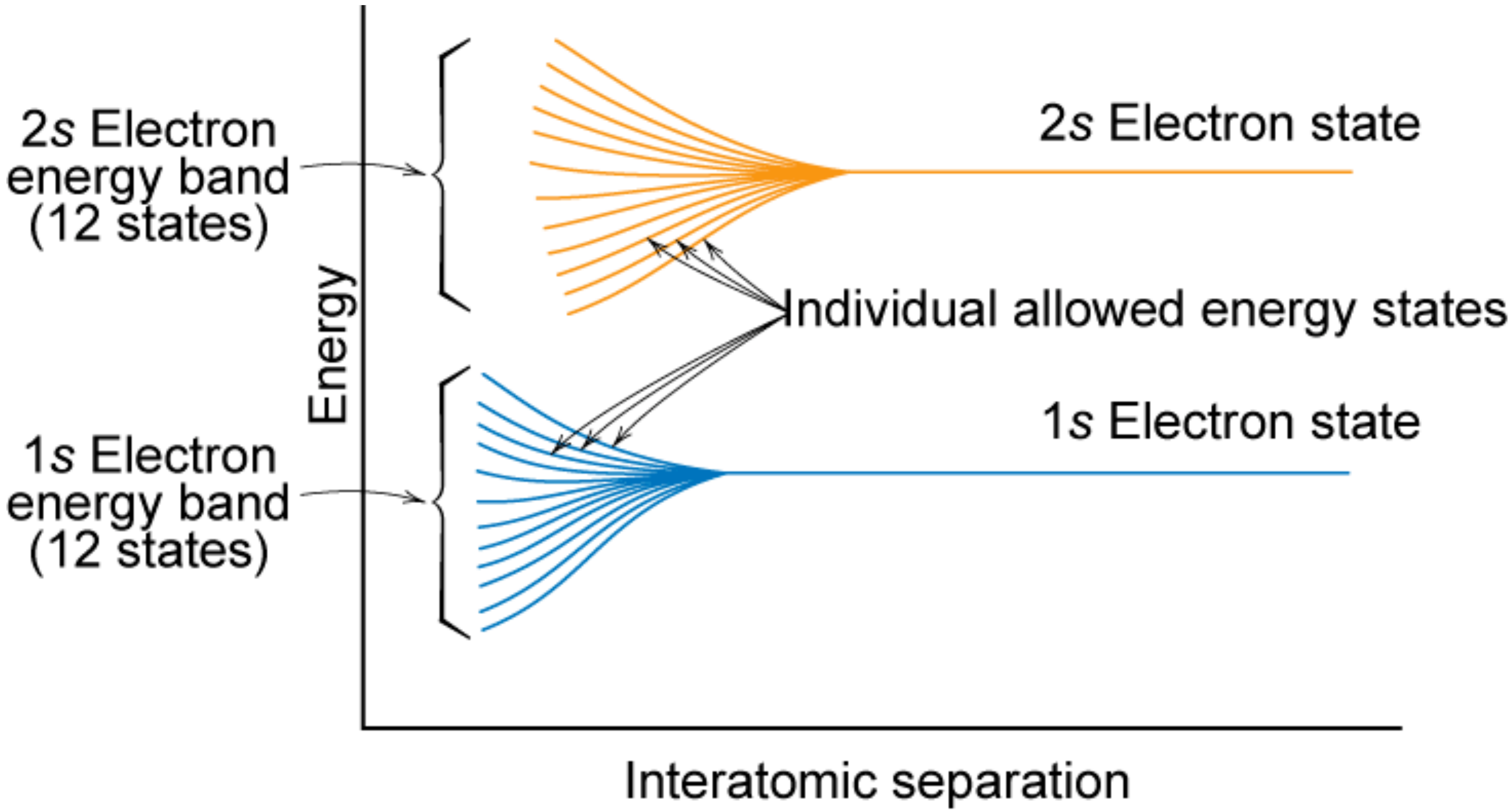
Chapter 18: Electrical Properties

- 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*?

