Materials of Engineering

ENGR 151

CORROSION
ELECTRICAL PROPERTIES

GALVANIC SERIES

- Ranking of the reactivity of metals/alloys in seawater

more cathodic (inert)

Platinum
Gold
Graphite
Titanium
Silver
316 Stainless Steel (passive)
Nickel (passive)
Copper
Nickel (active)
Tin
Lead
316 Stainless Steel (active)
Iron/Steel
Aluminum Alloys
Cadmium
Zinc
Magnesium

more anodic (active)

Table 17.2, *Callister & Rethwisch 9e*.
Source is M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986. Reprinted with permission)

FORMS OF CORROSION

- **Uniform Attack:** Occurs with equal intensity over the entire exposed surface
  - Often leaves behind a scale or residue
  - E.g. Rusting of steel and iron, tarnishing of silverware

- **Galvanic Corrosion:** Occurs when two metals or alloys having different compositions are electrically coupled when exposed to electrolyte
  - Constitutes an electrochemical cell
  - More reactive metal experiences corrosion
  - Seawater is a medium that is conducive to galvanic corrosion

FORMS OF CORROSION

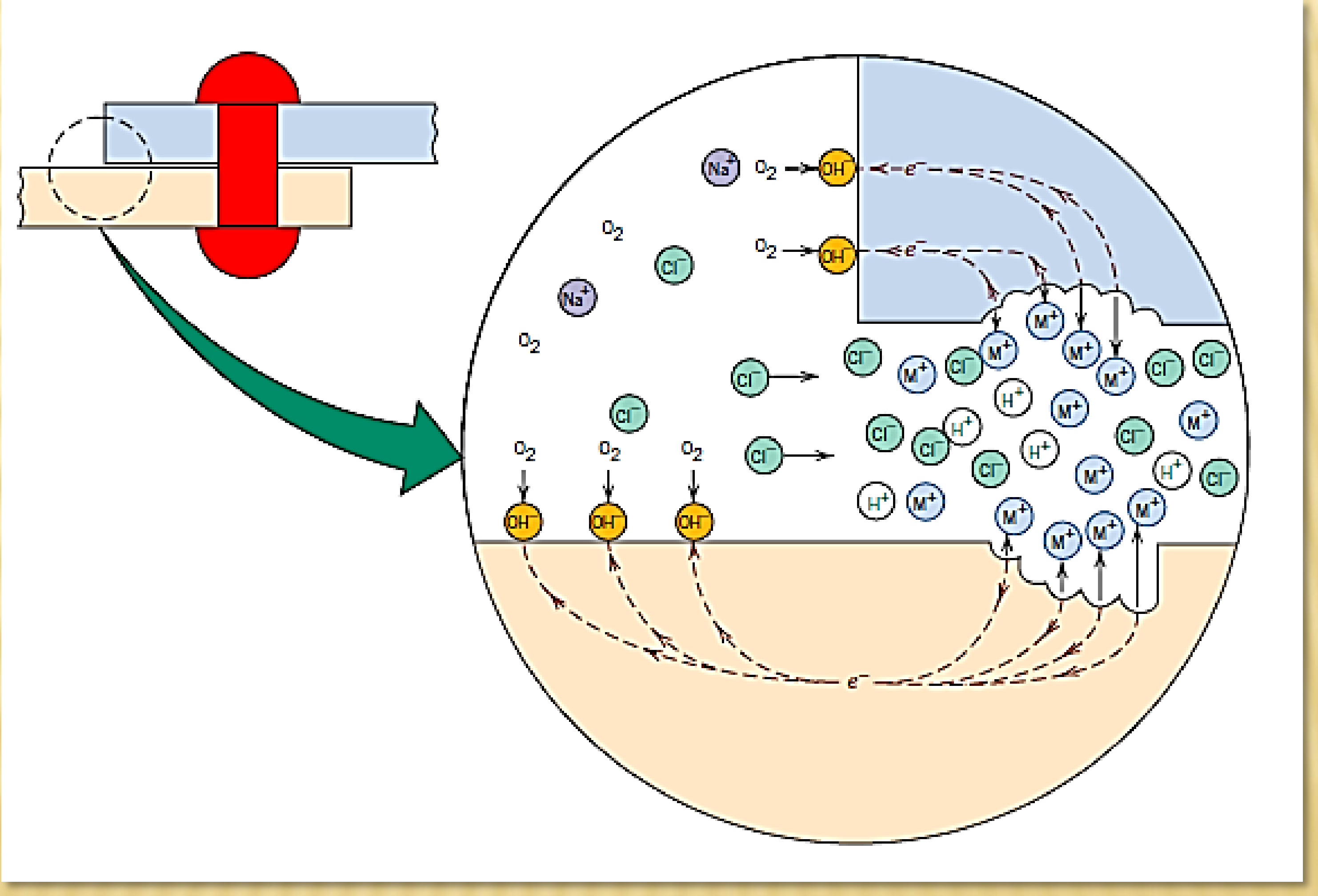
Example of Galvanic Corrosion

FORMS OF CORROSION

- **Crevice Corrosion:** May occur as a consequence of concentration differences of ions or dissolved gases in the electrolyte solution
  - Crevices are areas where concentration may drop, conducive to corrosion – crevice corrosion

