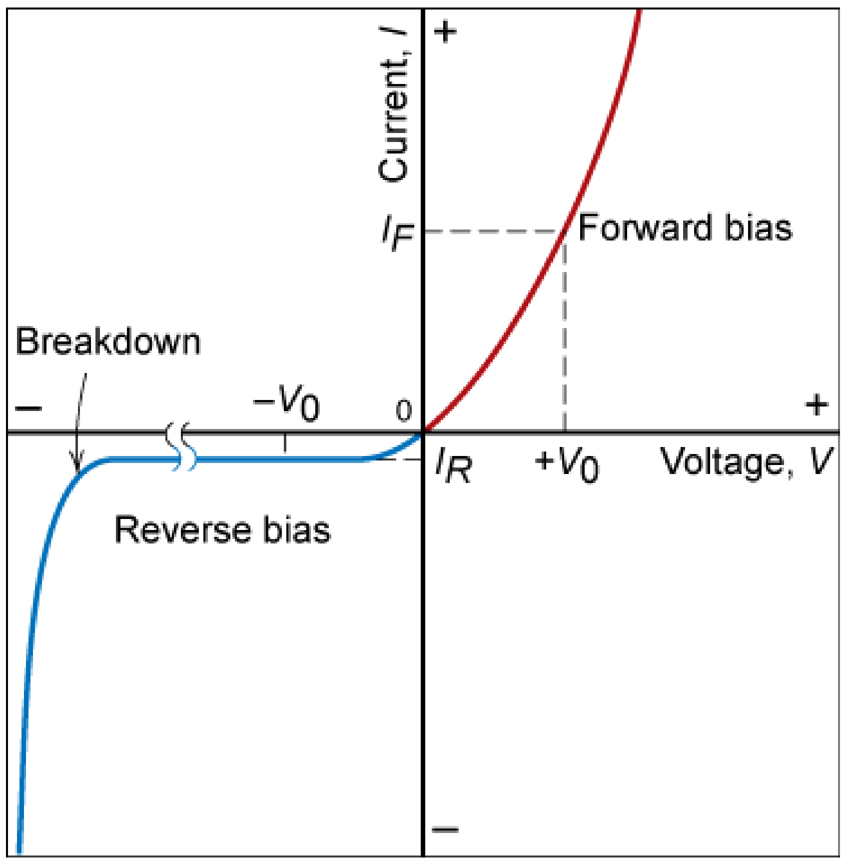


Fig. 18.22, *Callister 7e.*

