Today's objectives-Electrical Conduction

1. How do available electron energy states vary for atoms, molecules, large molecules, and solids?
2. Sketch a simple metallic, semiconducting, and insulating band diagram.
3. Draw band diagrams for metals, insulators, intrinsic semiconductor, and n and p type doped semiconductors, including E_c, E_f, and E_v.
4. How is conductivity described based on metal, semiconductor, and insulating band diagrams?
5. How does conductivity change as a function of temperature for metals and intrinsic semiconductors. What about for extrinsic (doped) semiconductors?

Reading for today

Semiconductors and Integrated Circuits

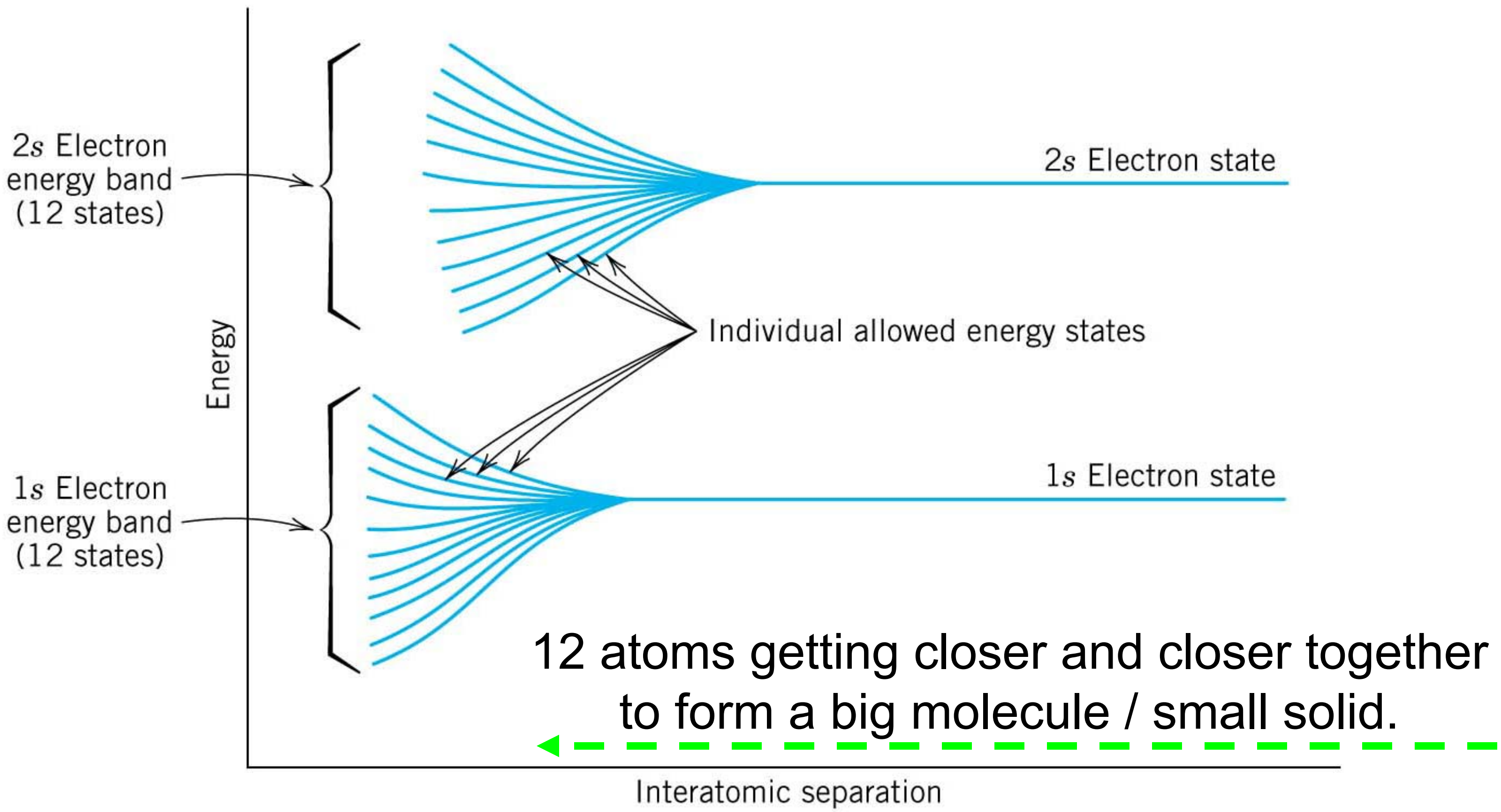
Chapter sections: 18.1-9

What about electronic structure

- To understand the electronic structure of a material, we have to consider several steps of increasing complication:
  1. Atoms
  2. Molecules
  3. Crystals
     a. Metals
     b. Semiconductors
     c. Insulators
  4. Combinations