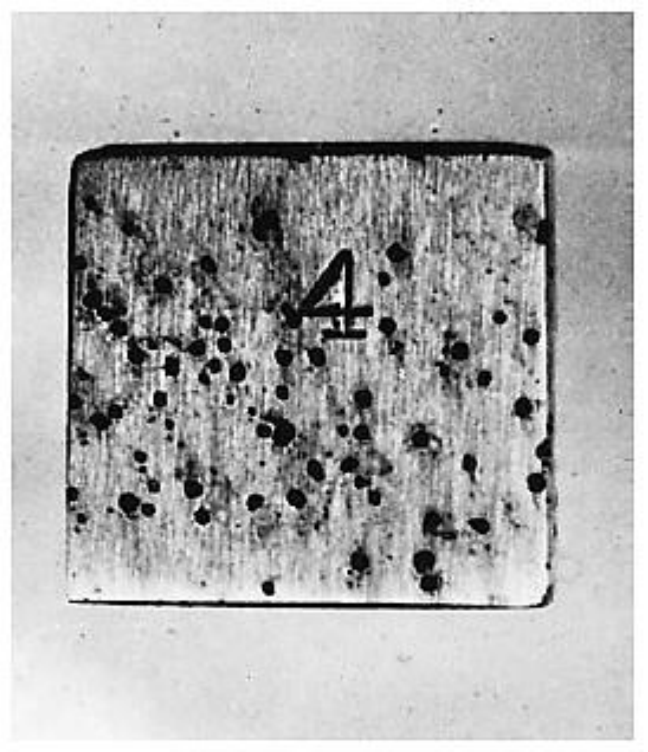
FORMS OF CORROSION

Crevice Corrosion – Schematic



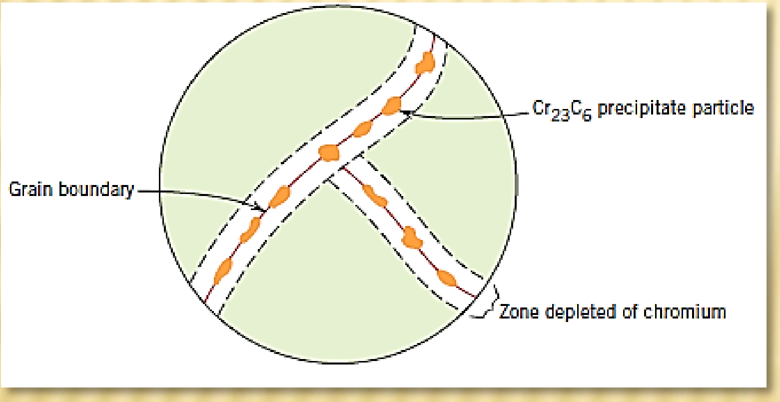
FORMS OF CORROSION

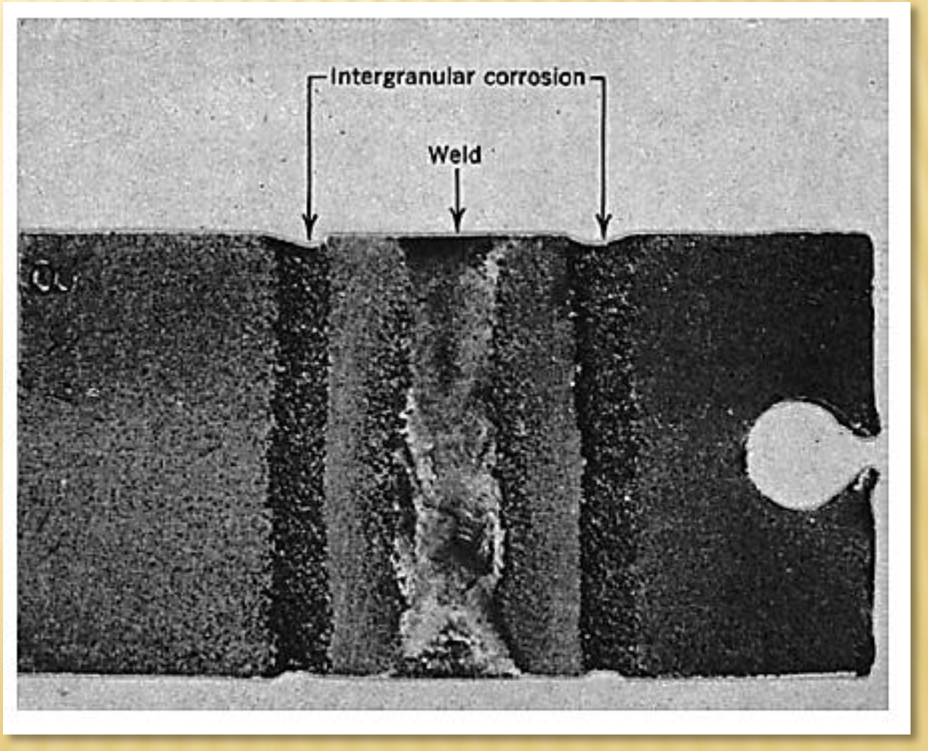
- **Pitting Corrosion:** Localized corrosion attack involving the formation of small pits or holes
  - Top-down direction, nearly vertical
  - Insidious, may go undetected till failure occurs
  - Similar mechanism to crevice corrosion



FORMS OF CORROSION

- **Intergranular Corrosion:** Occurs along grain boundaries
  - Macroscopic specimen disintegrates along grain boundaries