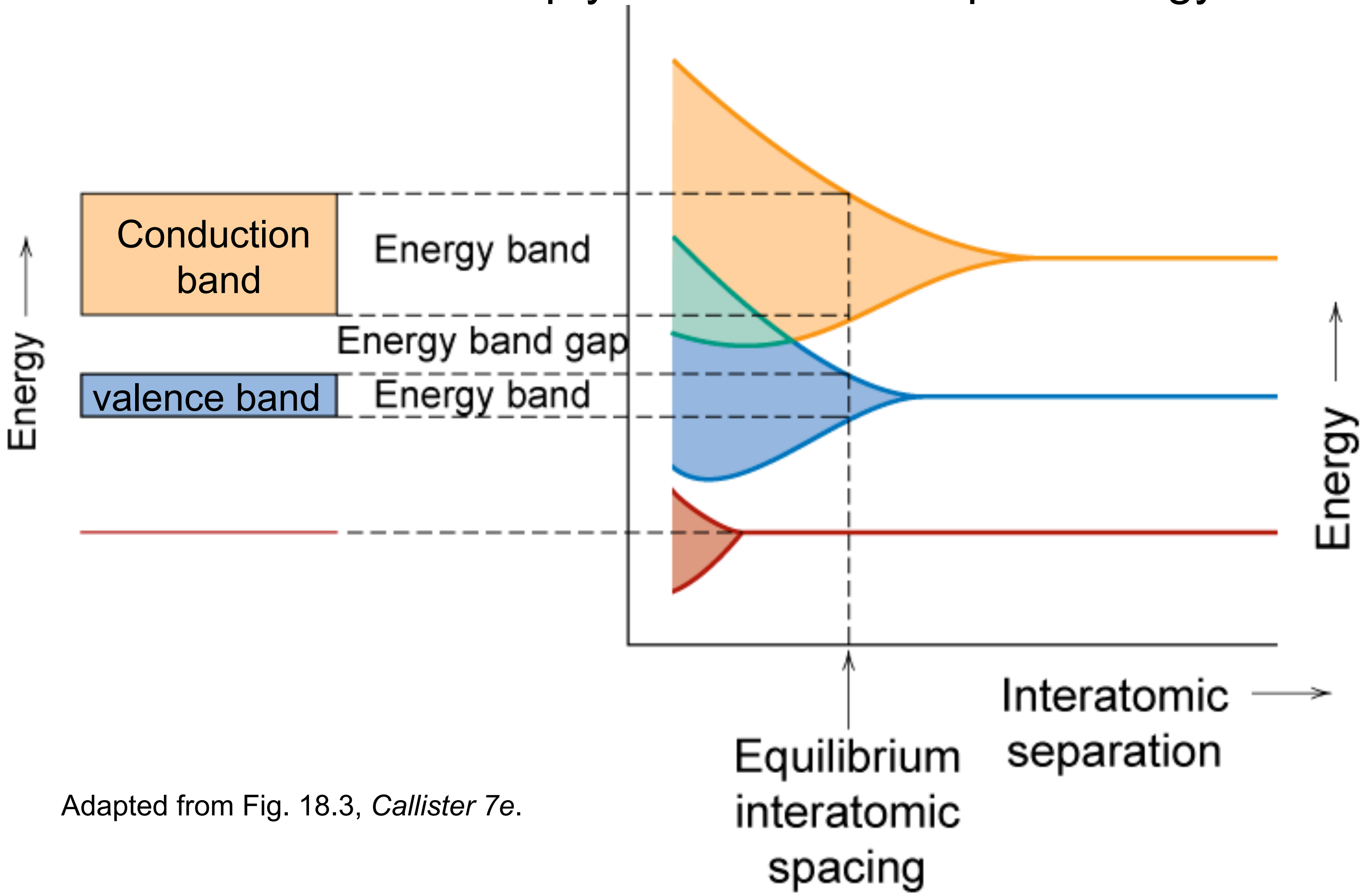
Electronic Band Structures



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

Band Structure

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

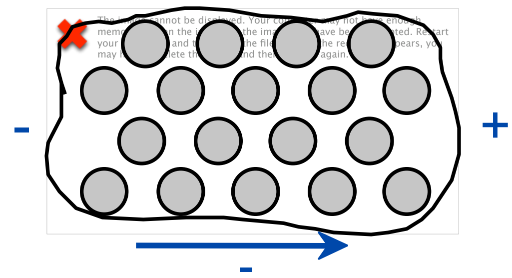


Adapted from Fig. 18.3, *Callister 7e*.

Conduction & Electron Transport

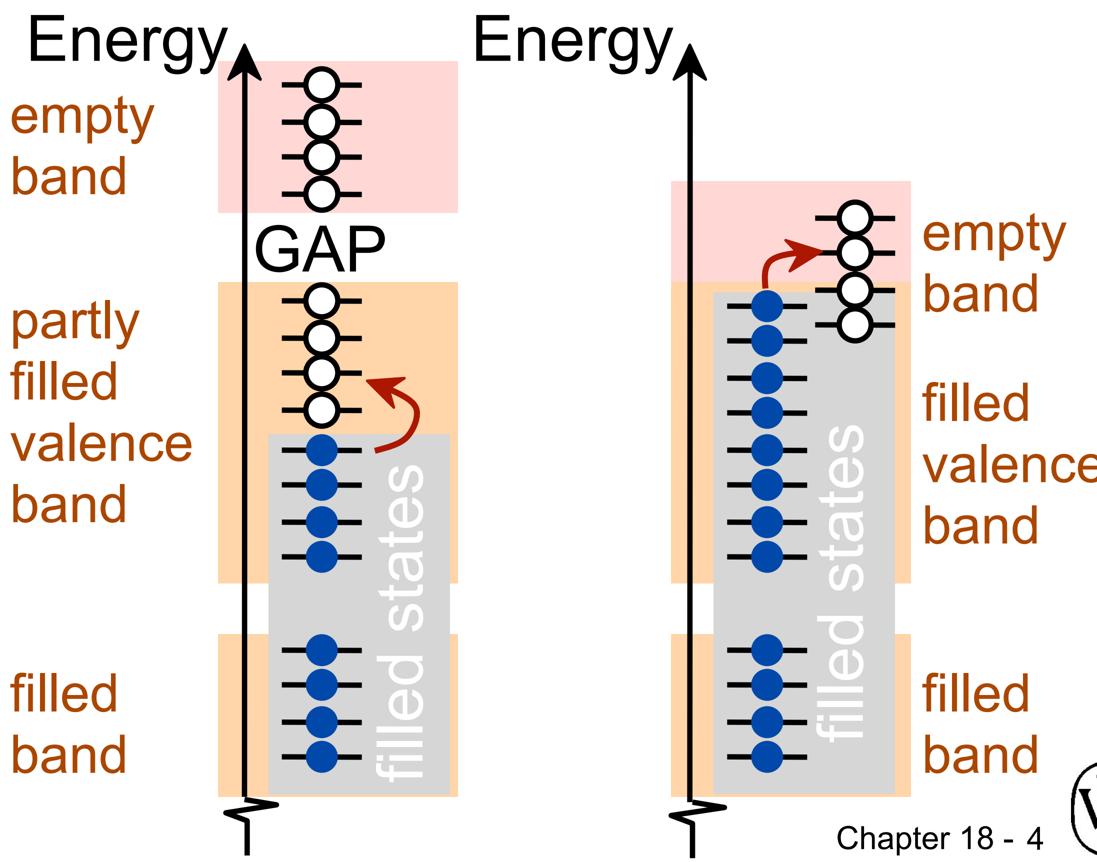
- Metals (Conductors):

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



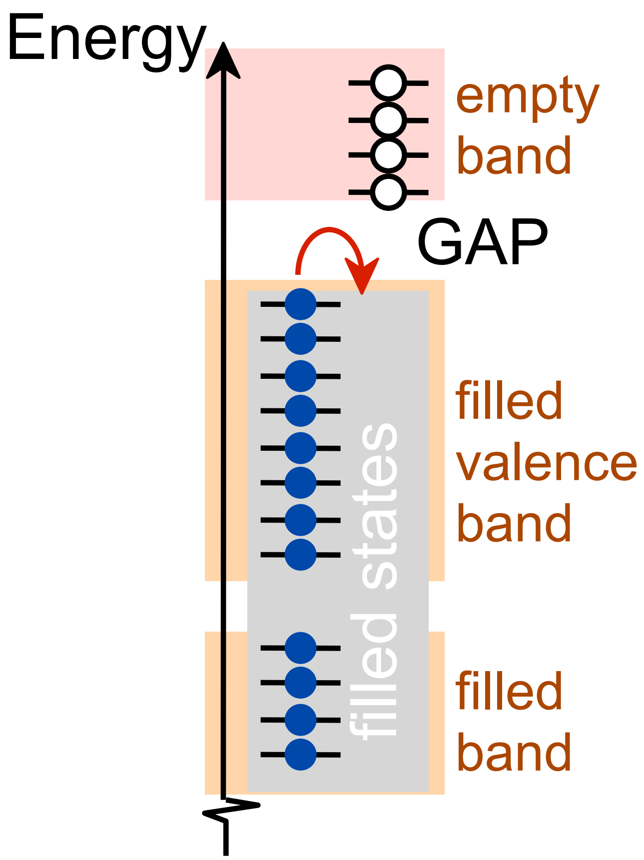
- Energy States:

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

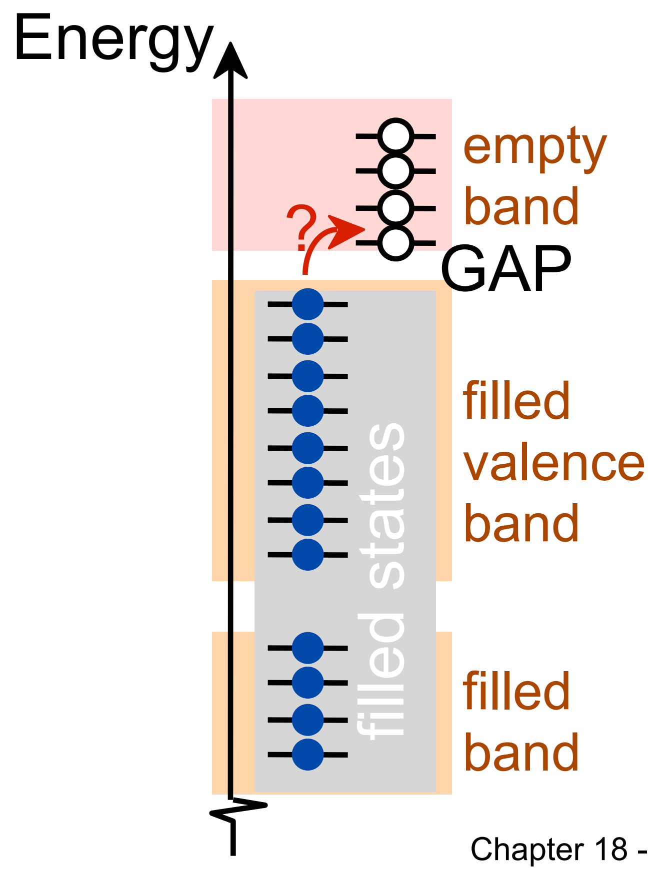


Energy States: Insulators & Semiconductors

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

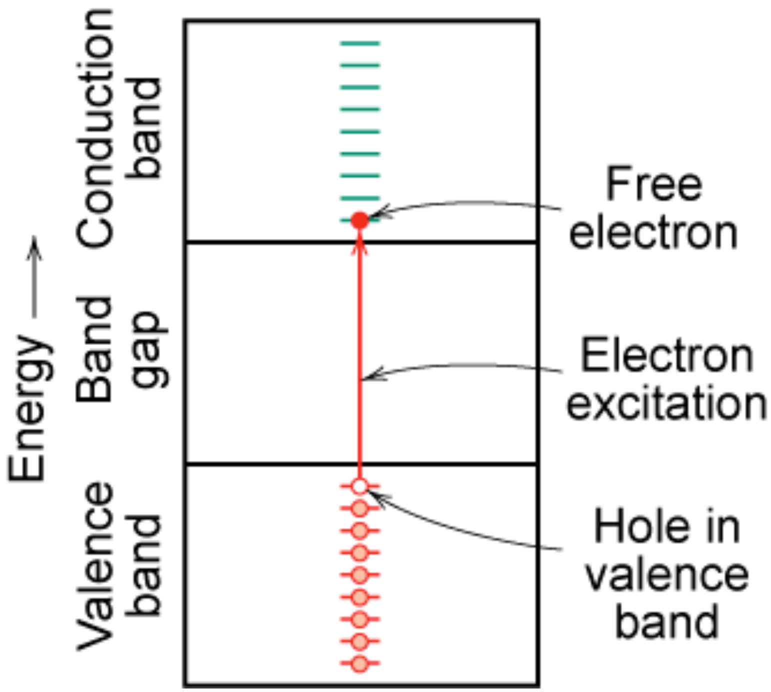


- Semiconductors:
  -- Higher energy states separated by smaller gap (< 2 eV).



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

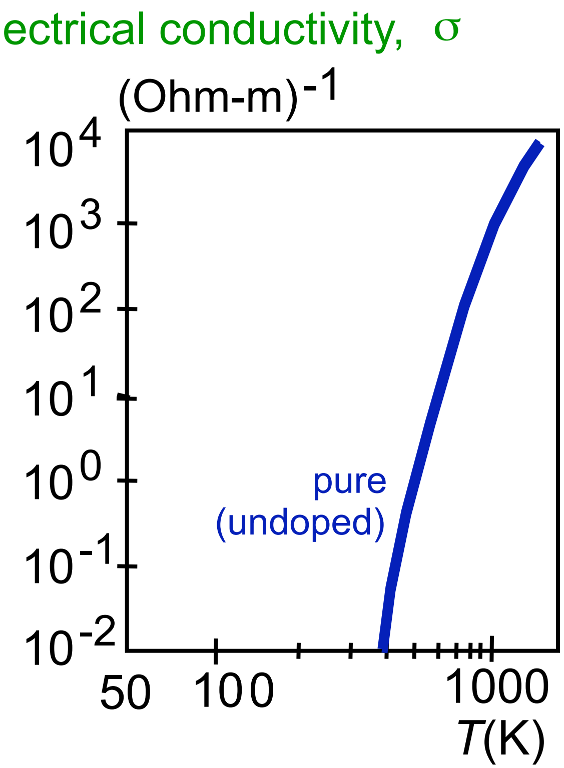
Higher temp. promotes more electrons into the conduction band

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

Electrons scattered by impurities, grain boundaries, etc.