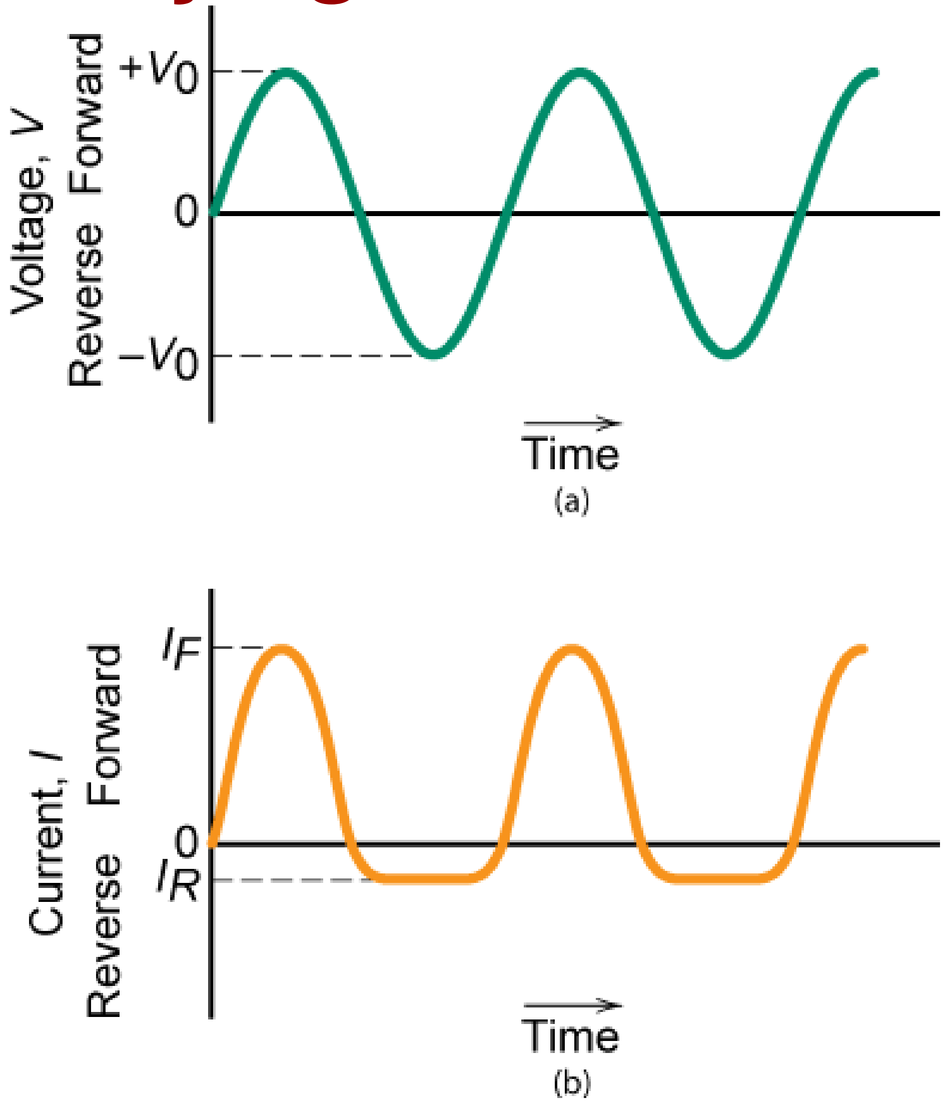
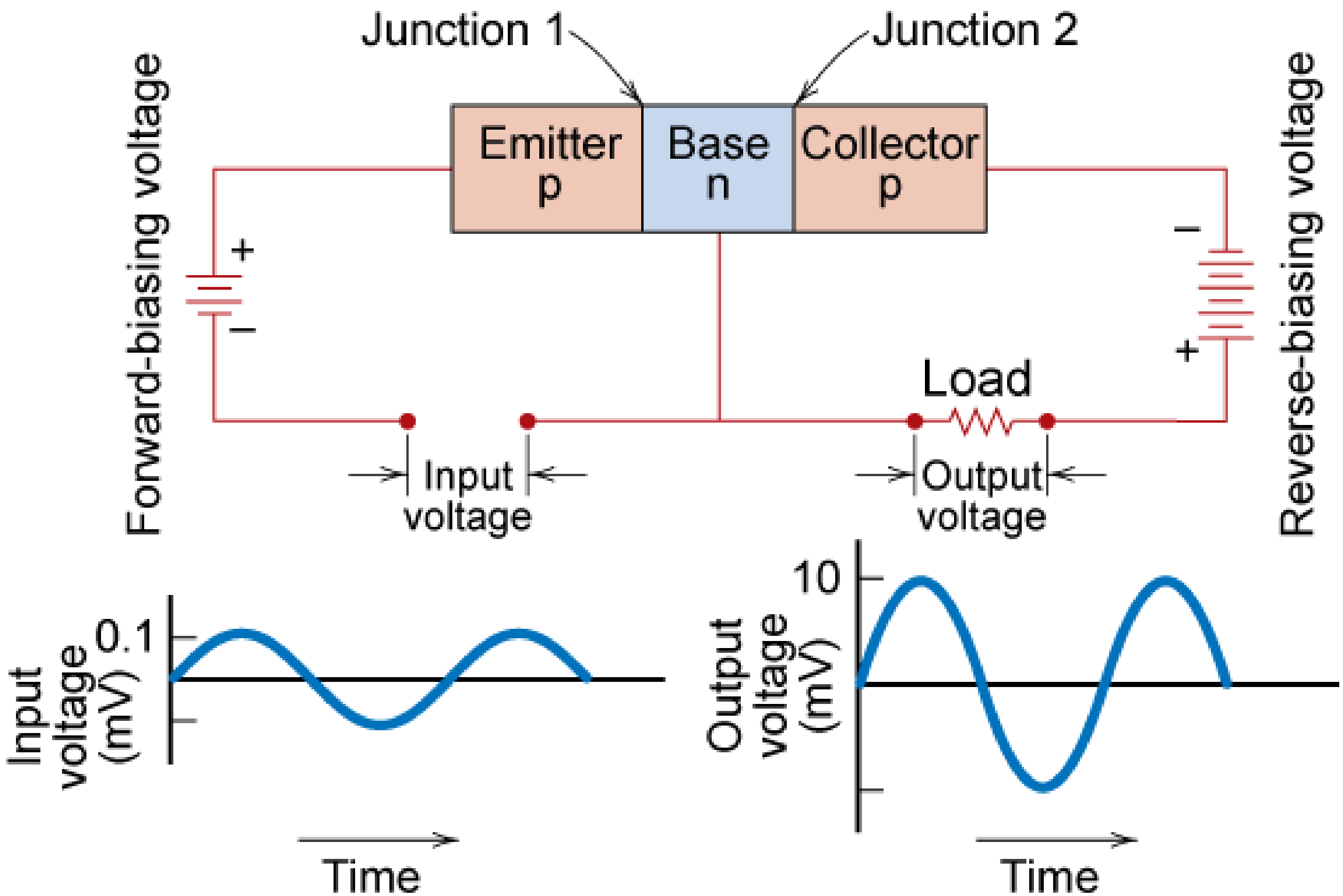


