

### Chapter 19 Electrical properties



- Electrical conduction
  - How many moveable electrons are there in a material (*carrier density*)?
  - How easily do they move (*mobility*)?
- Semiconductivity
  - Electrons and holes
  - Intrinsic and extrinsic carriers
  - Semiconductor devices: p-n junctions and transistors
- Conduction in polymers and ionic materials
- Dielectric behavior

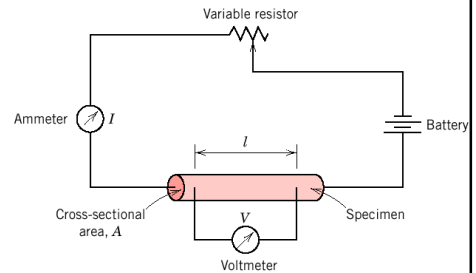
Optional reading: 19.13, 19.20, 19.23

### Basic laws and electrical properties of metals (I)

When an electrical potential  $V$  [volts, J/C] is applied across a piece of material, a current of magnitude  $I$  [amperes, C/s] flows. In most metals, at low values of  $V$ , the current is proportional to  $V$ , and can be described by **Ohm's law**:

$$I = V/R$$

where  $R$  is the electrical resistance [ohms,  $\Omega$ ].  $R$  depends on the intrinsic resistivity  $\rho$  of the material [ $\Omega\cdot\text{m}$ ] and on the geometry (length  $l$  and area  $A$  through which the current passes):  $R = \rho l/A$



In most materials (e.g. metals), the current is carried by electrons (**electronic conduction**). In ionic crystals, the charge carriers are ions (**ionic conduction**).

### Basic laws and electrical properties of metals (II)

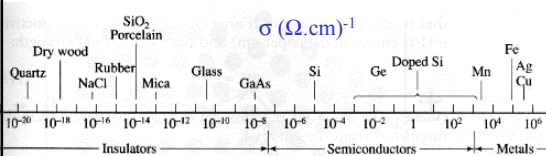
The electrical conductivity (the ability of a substance to conduct an electric current) is the inverse of the resistivity:

$$\sigma = 1/\rho$$

Since the electric field intensity in the material is  $E = V/l$ , Ohm's law can be rewritten in terms of the current density  $J = I/A$  as:

$$J = \sigma E$$

Electrical conductivity varies between different materials by over 27 orders of magnitude, the greatest variation of any physical property



**Metals:**  $\sigma > 10^5 \text{ } (\Omega\cdot\text{m})^{-1}$

**Semiconductors:**  $10^{-6} < \sigma < 10^5 \text{ } (\Omega\cdot\text{m})^{-1}$

**Insulators:**  $\sigma < 10^{-6} \text{ } (\Omega\cdot\text{m})^{-1}$

| Electrical Resistivity (ohm-m) | (log) | Electrical Conductivity (S/m)                  |
|--------------------------------|-------|--|
|                                | -8    | 8  |
| intercalated graphite          | -7    | 7  |
|                                |       | copper, silver<br>iron                         |
| graphite (in-plane)            | -6    | 6  |
| graphite (out of plane)        | -5    | 5  |
|                                |       | stainless steel, metallic glass                |
| polyacetylene (doped)          | -4    | 4  |
|                                |       | $\text{YBa}_2\text{Cu}_3\text{O}_7$ (ab plane) |
|                                |       | $\text{YBa}_2\text{Cu}_3\text{O}_7$ (c-axis)   |
|                                | -3    | 3  |
|                                |       | silicon (doped)                                |
| TTF-TCNQ                       | -2    | 2  |
|                                |       | ZnO (doped)                                    |
|                                |       | seawater                                       |
|                                | -1    | 1  |
|                                |       | $\text{Fe}_3\text{O}_4$                        |
|                                | 0     | 0  |
|                                |       | germanium                                      |
|                                | 1     | -1   |
|                                | 2     | -2   |
|                                |       | silicon  |
|                                | 3     | -3   |
|                                |       | InSb   |
|                                | 4     | -4   |
|                                |       | water  |
|                                | 5     | -5   |
|                                |       | AgCl   |
| polyacetylene (undoped)        | 6     | -6   |
|                                | 7     | -7   |
|                                | 8     | -8   |
|                                |       | ZnO (undoped)                                  |
|                                | 9     | -9   |
|                                | 10    | -10  |
| Bakelite                       | 11    | -11  |
|                                |       | NaCl   |
| polypyrrole                    | 12    | -12  |
|                                | 13    | -13  |
|                                | 14    | -14  |
| Lucite (PMMA)                  | 14    | -14  |
|                                |       | $\text{Al}_2\text{O}_3$                        |
| polyvinyl chloride             | 15    | -15  |
|                                |       | mica   |
|                                |       | silica   |
| polyethylene, teflon           | 16    | -16  |
|                                |       | diamond  |

Introduction to Materials Science, Chapter 19, Electrical properties

### Energy Band Structures in Solids (I)

In an isolated atom electrons occupy well defined energy states, as discussed in Chapter 2.

