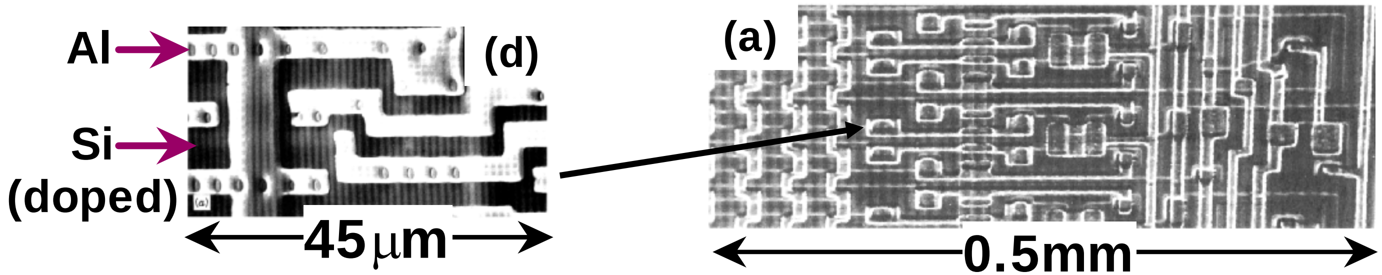
CHAPTER 18: ELECTRICAL PROPERTIES

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.

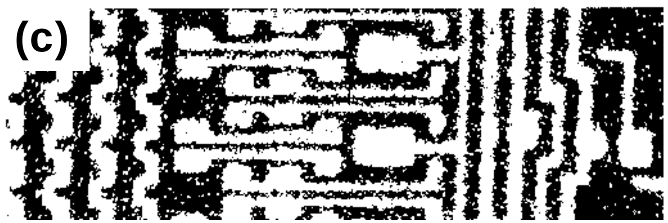


Fig. (d) from Fig. 18.25, *Callister 6e*. (Fig. 18.25 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Fig. (a), (b), (c) from Fig. 18.0, *Callister 6e*.

ELECTRICAL CONDUCTION

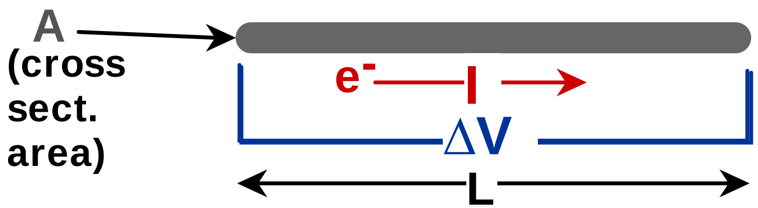
- **Ohm's Law:**

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

voltage drop (volts)

current (amps)

resistance (Ohms)



- **Resistivity, ρ and Conductivity, σ:**
  --geometry-independent forms of Ohm's Law

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

E: electric field intensity

resistivity (Ohm-m)

J: current density

conductivity

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

- **Resistance:** $R = \dfrac{\rho L}{A} = \dfrac{L}{A\sigma}$

CONDUCTIVITY: COMPARISON

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

conductors

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

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

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

semiconductors

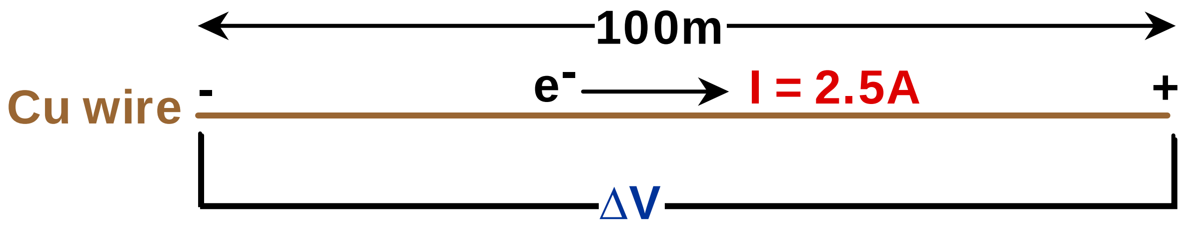
POLYMERS	
Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}-10^{-17}

insulators

Selected values from Tables 18.1, 18.2, and 18.3, *Callister 6e*.