  - Prevalent in some stainless steels





FORMS OF CORROSION

- **Selective Leaching:** Found in solid solution alloys when one constituent is preferentially removed as a result of corrosion processes

  - E.g. Dezincification of brass
    - Zinc is selectively leached from a copper-zinc brass alloy
    - Properties of alloy adversely affected

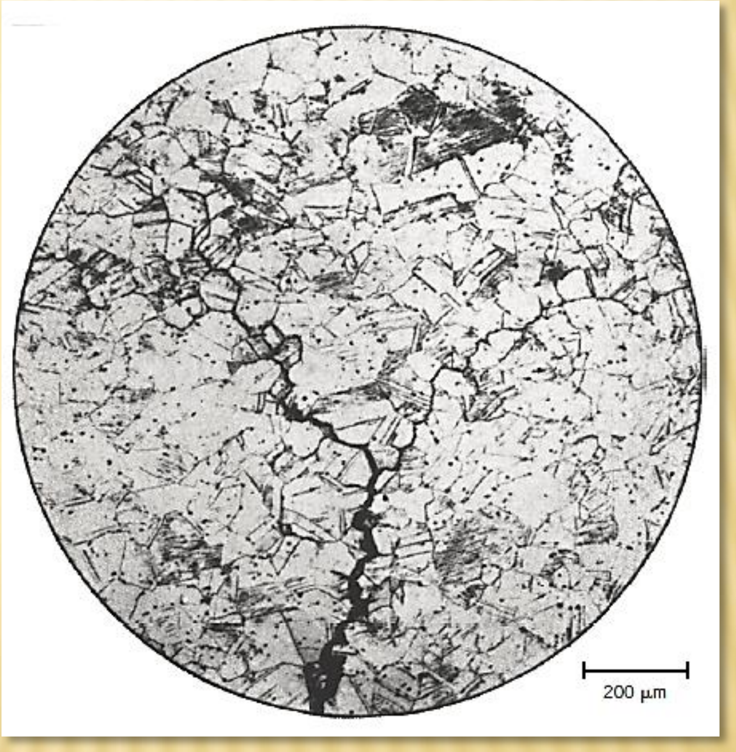
  - May also occur in other alloys in which aluminum, iron, cobalt, chromium and other elements are vulnerable to preferential removal