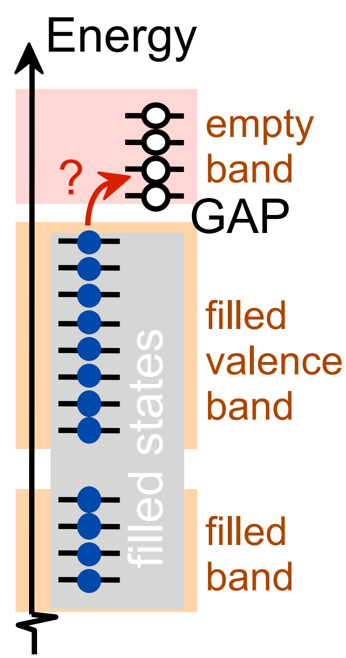
Pure Semiconductors: Conductivity vs T

- 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.)

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



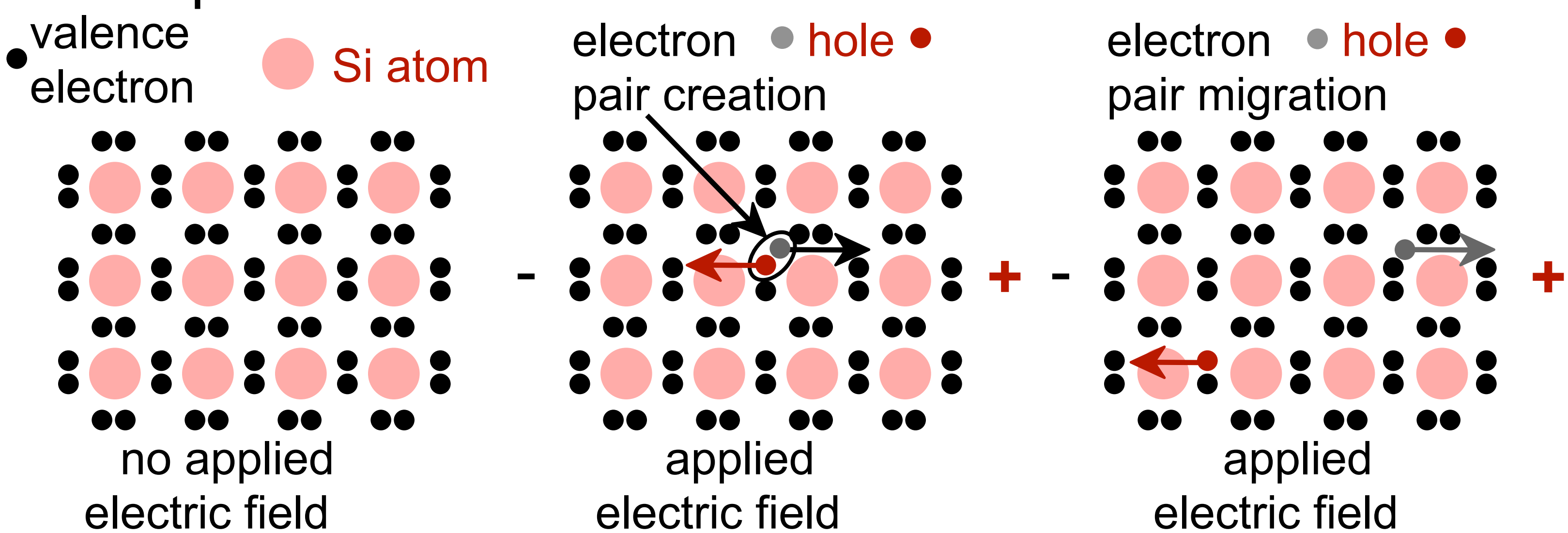
electrons can cross gap at higher *T*

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

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

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)

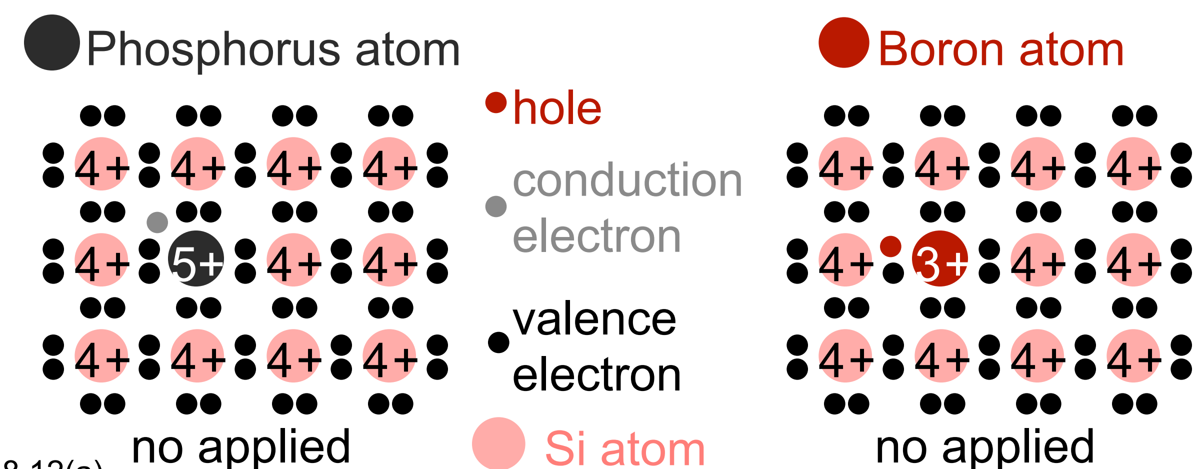
hole mobility (μ_h)

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

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

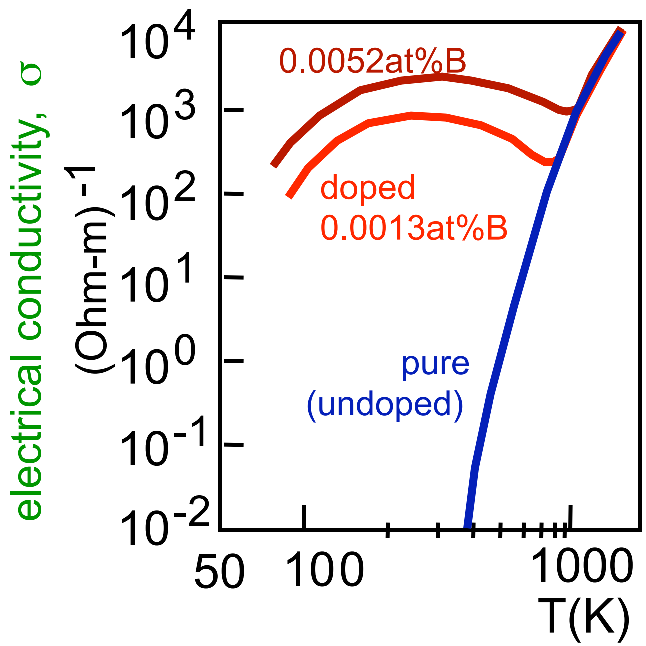
Adapted from Figs. 18.12(a) & 18.14(a), *Callister 7e.*

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.