EX: CONDUCTIVITY PROBLEM

- **Question 18.2, p. 649, *Callister 6e*:**



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

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

100m → L

< 1.5V → ΔV

2.5A → I

$\frac{\pi D^2}{4}$ → A

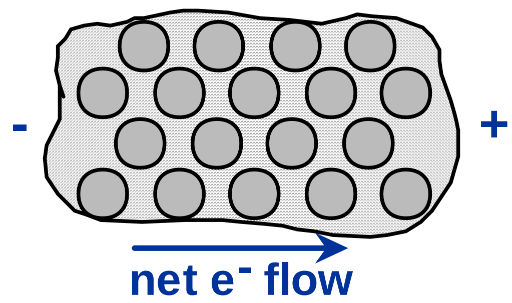
6.07 x 10^{7} (Ohm-m)$^{-1}$ → σ

Solve to get D > 1.88 mm

CONDUCTION & ELECTRON TRANSPORT

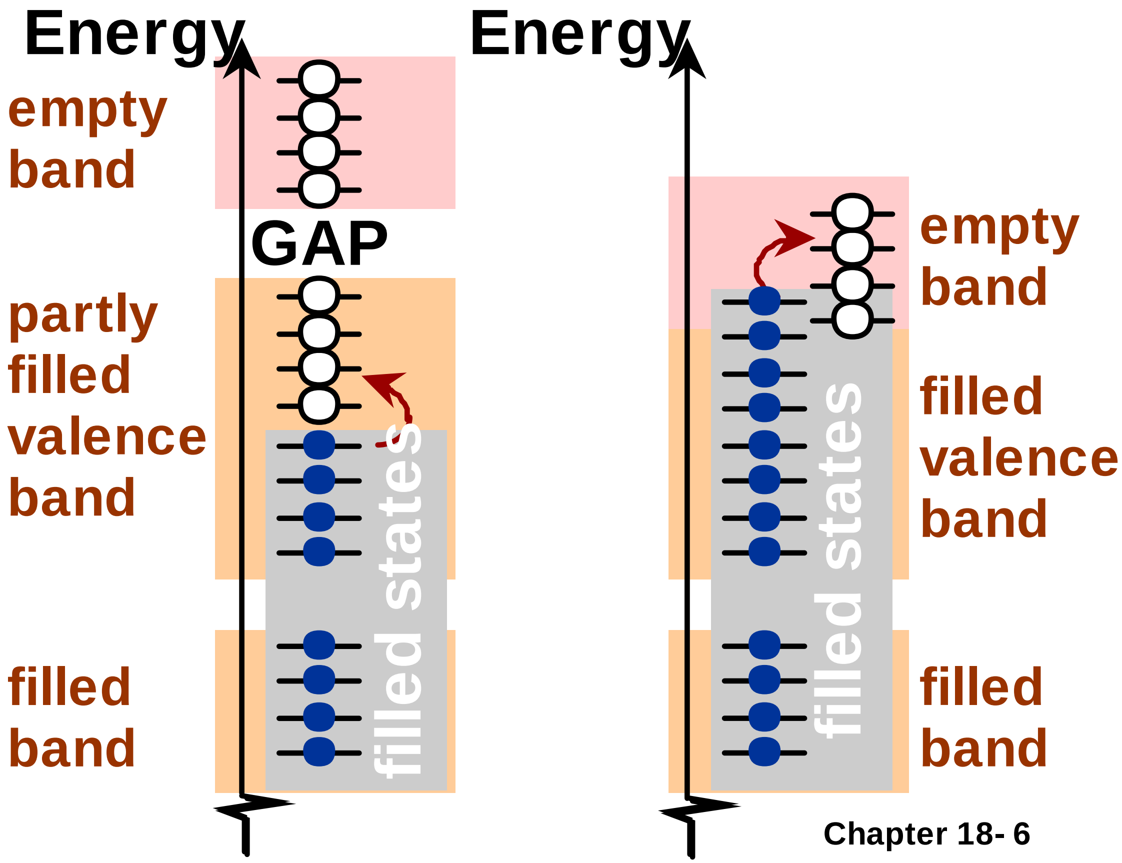