FORMS OF CORROSION

- **Stress Corrosion:** Also known as corrosion cracking – combined action of a tensile stress and a corrosive environment
  - Some materials which are virtually inert in a particular corrosive environment become susceptible to corrosion when a stress is applied
  - Small cracks form and propagate in a direction perpendicular to the stress

FORMS OF CORROSION

Stress Corrosion – Examples



Along grain boundaries

FORMS OF CORROSION

- **Hydrogen Embrittlement:** Significant reduction in ductility and tensile strength when atomic hydrogen penetrates into the material
    - Seen in various metal alloys and some steels
    - Atomic hydrogen (H) diffuses interstitially through the crystal lattice, causing cracking

FORMS OF CORROSION

- Stress corrosion

Corrosion at crack tips when a tensile stress is present.

- Uniform Attack

Oxidation & reduction reactions occur uniformly over surfaces.

- Erosion-corrosion

Combined chemical attack and mechanical wear (e.g., pipe elbows).

- Selective Leaching

Preferred corrosion of one element/constituent [e.g., Zn from brass (Cu-Zn)].

Forms of corrosion

- Pitting

Downward propagation of small pits and holes.

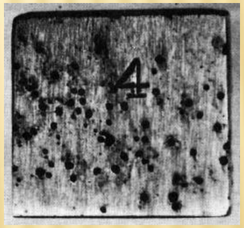


Fig. 17.17, *Callister & Rethwisch 9e*. (From M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986.)

- Intergranular

Corrosion along grain boundaries, often where precip. particles form.

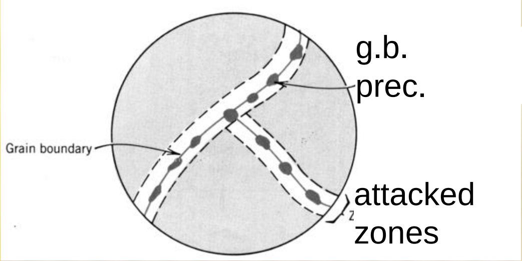


Fig. 17.18, *Callister & Rethwisch 9e*.

- Galvanic

Dissimilar metals are physically joined in the presence of an electrolyte. The more anodic metal corrodes.

- Crevice Narrow and confined spaces.

Fig. 17.15, *Callister & Rethwisch 9e*. (Courtesy LaQue Center for Corrosion Technology, Inc.)

CORROSION PREVENTION (I)

- Materials Selection
  -- Use metals that are relatively unreactive in the corrosion environment -- e.g., Ni in basic solutions

  -- Use metals that passivate
  - These metals form a thin, adhering oxide layer that slows corrosion.

- Lower the temperature (reduces rates of oxidation and reduction)
- Apply physical barriers -- e.g., films and coatings

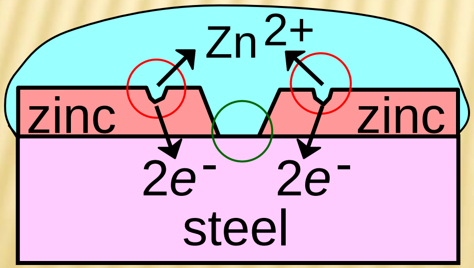
CORROSION PREVENTION (II)

- Add inhibitors (substances added to solution that decrease its reactivity)
  - -- Slow oxidation/reduction reactions by removing reactants (e.g., remove O_2 gas by reacting it w/an inhibitor).
  - -- Slow oxidation reaction by attaching species to the surface.

- Cathodic (or sacrificial) protection
  - -- Attach a more anodic material to the one to be protected.