Fig. 18.23, *Callister 7e.*

Transistor MOSFET

- MOSFET (metal oxide semiconductor field effect transistor)

Fig. 18.24, *Callister 7e*.



Integrated Circuit Devices

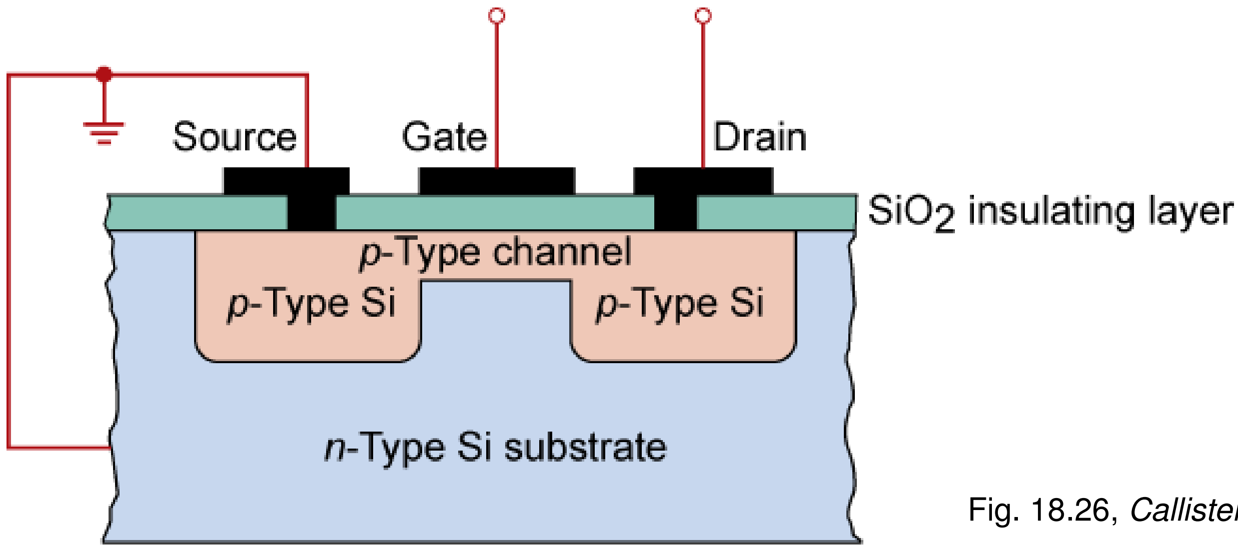


Fig. 18.26, *Callister 6e*.