- **Metals:**

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



- **Energy States:**

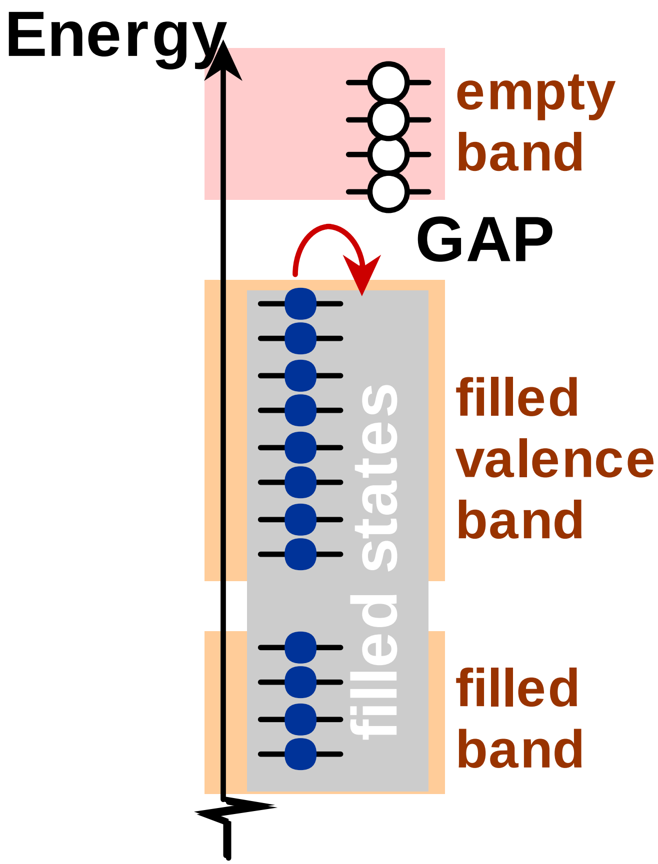
-- the cases below for metals show that nearby energy states are accessible by thermal fluctuations.



ENERGY STATES: INSULATORS AND SEMICONDUCTORS

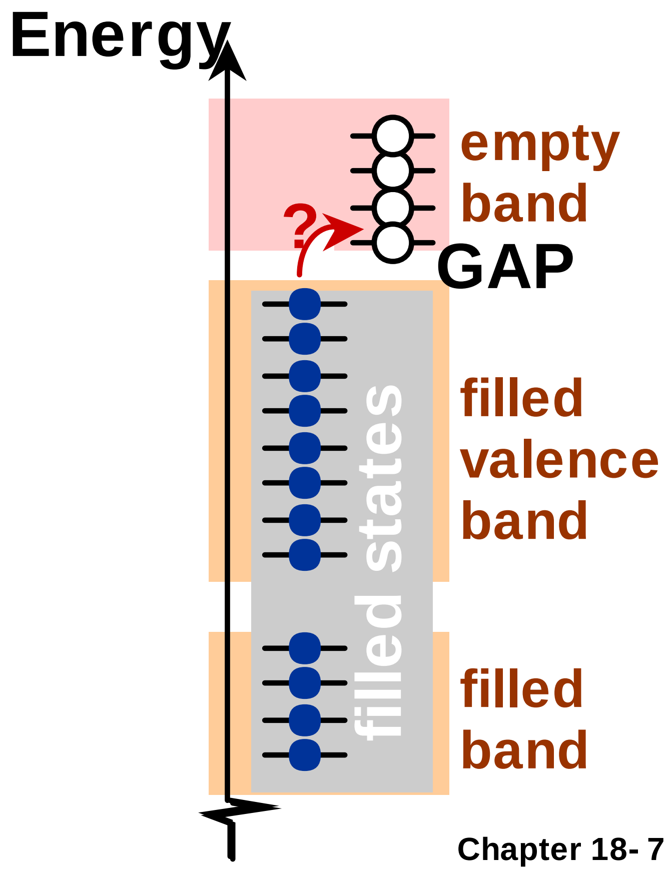
- **Insulators:**

  --Higher energy states not accessible due to gap.



