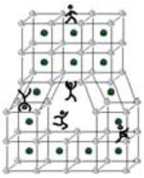
Intro to Electronic Properties



- Conduction
- Energy Bands
- Fermi-Dirac Function
- Classes of Materials

Monday, Oct. 20, 2003

MATS275: INTRODUCTION TO MATERIALS SCIENCE

Outline of Next Few Lectures

I. Phenomenological Introduction (Schaffer)
II. Intro to Quantum Mechanics (Hummel)
III. Reciprocal Space / Electrons In A Crystal (Hummel)
IV. Semiconductors (Schaffer / Hummel)
V. Semiconductor Devices (Schaffer / Hummel)

What Do We Mean by Electrical Properties?

- Response of a material to an external electric field
- Once again the factors influencing the electrical properties are:
  - chemical bonding
  - number of electrons per atom
  - degree of crystallinity
  - defect density
  - microstructure
  - temperature
  - macroscopic sample dimensions
- Sound familiar?

Conduction

- Ho do free electrons, move?
- OHM'S LAW

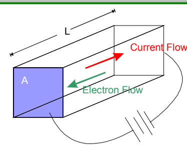
$$V = IR$$

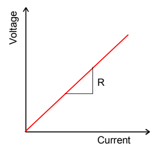
or more appropriately...

$$\vec{J} = \sigma \vec{E}$$

σ is conductivity ($1/\Omega$-m)

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





Conductivity (25 orders of magnitude!!!)

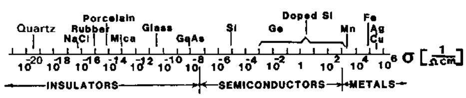


Figure 7.1. Room-temperature conductivity of various materials. (Superconductors, having conductivities of many orders of magnitude larger than copper, near 0 K, are not shown. The conductivity of semiconductors varies substantially with temperature and purity.) It is customary in engineering to use the centimeter as unit of length rather than the meter. We follow this practice.

From R.E. Hummel, Electronic Properties of Materials, 2nd. Ed., Springer-Verlag, 76 (1993)

Applying a Field

- If I apply a field to a conductor:

$$\vec{F} = m\vec{a}$$

$$\vec{F} = m^* \frac{d\vec{v}}{dt} = \frac{d}{dt}\vec{p} = -e\vec{E}$$

- Every τ seconds, an electron will scatter:

$$-eE\tau = m^* \Delta v$$

$$\frac{-e\tau}{m^*} E = v_{drift}$$

Mobility $\boxed{\mu_e = \frac{-e\tau}{m^*}}$

Electrons Drifting in an Electric Field

- Classical equation of an electron drifting under the influence of an electric field, with a friction force opposing the field

$$m\frac{dv}{dt} = eE - \gamma v$$

- Solution:

$$v = a[1 - exp(-bt)] \quad \Rightarrow \quad v = v_f\left[1 - exp\left(-\frac{eE}{mv_f}t\right)\right]$$

- Drift Velocity:

$$\tau = \frac{mv_f}{eE} \quad \Rightarrow \quad v_f = \frac{\tau eE}{m}$$

Mobility and Conductivity

- If the current density is just the number of carriers times the charge times their drift velocity, then...

$$\vec{J} = \sigma\vec{E}$$

$$\frac{-e\tau}{m}E = v_f$$

$$N_f v_f e = \frac{N_f e^2 \tau}{m}E$$

$$\frac{1}{\rho} = \sigma = \frac{ne^2\tau}{m^*} = ne\mu$$

Mobility like Diffusion Constant

- Charge Carriers: Ions and electrons
  - Ions: move through lattice by diffusion
  - Electrons: Move through lattice relatively unimpeded due to their small size

Electrons in Cu

- The conductivity of Cu at 300 K is 5.88 x 10^5 ohm-cm. What is the scattering time?