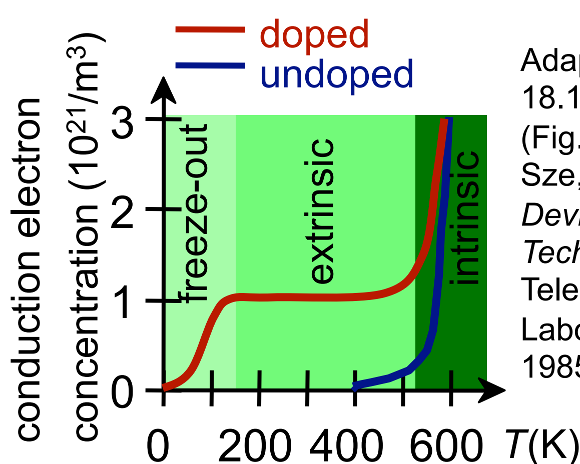
Doped Semiconductor: Conductivity vs. T

- 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

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

- 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 $\qquad n = 4.8 \times 10^{24}\ \mathrm{m^{-3}}$

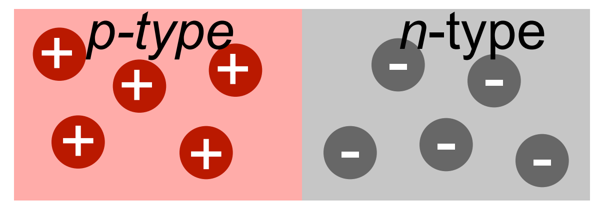
For Si $\qquad n = 1.3 \times 10^{16}\ \mathrm{m^{-3}}$

p-n Rectifying Junction

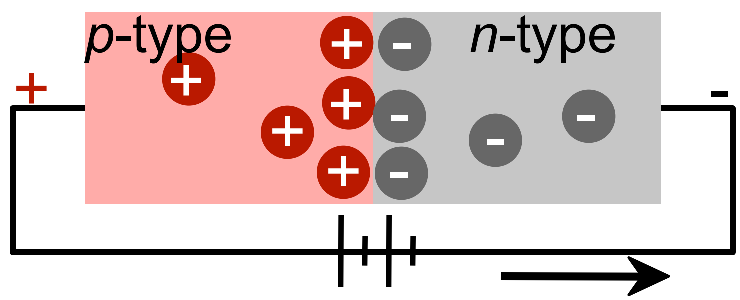
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.
- Processing: diffuse P into one side of a B-doped crystal.
- Results:

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

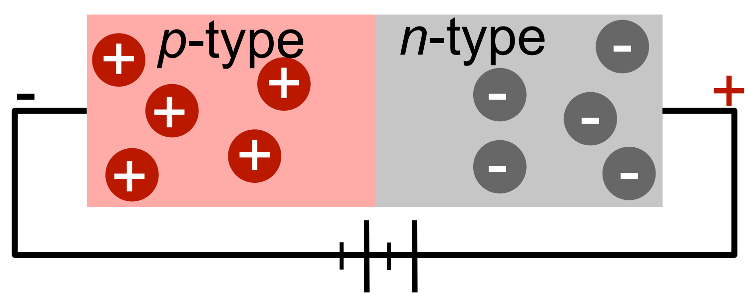
--No applied potential: no net current flow.



--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

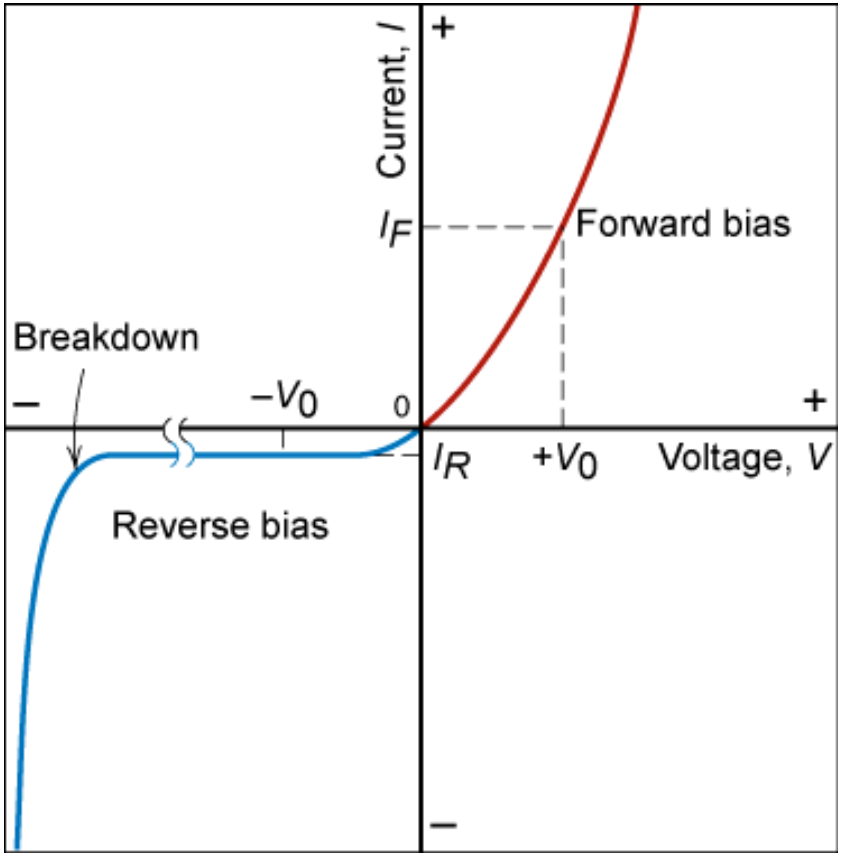


Fig. 18.22, *Callister 7e*.