When atoms come together to form a solid, their valence electrons interact with each other and with nuclei due to Coulomb forces. In addition, two specific quantum mechanical effects happen. First, by Heisenberg's uncertainty principle, constraining the electrons to a small volume raises their energy, this is called *promotion*. The second effect, due to the Pauli exclusion principle, limits the number of electrons that can have the same energy.

As a result of these effects, the valence electrons of atoms form wide **electron energy bands** when they form a solid. The bands are separated by **gaps**, where electrons cannot exist.

Introduction to Materials Science, Chapter 19, Electrical properties

### Energy Band Structures and Conductivity

- **Fermi Energy ( $E_F$ )** - highest filled state at 0 K
- **Conduction band** - a partially filled or empty energy band
- **Valence band** - the highest partially or completely filled band

In **semiconductors and insulators**, the valence band is filled, and no more electrons can be added (Pauli's principle).

Electrical conduction requires that electrons be able to gain energy in an electric field. This is not possible in these materials because that would imply that the electrons are promoted into the forbidden band gap.

University of Virginia, Dept. of Materials Science and Engineering 6

Introduction to Materials Science, Chapter 19, Electrical properties

### Energy Band Structures and Conductivity (semiconductors and insulators)

- In semiconductors and insulators, electrons have to jump across the band gap into conduction band to find conducting states above  $E_F$
- The energy needed for the jump may come from heat, or from irradiation at sufficiently small wavelength.
- The difference between semiconductors and insulators is that in semiconductors electrons can reach the conduction band at ordinary temperatures, where in insulators they cannot.
- The probability that an electron reaches the conduction band is about  $\exp(-E_g/2kT)$  where  $E_g$  is the band gap. If this probability is  $< 10^{-24}$  one would not find a single electron in the conduction band in a solid of  $1 \text{ cm}^3$ . This requires  $E_g/2kT > 55$ . At room temperature,  $2kT = 0.05 \text{ eV} \Rightarrow E_g > 2.8 \text{ eV}$  corresponds to an insulator.
- An electron promoted into the conduction band leaves a **hole** (positive charge) in the valence band, that can also participate in conduction. Holes exist in metals as well, but are more important in semiconductors and insulators.

University of Virginia, Dept. of Materials Science and Engineering 7

Introduction to Materials Science, Chapter 19, Electrical properties

### Energy Band Structures and Conductivity (metals)

In **metals**, highest occupied band is partially filled or bands overlap.

Conduction occurs by promoting electrons into conducting states, that starts right above the Fermi level. The conducting states are separated from the valence band by an infinitesimal amount.

Energy provided by an electric field is sufficient to excite many electrons into conducting states.  $\Rightarrow$  High conductivity.

University of Virginia, Dept. of Materials Science and Engineering 8

Introduction to Materials Science, Chapter 19, Electrical properties

### Energy Band Structures and Bonding (metals, semiconductors, insulators)

Relation to atomic bonding:

- **Insulators** – valence electrons are tightly bound to (or shared with) the individual atoms – strongest ionic (partially covalent) bonding.
- **Semiconductors** - mostly covalent bonding somewhat weaker bonding.
- **Metals** – valence electrons form an “electron gas” that are not bound to any particular ion.

University of Virginia, Dept. of Materials Science and Engineering 9

Introduction to Materials Science, Chapter 19, Electrical properties

### Energy Band Structures and Conductivity

**Metals**

**Semiconductors and Insulators**

University of Virginia, Dept. of Materials Science and Engineering 10

Introduction to Materials Science, Chapter 19, Electrical properties

### Electron Mobility

- The force acting on the electron is  $-eE$ , where  $e$  is the electric charge.
- This force produces a constant acceleration so that, in the absence of obstacles the electron speeds up continuously in an electric field. This is the case in vacuum (e.g. inside a TV tube) **or in a perfect crystal** (this is a conclusion from quantum mechanics).
- In a real solid, the electrons **scatter** by collisions with imperfections and due to atomic thermal vibrations.  $\Rightarrow$  “frictional forces”  $\Rightarrow$  resistance  $\Rightarrow$  a net **drift velocity** of electron motion is established:

$$v_d = \mu_e E$$

where  $\mu_e$  – **electron mobility** [ $m^2/V\cdot s$ ]. The “friction” transfers part of the energy supplied by the electric field into the lattice as heat. That is how electric heaters work.