- **Semiconductors:**

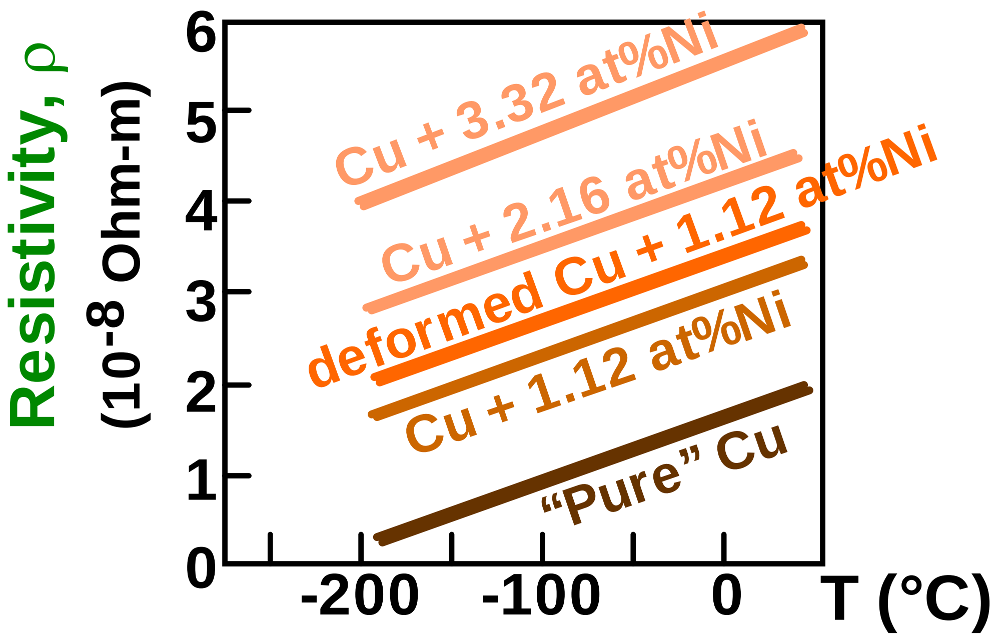
  --Higher energy states separated by a smaller gap.



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 6e*. (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.)

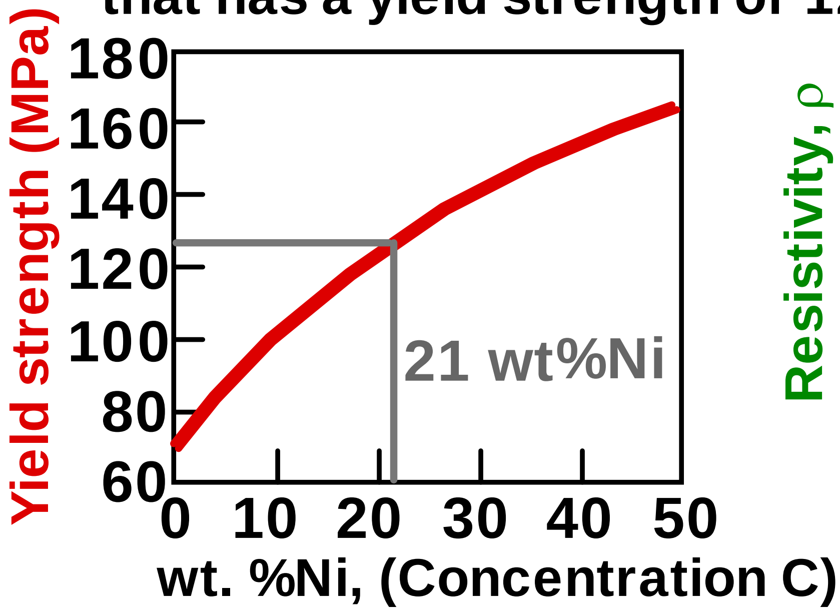
- **Resistivity increases with:**
  - --temperature
  - --wt% impurity
  - --%CW