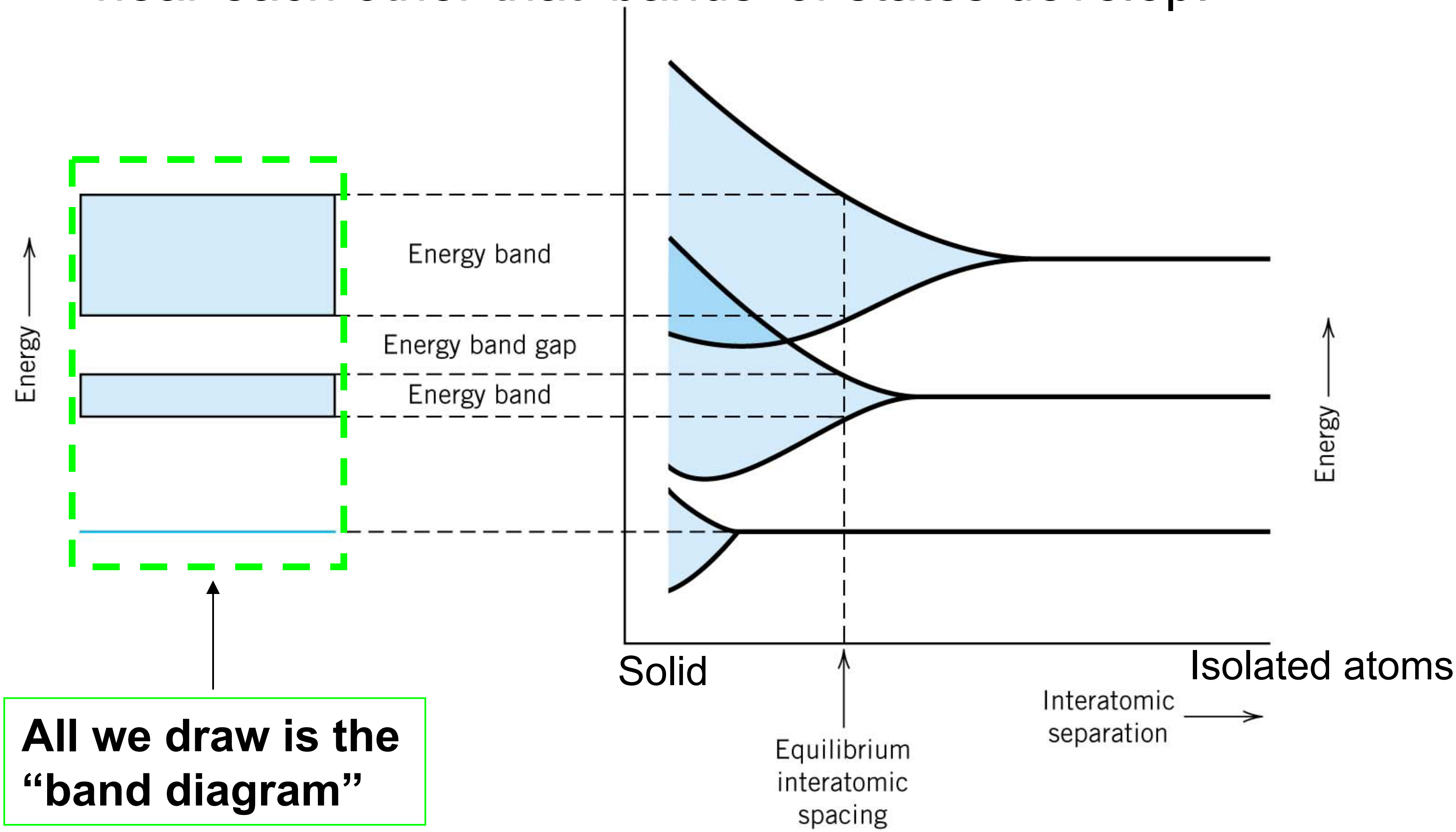
Electrons in large molecules

- More electrons = more bonding and antibonding orbitals.
  - Different molecules have distinct energies between them.
- As the number of atoms in a molecule increases, so does the number of allowable energy states.