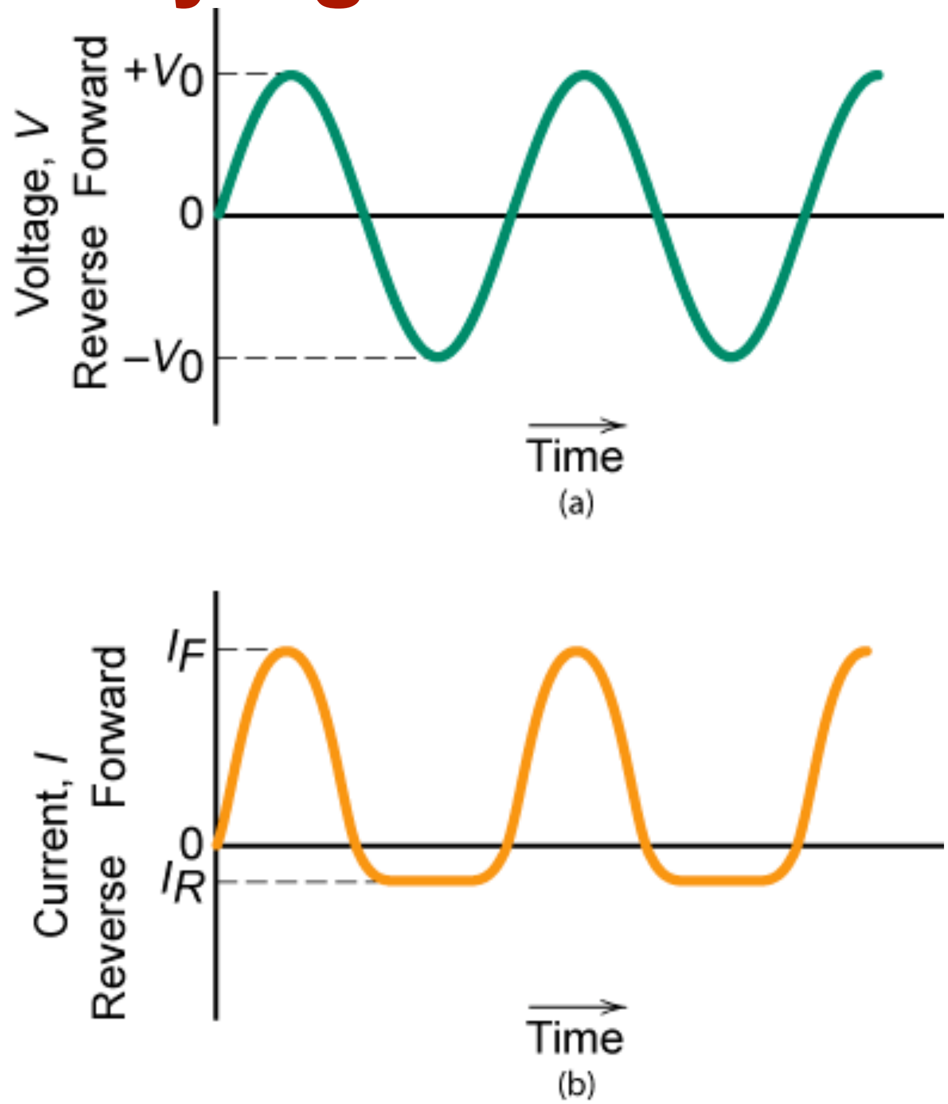


Fig. 18.23, *Callister 7e*.

Transistor MOSFET

- MOSFET (metal oxide semiconductor field effect transistor)