$$\rho = \rho_{thermal} + \rho_{thermal} + \rho_{def}$$

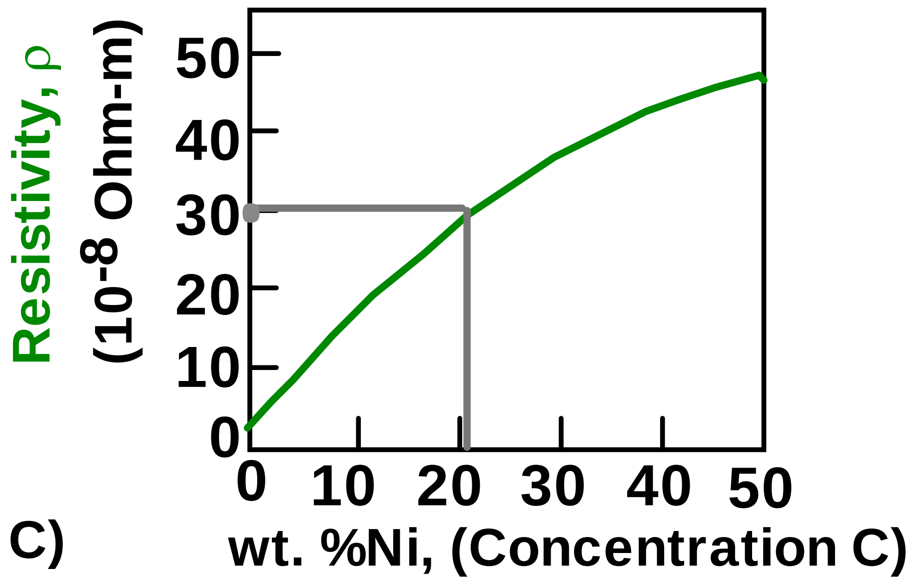
EX: ESTIMATING CONDUCTIVITY

- **Question:**

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



Adapted from Fig. 7.14(b), *Callister 6e*.



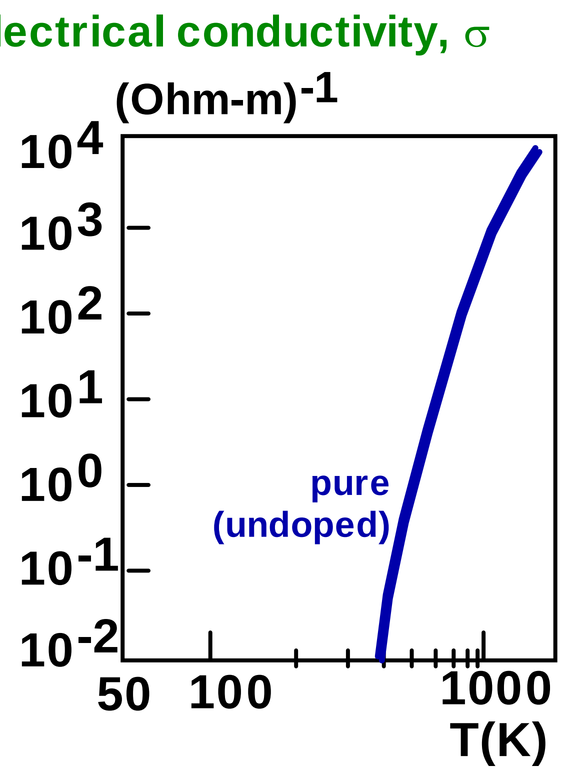
Adapted from Fig. 18.9, *Callister 6e*.

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

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

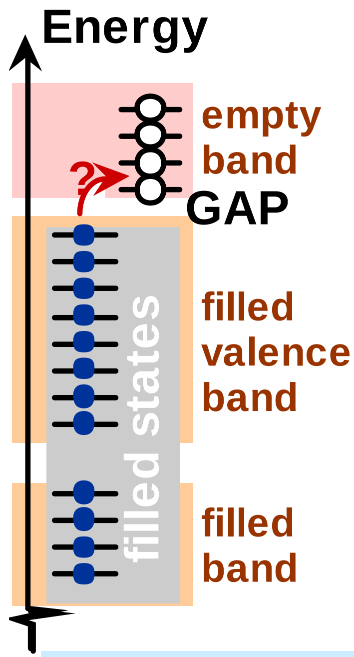
PURE SEMICONDUCTORS: CONDUCTIVITY VS T

- 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.)