  - If each is the same atom, the energy for each initial orbital is the same.
  - Therefore, the energy separation between the bonding and antibonding orbitals necessarily gets very small.



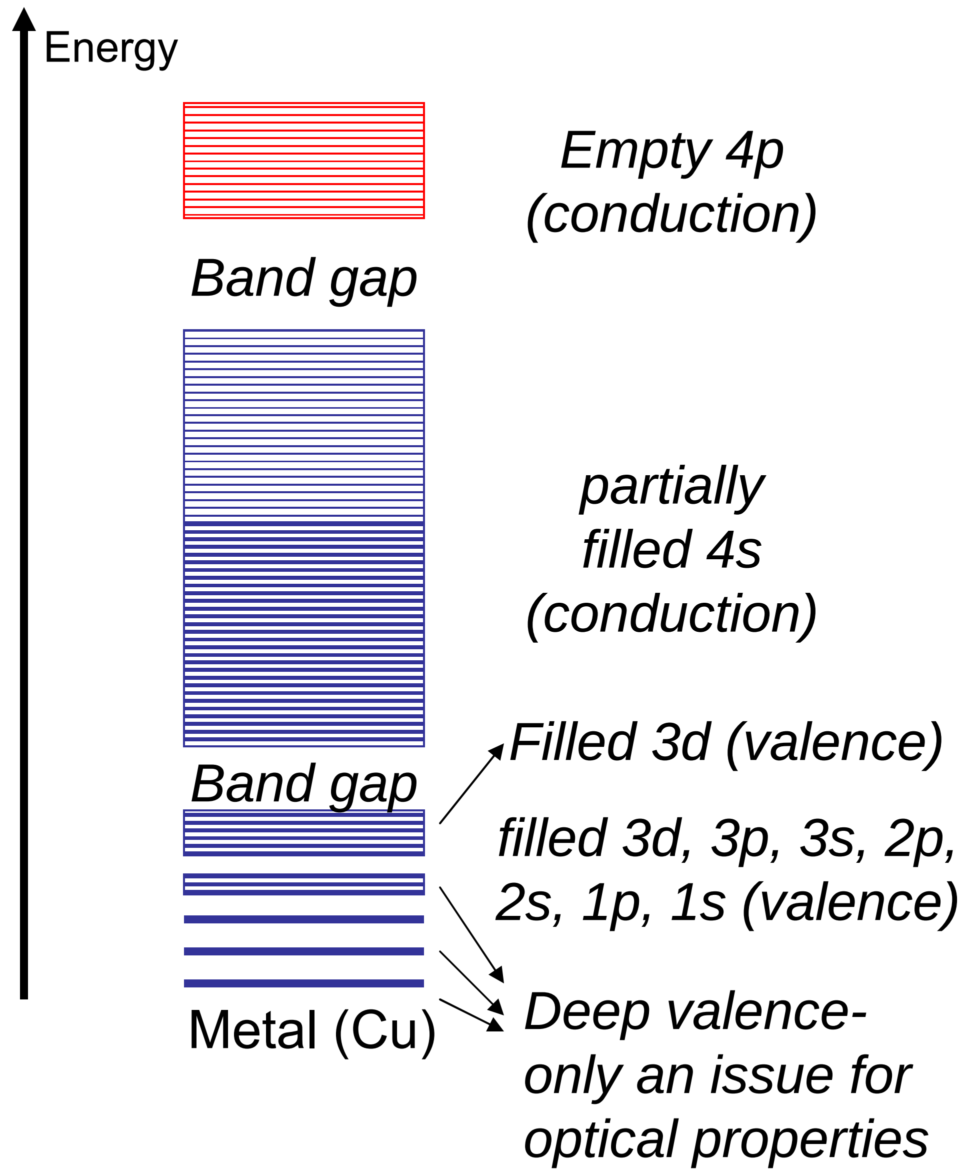
Electrons in solids

- In a solid, there are so many electrons with energies very near each other that 'bands' of states develop.