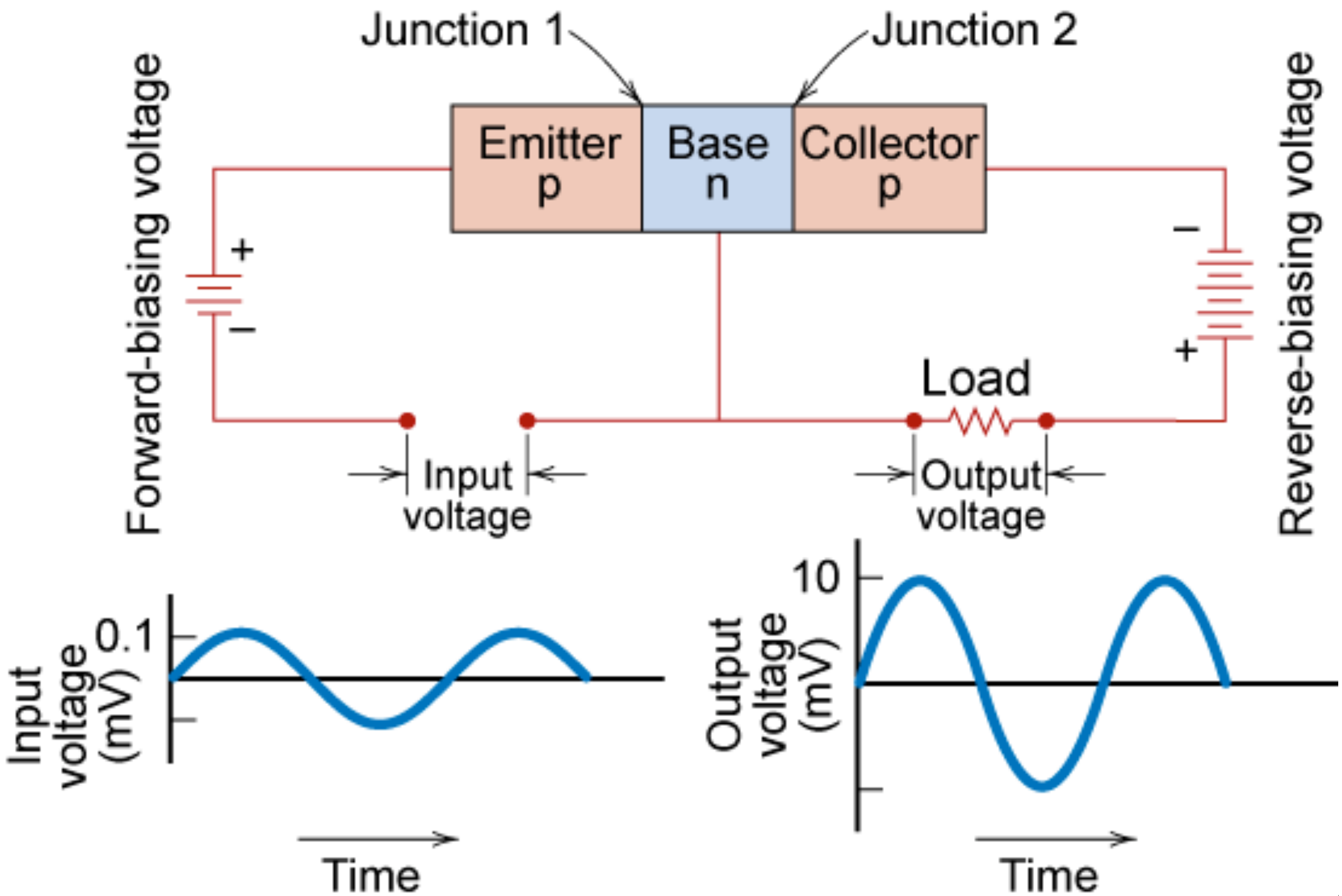


Fig. 18.24, *Callister 7e*.

Integrated Circuit Devices

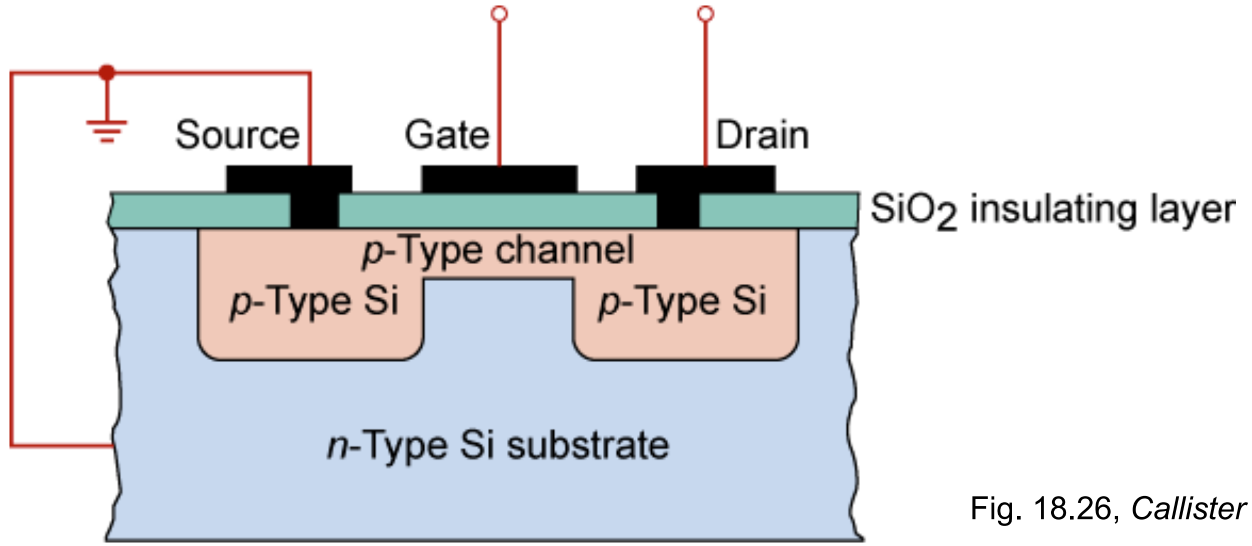
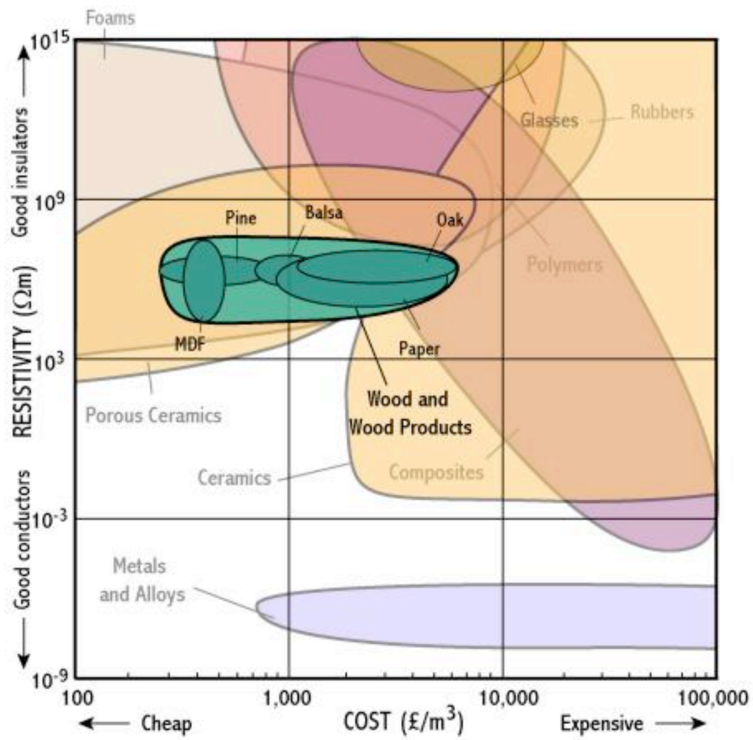


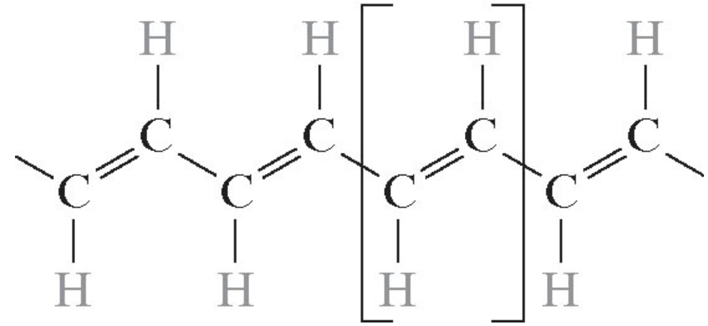
Fig. 18.26, *Callister 6e*.