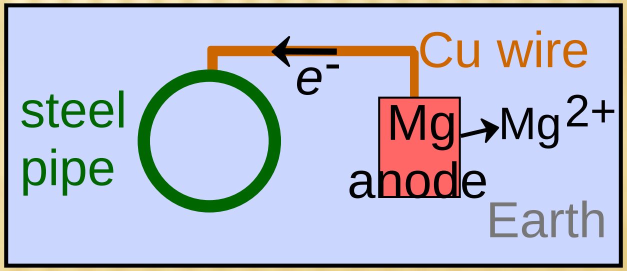
Galvanized Steel

Adapted from Fig. 17.24, *Callister & Rethwisch 9e*.



e.g., zinc-coated nail

Using a sacrificial anode

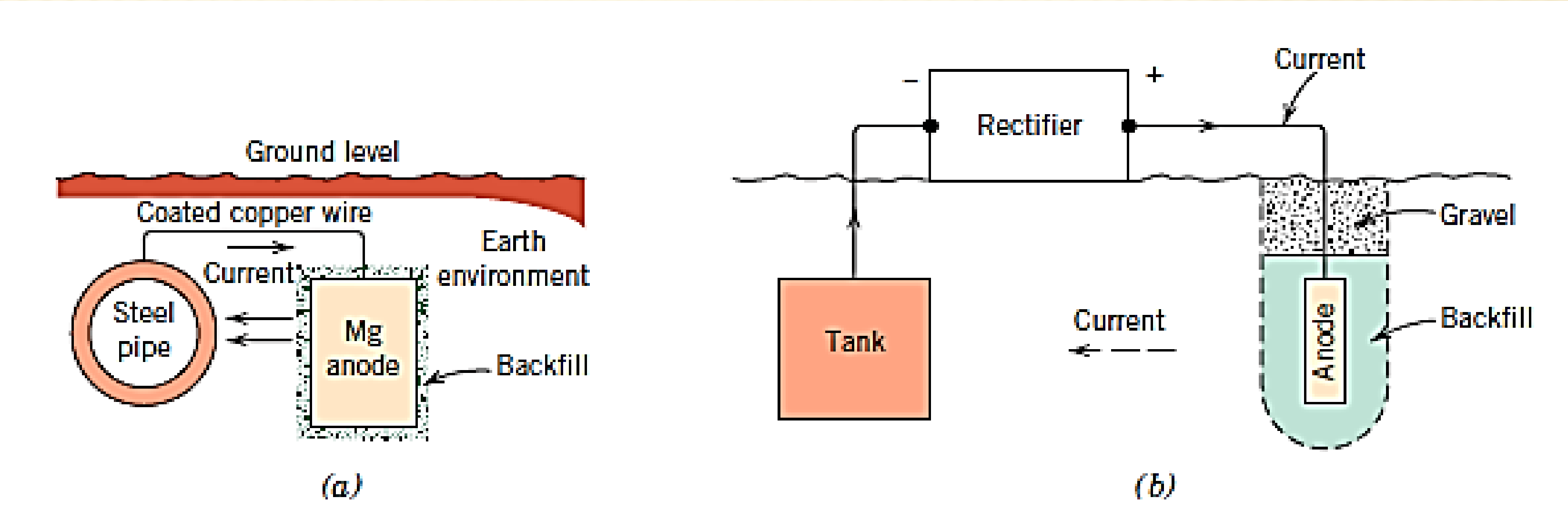


Adapted from Fig. 17.23(a), *Callister & Rethwisch 9e*.