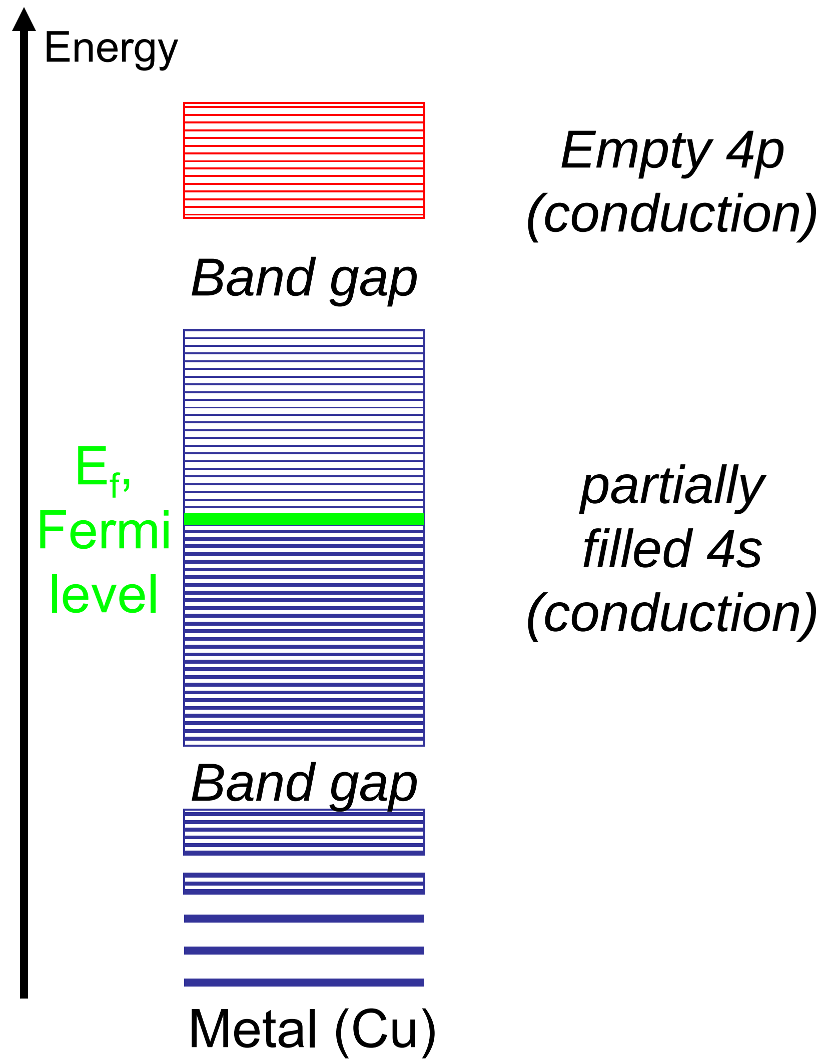


Energy band structures

- Partially filled or empty bands are called 'conduction bands.'
- Any band that is totally filled is considered to be a "valence band."
  - We usually ignore 'deep' valence bands.