$$\sigma = \frac{ne^2\tau}{m^*}$$

$$\tau = \frac{m^*\sigma}{ne^2} = \frac{(9.11\times10^{-31}\,kg)(5.88\times10^{7}\,\Omega\cdot m)}{(10^{29}\,m^{-3})(1.602\times10^{-19}\,C)^2}$$

$$\tau = 2.08\times10^{-14}\,s$$

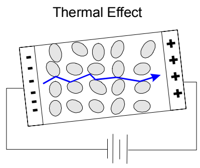
Adding Resistivities

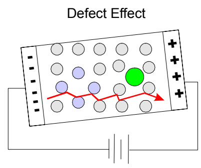
- 1/t can be thought of as a rate. The total rate at which electrons are scattered will be the sum of the rates due to different causes:

$$\frac{1}{\tau} \propto \rho \quad \Rightarrow \quad \rho_{tot} = \underbrace{\rho_t}_{\text{phonons}} + \underbrace{\rho_i}_{\text{impurities}} + \underbrace{\rho_d}_{\text{deformation}}$$

Mathiessen's Rule

Temperature and Defects--Lower Mobility





Dependence on Impurities

- Note that it is quite linear over a certain range:

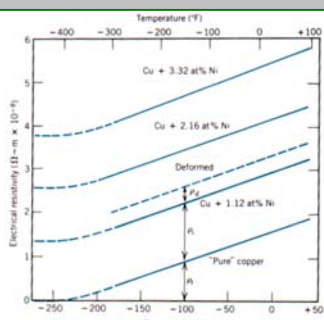
$$\rho_t = \rho_0 + \alpha T$$

- Varies due to impurities:

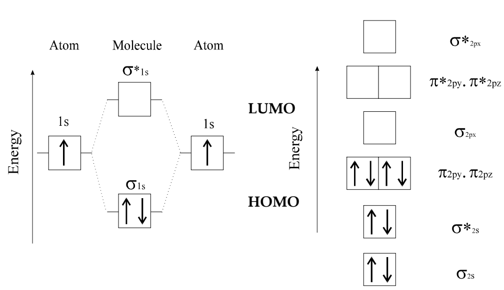
$$\rho_i = Ac_i(1 - c_i)$$

- Increased by deformation.

Resistivities



Bonding in Molecules



Energy Bands from MO Diagrams

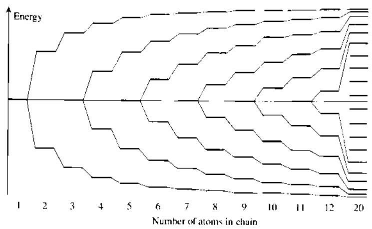
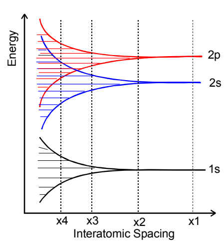
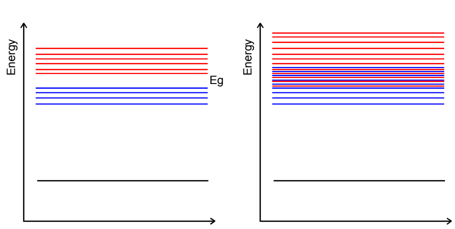


Fig. B.2 The energy levels of *N* atoms in a chain on the assumption that only nearest-neighbour interactions contribute to bonding. (The Hückel approximation has been used for the calculation.) Note how the density of energy levels in the band increases but that the width remains finite.

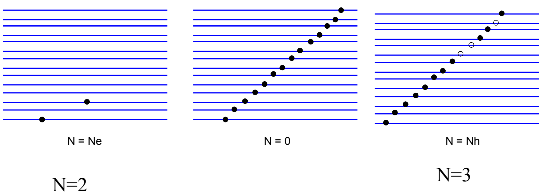
Energy Bands



Band Gap vs. Overlapping Bands

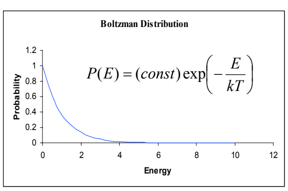


Carrier concentration



It's All Just Statistical

- Macroscopic things (molecules, dust, trucks) can be described with Boltzmann Statistics.