- 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”

Ferroelectric Ceramics

Ferroelectric Ceramics are dipolar below Curie T_C = 120ºC

- cooled below T_c in strong electric field - make material with strong dipole moment

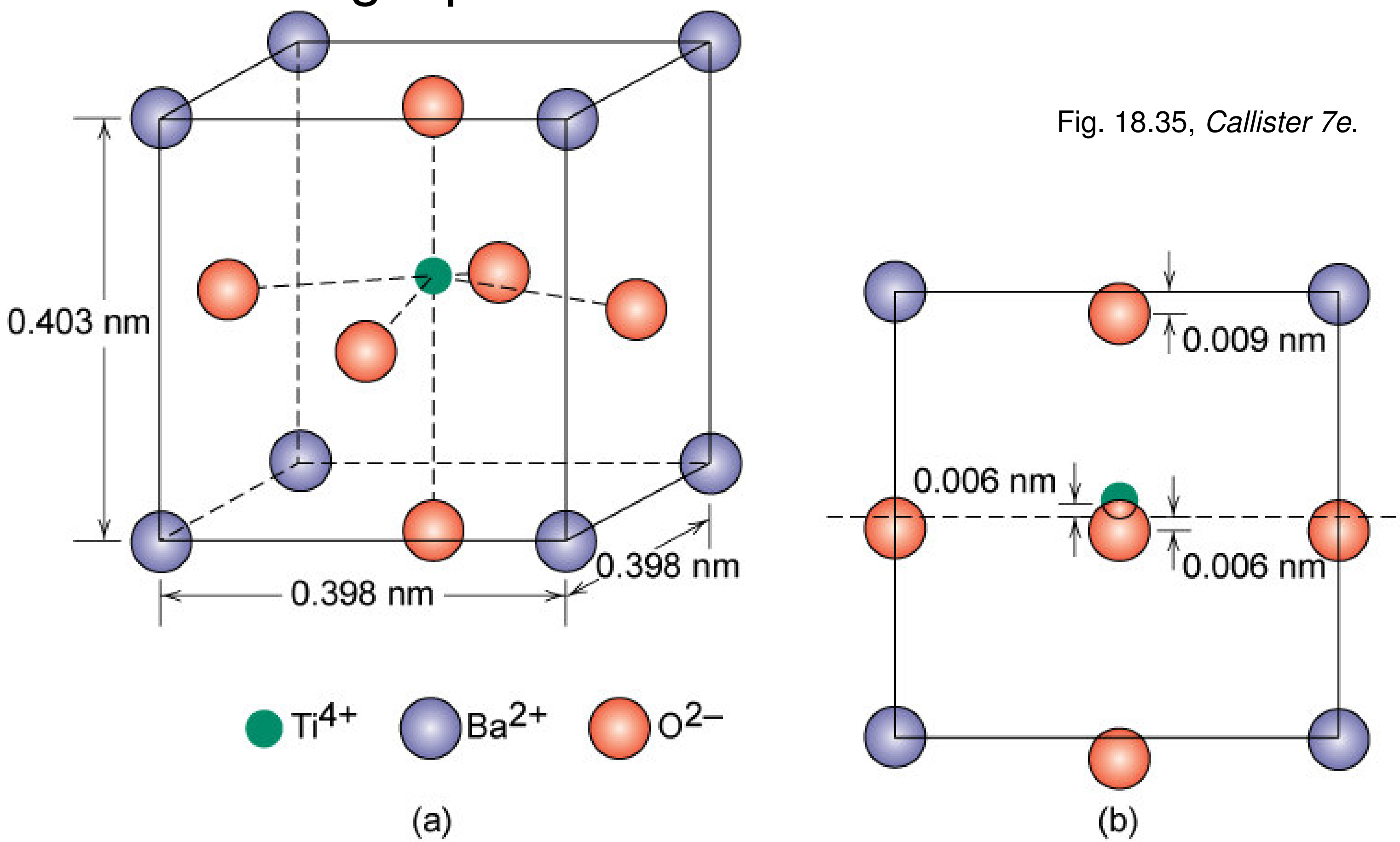
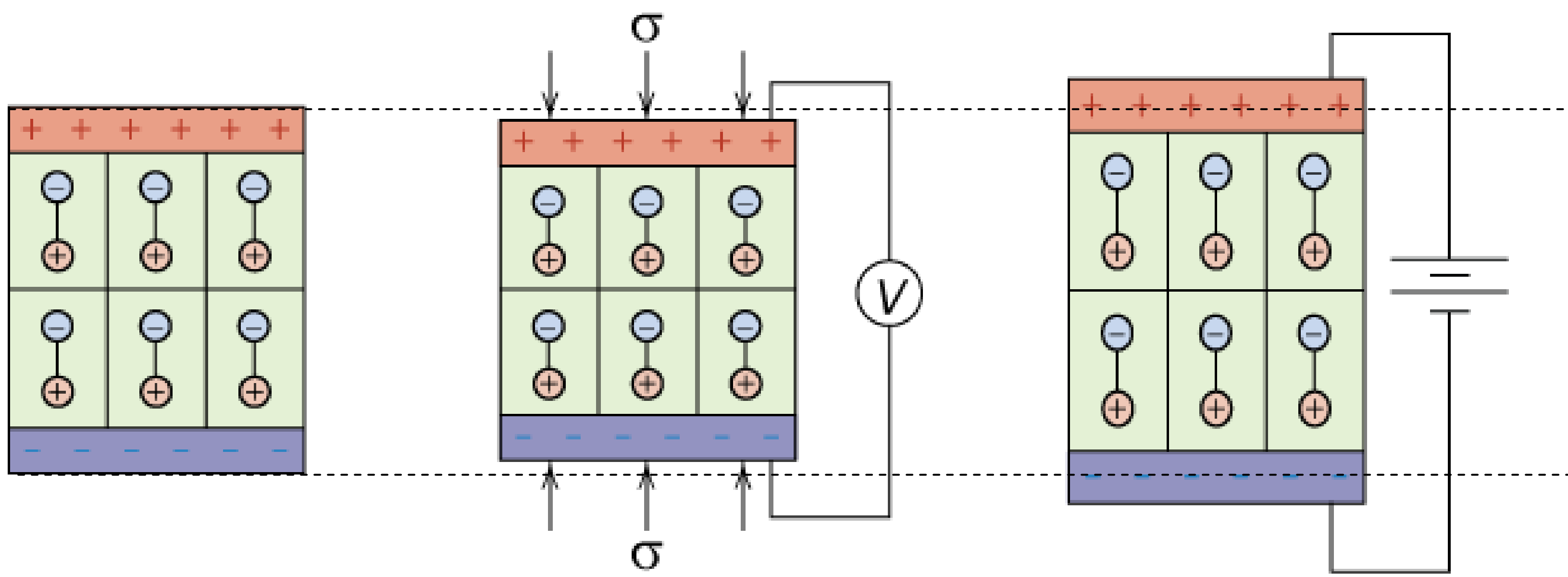


Fig. 18.35, *Callister 7e*.

Piezoelectric Materials

Piezoelectricity – application of pressure produces current



at rest

compression induces voltage

applied voltage induces expansion

Adapted from Fig. 18.36, *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.
- For pure semiconductors, conductivity is increased by
  -- increasing temperature
  -- doping (e.g., adding B to Si (*p*-type) or P to Si (*n*-type).