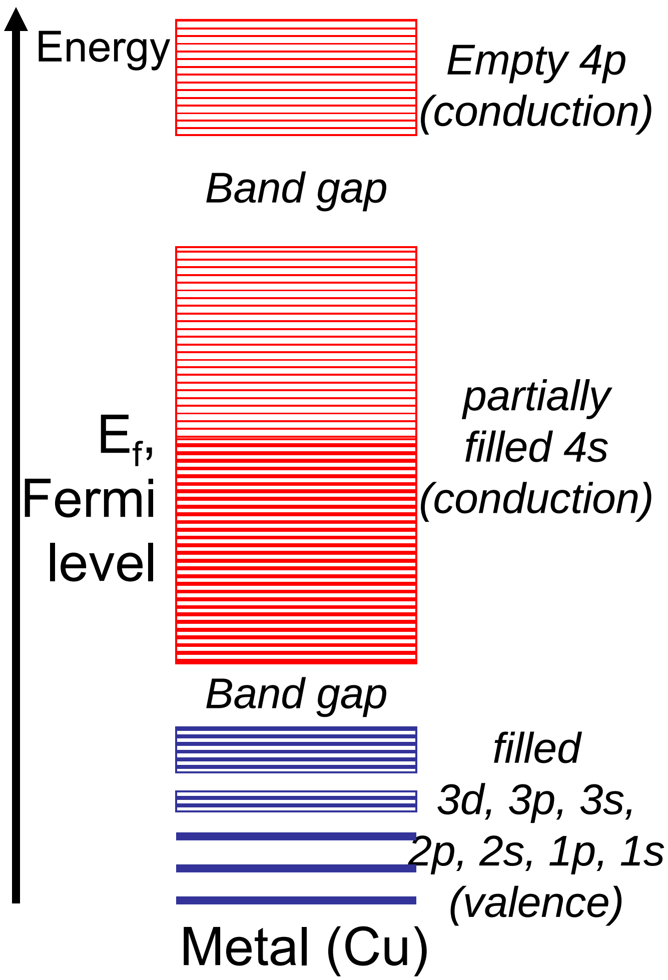


- An important concept in electronic properties is the “Fermi level,” E_f
  - Essentially the highest energy ground-state electron
- Separates conduction and valence electron activity
  - Sometimes within a band
  - Sometimes between bands
  - Sometimes in a gap between bands



Types of metals

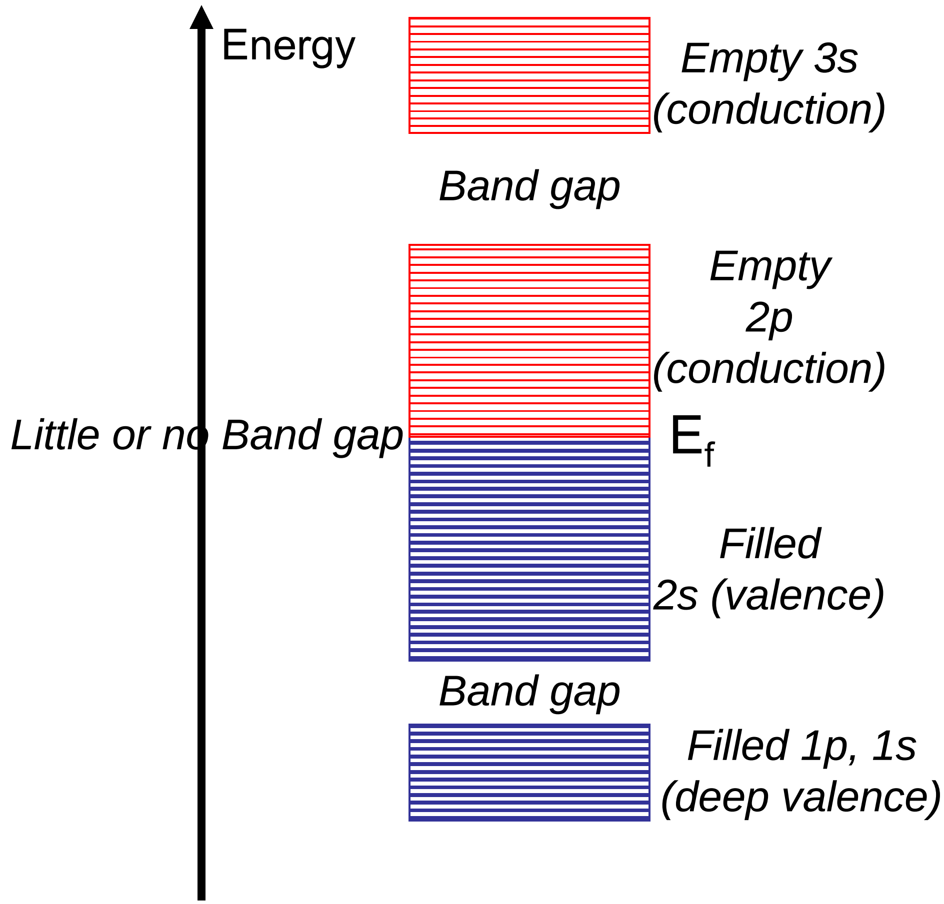
- Metals are materials where the:
  - conduction band is **partially** filled (valence band is totally filled).



conducting

Types of metals II

- Or, metals can have the:
  - valence band filled, and conduction band empty, but **little if any gap in between** (really a 'semimetal').