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



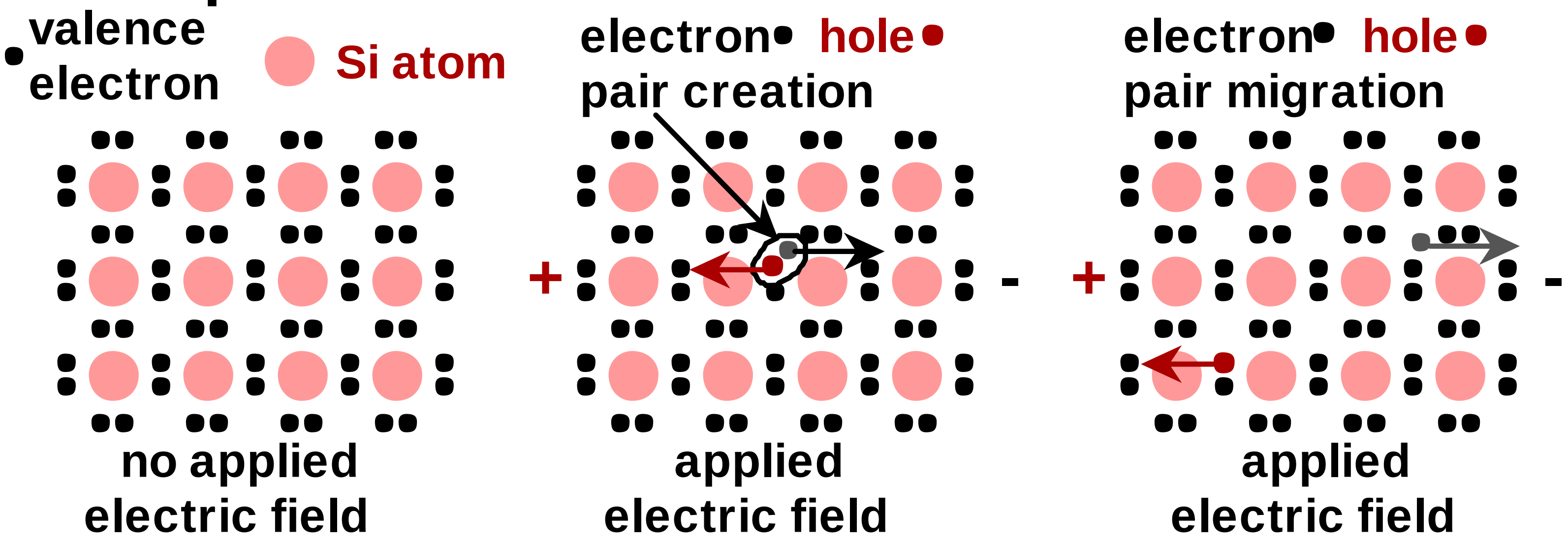
electrons can cross gap at higher T

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

Selected values from Table 18.2, *Callister 6e*.

CONDUCTION IN TERMS OF ELECTRON AND HOLE MIGRATION

- **Concept of electrons and holes:**



Adapted from Fig. 18.10, *Callister 6e*.