e.g., Mg Anode

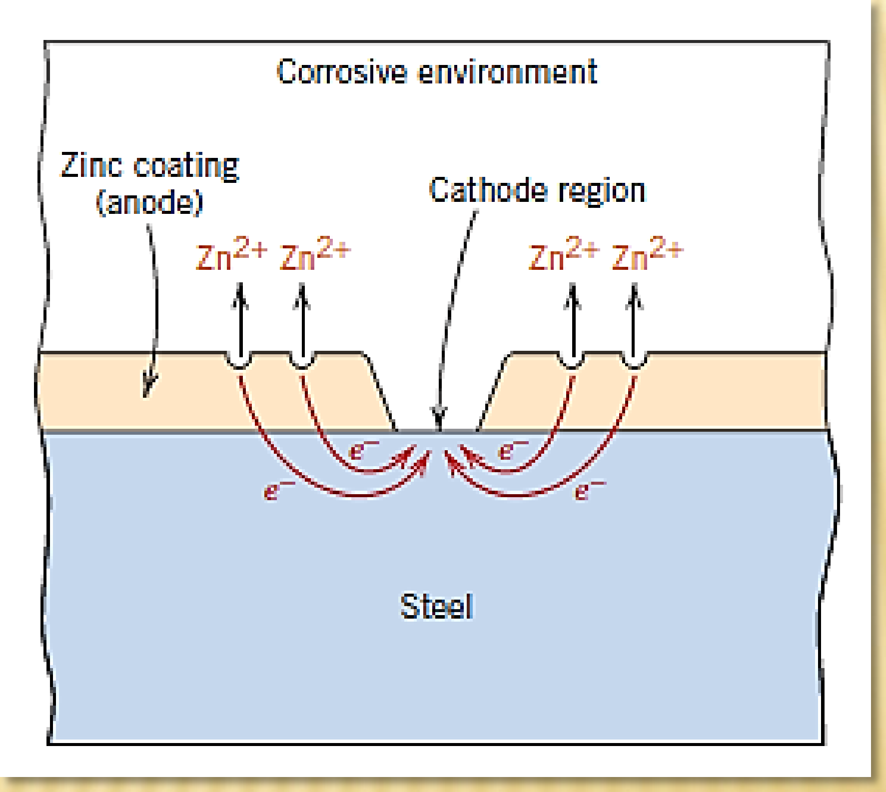
CORROSION PREVENTION (III)

Cathodic (or sacrificial) protection



CORROSION PREVENTION (IV)

Galvanic protection



SUMMARY

- Metallic corrosion involves electrochemical reactions
  -- electrons are given up by metals in an oxidation reaction
  -- these electrons are consumed in a reduction reaction
- Metals and alloys are ranked according to their corrosiveness in standard emf and galvanic series.
- Temperature and solution composition affect corrosion rates.
- Forms of corrosion are classified according to mechanism
- Corrosion may be prevented or controlled by:
  -- materials selection
  -- reducing the temperature
  -- applying physical barriers
  -- adding inhibitors
  -- cathodic protection

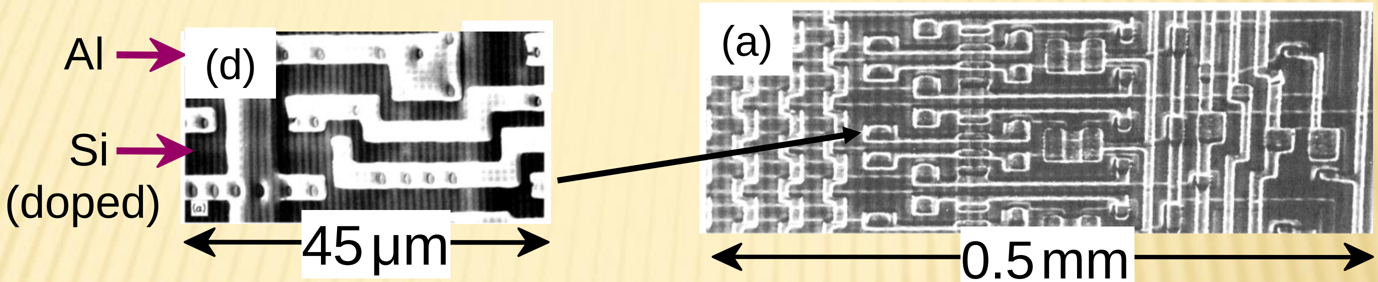
CHAPTER 18: ELECTRICAL PROPERTIES

ISSUES TO ADDRESS...

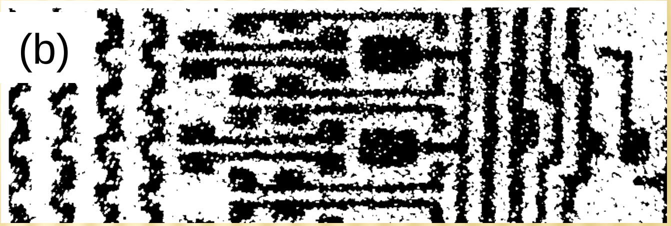
- How are electrical conductance and resistance characterized?
- What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
- For metals, how is conductivity affected by imperfections, temperature, and deformation?
- For semiconductors, how is conductivity affected by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

VIEW OF AN INTEGRATED CIRCUIT

- Scanning electron micrographs 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.