Fermi-Dirac Statistics

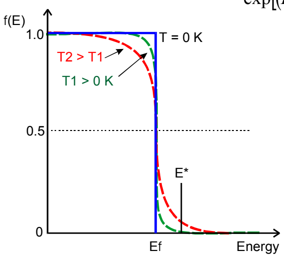
- Electrons obey Fermi-Dirac statistics according to the following relationship:

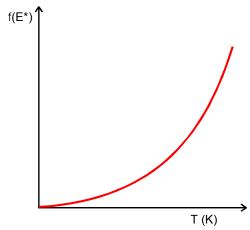
$$f(E) = \frac{1}{\exp\left[\left(E - E_f\right)/kT\right] + 1}$$

- where E is the energy level in question, E_f is the Fermi energy, and k is Boltzmann's constant

Fermi-Dirac Function

$$f(E) = \frac{1}{\exp\left[\left(E - E_f\right)/kT\right] + 1}$$

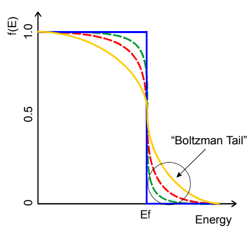




Boltzmann vs. Fermi-Dirac

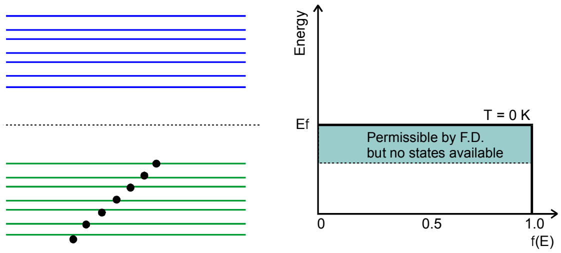
- At very large energies (E >> Ef), we get the Boltzmann distribution

$$f(E) = P(E)$$

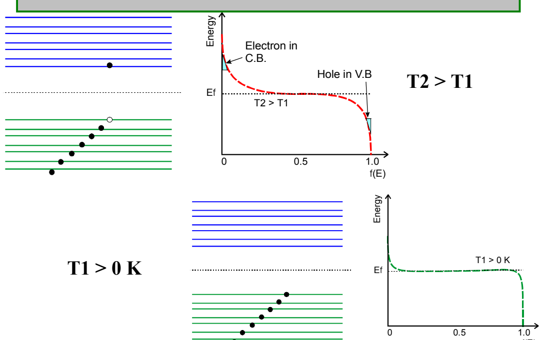


How do electrons fill in a band?

Band Filling in a Gap Material at 0 K

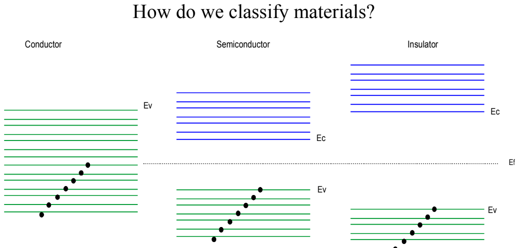


Band Filling in a Gap Material above 0 K

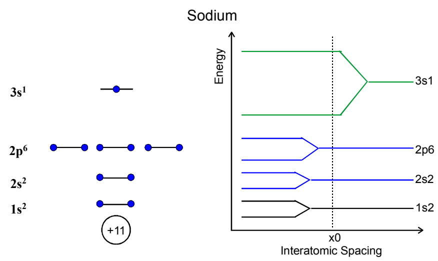


Remember that 25 Orders of Magnitude?

How do we classify materials?

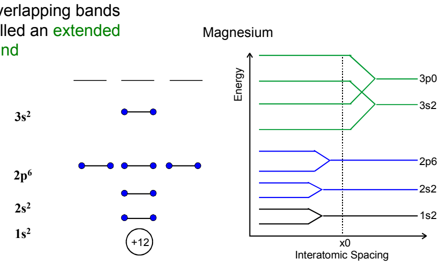


Conductors--Partially Filled Band



Conductors--Extended Band

- Overlapping bands called an extended band

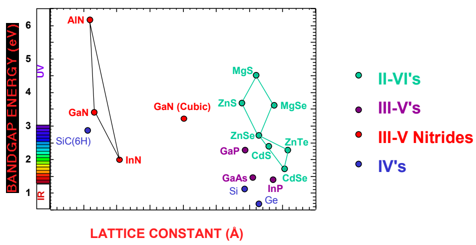


Semiconductors

- Generally covalent solids such as Si, Ge, GaAs (this is due to hybridization of the s and p orbitals which yields a tetrahedrally bonded solid) This results in a FCC or zinc-blende crystal structure
- Most covalent solids are either semiconductors or insulators because of this.
- Called Group IV, III-V, II-VI

- In addition, most ionic solids are band gap solids which are either an insulator or a semiconductor

Band Gap Energies



Insulators

- Generally metal oxides
- Silicate ceramics
- Organic polymers

- All have large band gaps