- **Electrical Conductivity given by:**

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

holes/m^3

hole mobility

electrons/m^3

electron mobility

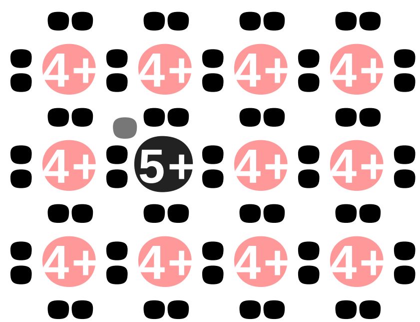
INTRINSIC VS EXTRINSIC CONDUCTION

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

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

Phosphorus atom

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



no applied electric field

hole

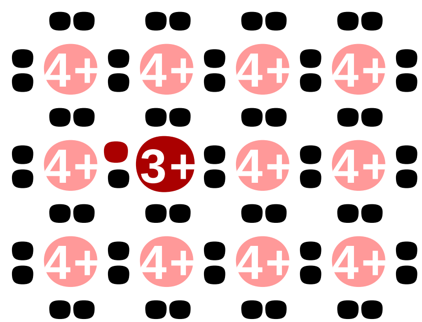
conduction electron

valence electron

Si atom

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

Boron atom

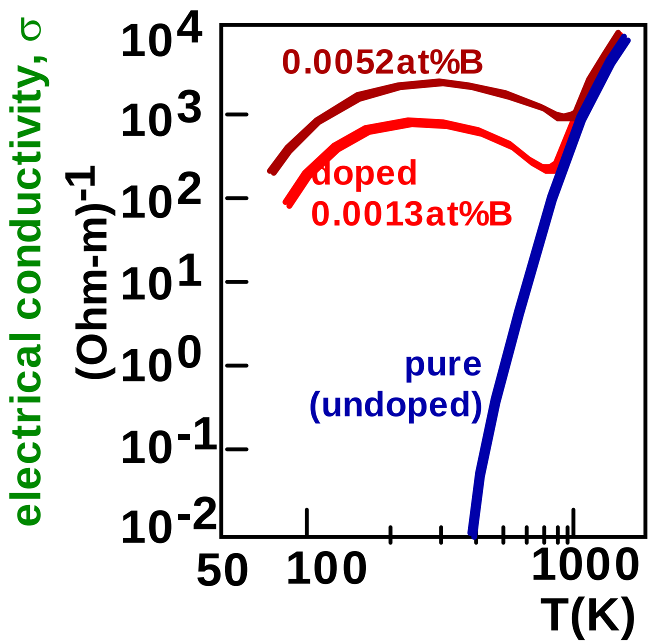


no applied electric field

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

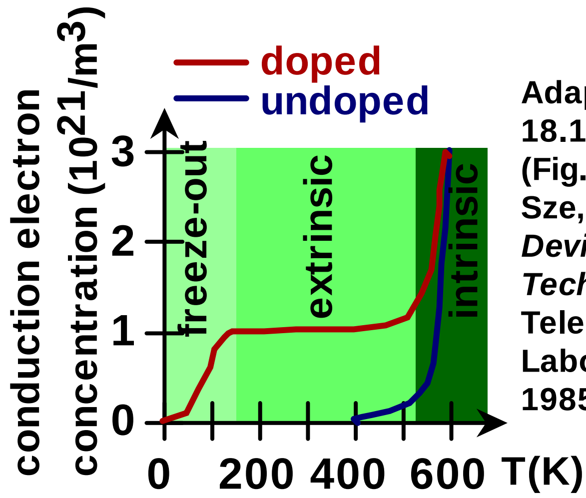
DOPED SEMICON: CONDUCTIVITY VS T

- 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 < 100K: "freeze-out" thermal energy insufficient to excite electrons.
  --for 150K < T < 450K: "extrinsic"
  --for T >> 450K: "intrinsic"

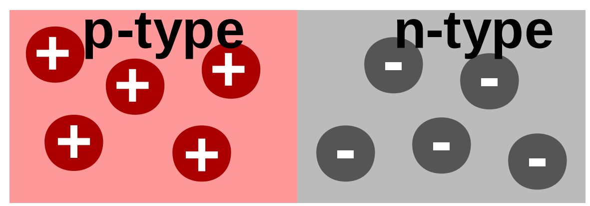


Adapted from Fig. 18.16, *Callister 6e*. (Fig. 18.16 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

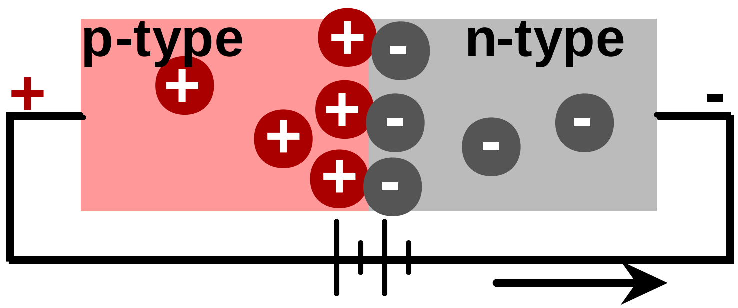
P-N RECTIFYING JUNCTION

- **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:**

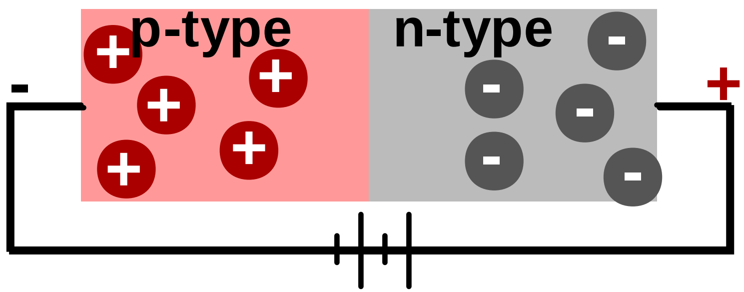
--No applied potential: no net current flow.



--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.



SUMMARY

- Electrical conductivity and resistivity are:
  --material parameters.
  --geometry independent.
- Electrical resistance is:
  --a geometry and material dependent parameter.
- Conductors, semiconductors, and insulators...
  --different in whether there are accessible 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).