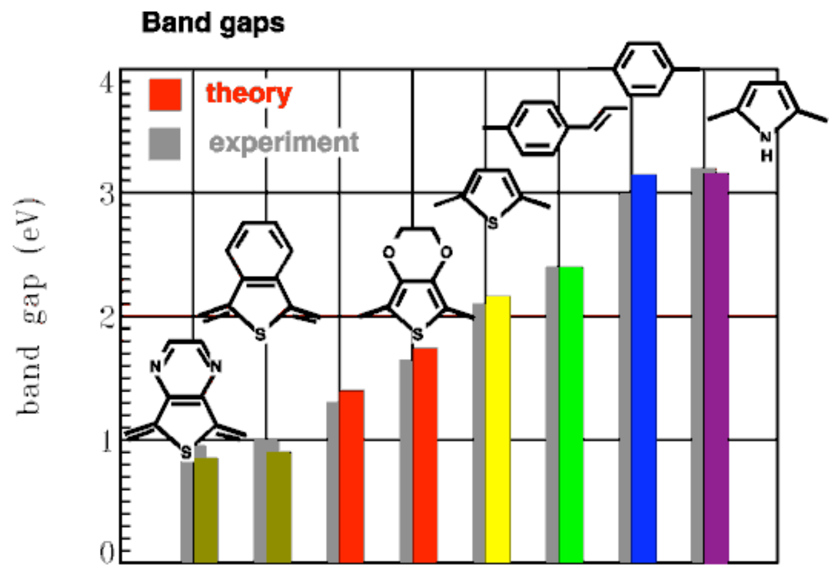
- Integrated circuits - state of the art ca. 50 nm line width
  - 1 Mbyte cache on board
  - > 100,000,000 components on chip
  - chip formed layer by layer
    - Al is the “wire”

Electrical Properties of Polymers



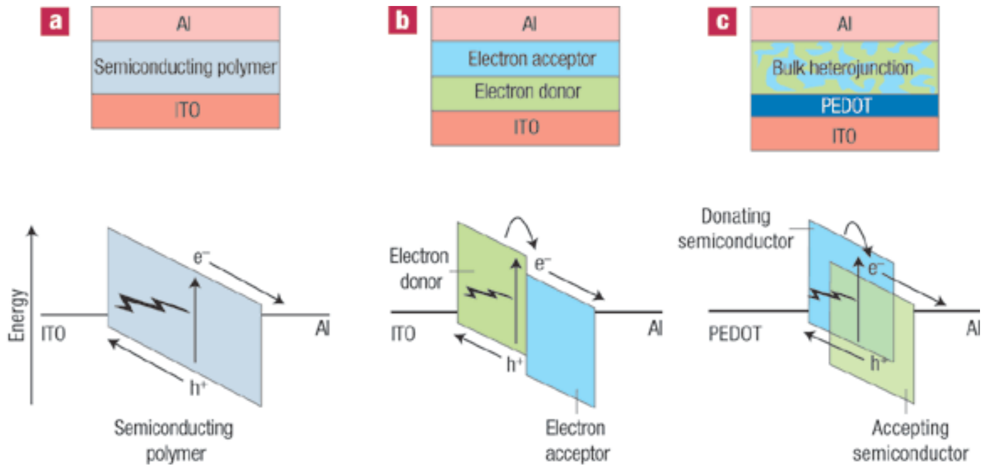
http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/resistivity-cost/NS6Chart.html

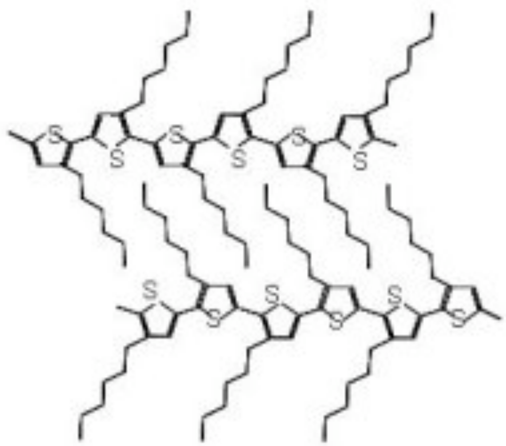


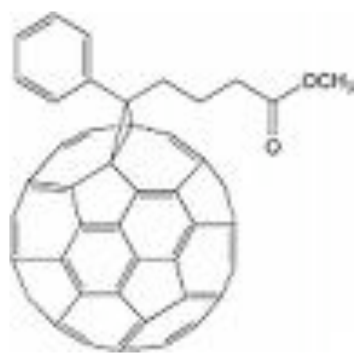


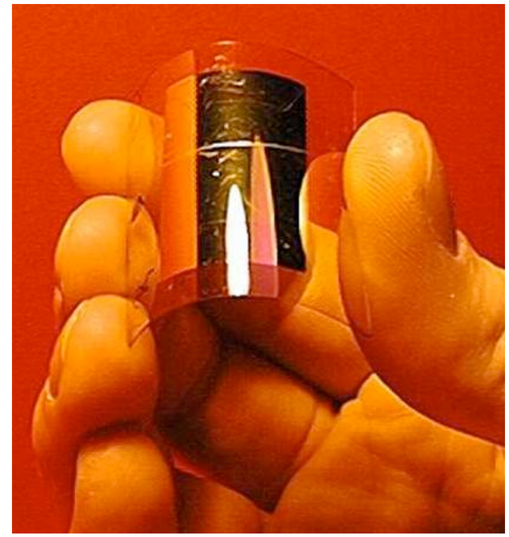
http://www.infochembio.ethz.ch/links/en/polymer_leitend.html

Polymer Solar Cells









ehf.uni-oldenburg.de

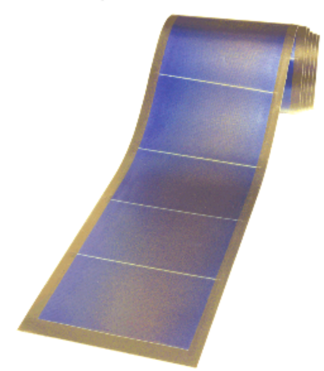


Photo courtesy of United Solar Ovonic, LLC

Nature Materials ***5*, 675 - 676 (2006)**

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).