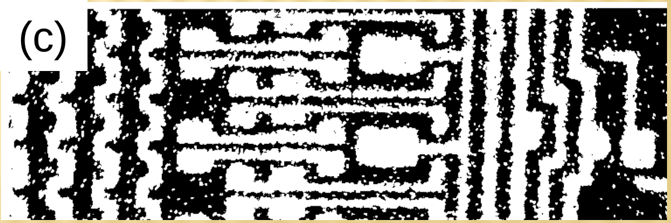
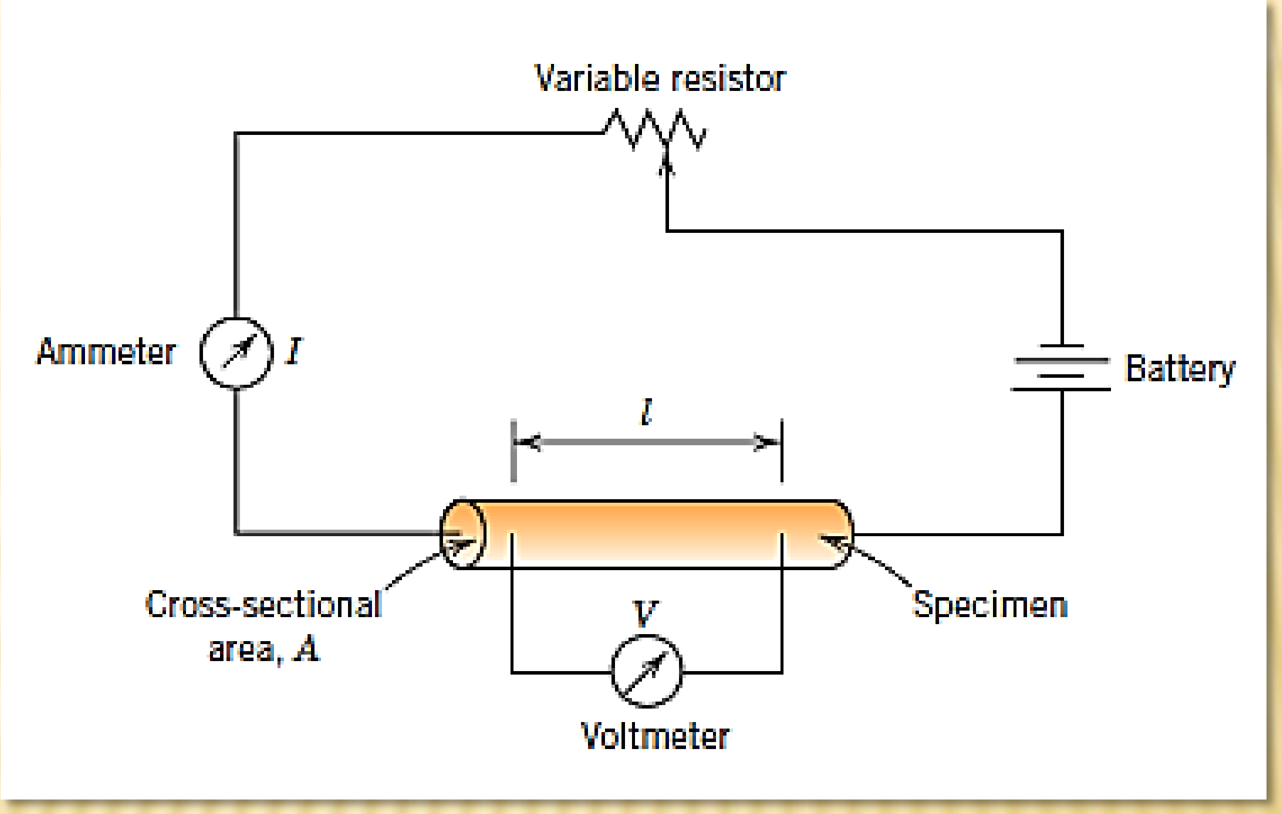


Fig. (d) from Fig. 12.27 (a), *Callister & Rethwisch 3e.* (Courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Figs. (a), (b), (c) from Fig. 18.27, *Callister & Rethwisch 9e.*