University of Virginia, Dept. of Materials Science and Engineering 11

Introduction to Materials Science, Chapter 19, Electrical properties

### Electron Mobility

- **Electrical conductivity** is proportional to number of free electrons and electron mobility:

$$\sigma = N_e |e| \mu_e$$

$N_e$  - number of “free” or conduction electrons per unit volume

| (m) = Metal<br>(s) = Semicon | Mobility (RT)<br>$\mu$ ( $m^2V^{-1}s^{-1}$ ) | Carrier Density<br>$N_e$ ( $m^{-3}$ ) |
|------------------------------|--|---------------------------------------|
| Na (m)                       | 0.0053                                       | $2.6 \times 10^{28}$                  |
| Ag (m)                       | 0.0057                                       | $5.9 \times 10^{28}$                  |
| Al (m)                       | 0.0013                                       | $1.8 \times 10^{29}$                  |
| Si (s)                       | 0.15   | $1.5 \times 10^{10}$                  |
| GaAs (s)                     | 0.85   | $1.8 \times 10^6$                     |
| InSb (s)                     | 8.00   |                                       |

$N_{metal} \gg N_{semi}$   
 $\mu_{metal} < \mu_{semi}$   $\Rightarrow$   $\sigma_{metal} \gg \sigma_{semi}$

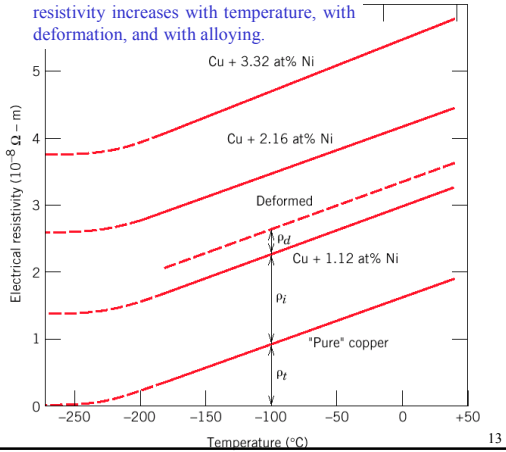
University of Virginia, Dept. of Materials Science and Engineering 12

### Conductivity / Resistivity of Metals

The resistivity  $\rho$  is defined by scattering events due to the imperfections and thermal vibrations. Total resistivity  $\rho_{tot}$  can be described by the Matthiessen rule:

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

$\rho_{thermal}$  - from thermal vibrations,  $\rho_{impurity}$  - from impurities,  $\rho_{deformation}$  - from deformation-induced defects



### Conductivity / Resistivity of Metals

#### Influence of temperature:

Resistivity rises linearly with temperature (increasing thermal vibrations and density of vacancies)

$$\rho_T = \rho_0 + aT$$

#### Influence of impurities:

- Impurities that form solid solution

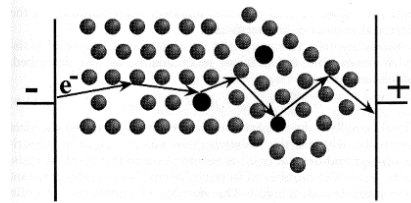
$$\rho_I = A c_i (1 - c_i)$$

where  $c_i$  is impurity concentration

- Two-phase alloy ( $\alpha$  and  $\beta$  phases):

$$\rho_i = \rho_{\alpha} V_{\alpha} + \rho_{\beta} V_{\beta}$$

#### Influence of plastic deformation:



### Materials of Choice for Metal Conductors

- One of the best material for electrical conduction (low resistivity) is **silver**, but use restricted due to high cost
- Most widely used conductor is **copper**: inexpensive, abundant, high  $\sigma$ , but rather soft – cannot be used in applications where mechanical strength is important.
- Solid solution alloying and cold working improve strength but decrease conductivity. **Precipitation hardening** is preferred, e.g. Cu-Be alloy
- When weight is important one uses **aluminum**, which is half as good as Cu and more resistant to corrosion.
- **Heating elements** require low  $\sigma$  (high R), and resistance to high temperature oxidation: **nickel-chromium** alloy

| Metal               | Electrical Conductivity<br>[[ $\Omega \cdot m$ ] $^{-1}$ ] |
|---------------------|--|
| Silver              | $6.8 \times 10^7$  |
| Copper              | $6.0 \times 10^7$  |
| Gold                | $4.3 \times 10^7$  |
| Aluminum            | $3.8 \times 10^7$  |
| Iron                | $1.0 \times 10^7$  |
| Brass (70 Cu–30 Zn) | $1.6 \times 10^7$  |
| Platinum            | $0.94 \times 10^7$   |
| Plain carbon steel  | $0.6 \times 10^7$  |
| Stainless steel     | $0.2 \times 10^7$  |