ELECTRICAL CONDUCTION



ELECTRICAL CONDUCTION

- Ohm's Law: $$V = I R$$

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

current (amps = C/s)

resistance (Ohms)

- Resistivity, ρ:

-- a material property that is independent of sample size and geometry

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

cross-sectional area of current flow

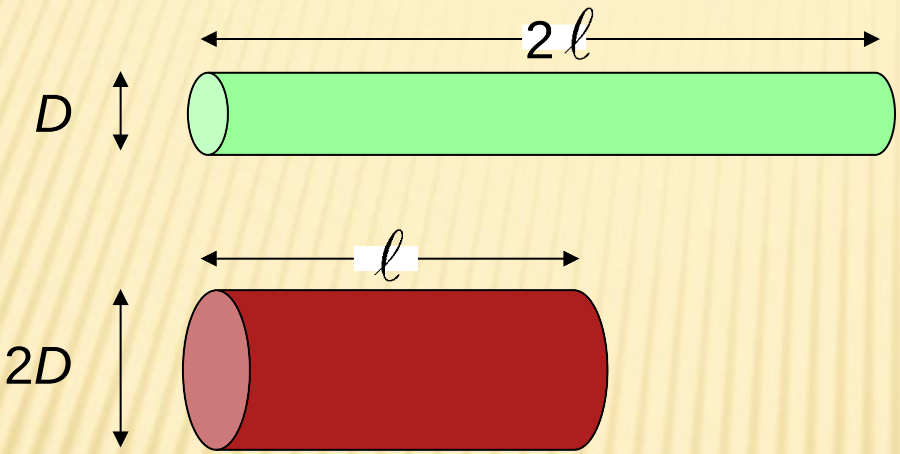
current flow path length

- Conductivity, σ

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

ELECTRICAL PROPERTIES

- Which will have the greater resistance?



$$R_1 = \frac{2\rho\ell}{\pi\left(\frac{D}{2}\right)^2} = \frac{8\rho\ell}{\pi D^2}$$

$$R_2 = \frac{\rho\ell}{\pi\left(\frac{2D}{2}\right)^2} = \frac{\rho\ell}{\pi D^2} = \frac{R_1}{8}$$

- Analogous to flow of water in a pipe
- Resistance depends on sample geometry and size.

DEFINITIONS

Further definitions

$$J = \sigma E$$ <= another way to state Ohm's law

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

$E \equiv$ electric field potential $= V/\ell$

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

Electron flux conductivity voltage gradient

CONDUCTIVITY: COMPARISON

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

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

CERAMICS	
Soda-lime glass	10^{-10}-10^{-11}
Concrete	10^{-9}
Aluminum oxide	$<10^{-13}$

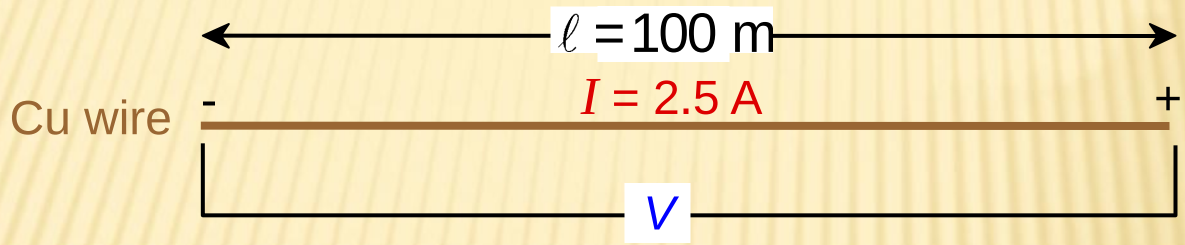
SEMICONDUCTORS	
Silicon	4×10^{-4}
Germanium	2×10^{0}
GaAs	10^{-6}
	semiconductors

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

Selected values from Tables 18.1, 18.3, and 18.4, *Callister & Rethwisch 9e.*

EXAMPLE: CONDUCTIVITY PROBLEM

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



$$R = \frac{\ell}{A\sigma} = \frac{V}{I}$$

- ℓ: 100 m
- A: $\frac{\pi D^2}{4}$
- σ: 6.07 x 10^7 (Ohm-m)$^{-1}$
- V: < 1.5 V
- I: 2.5 A

Solve to get $D > 1.87$ mm