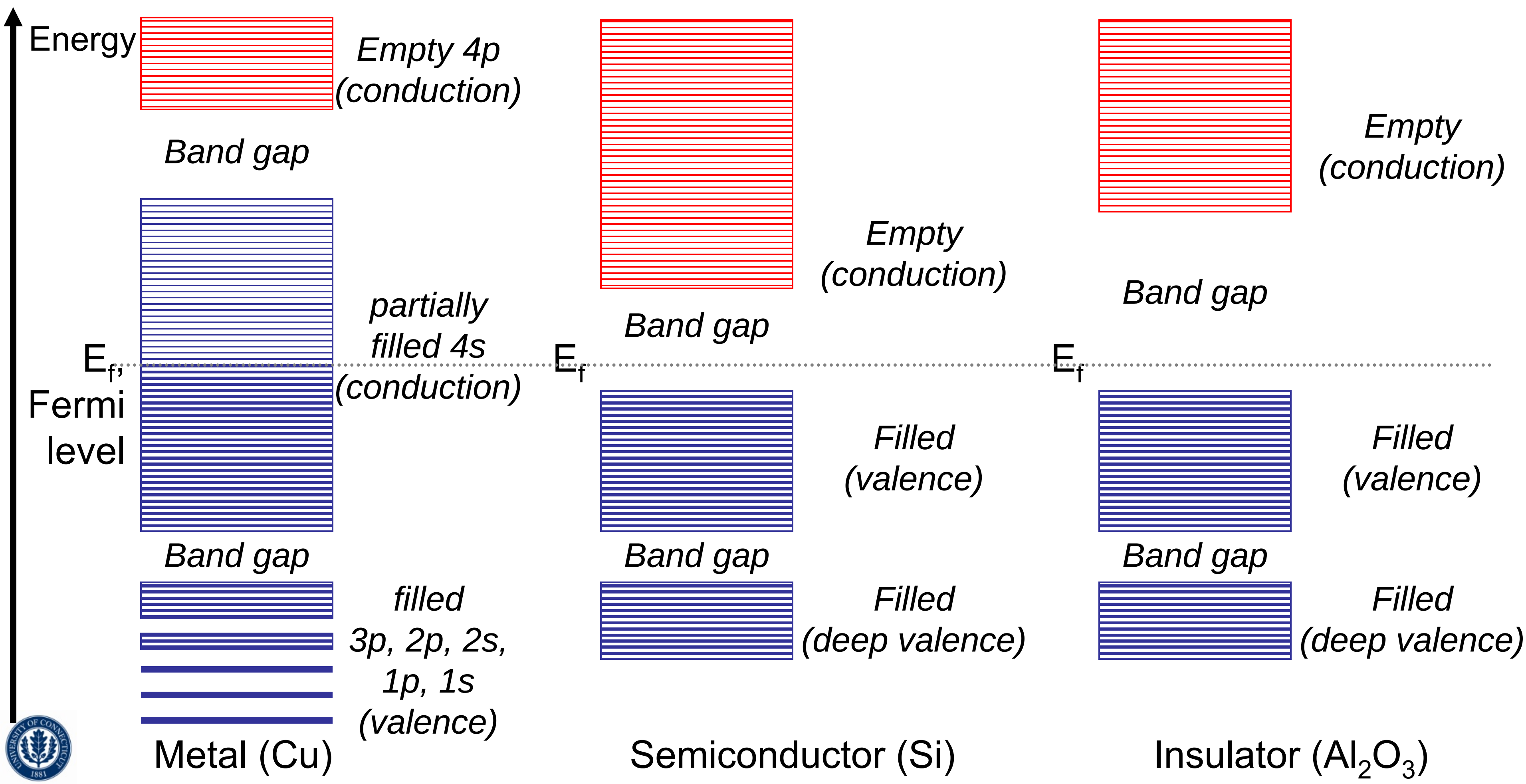


semimetal (Bi)

conducting

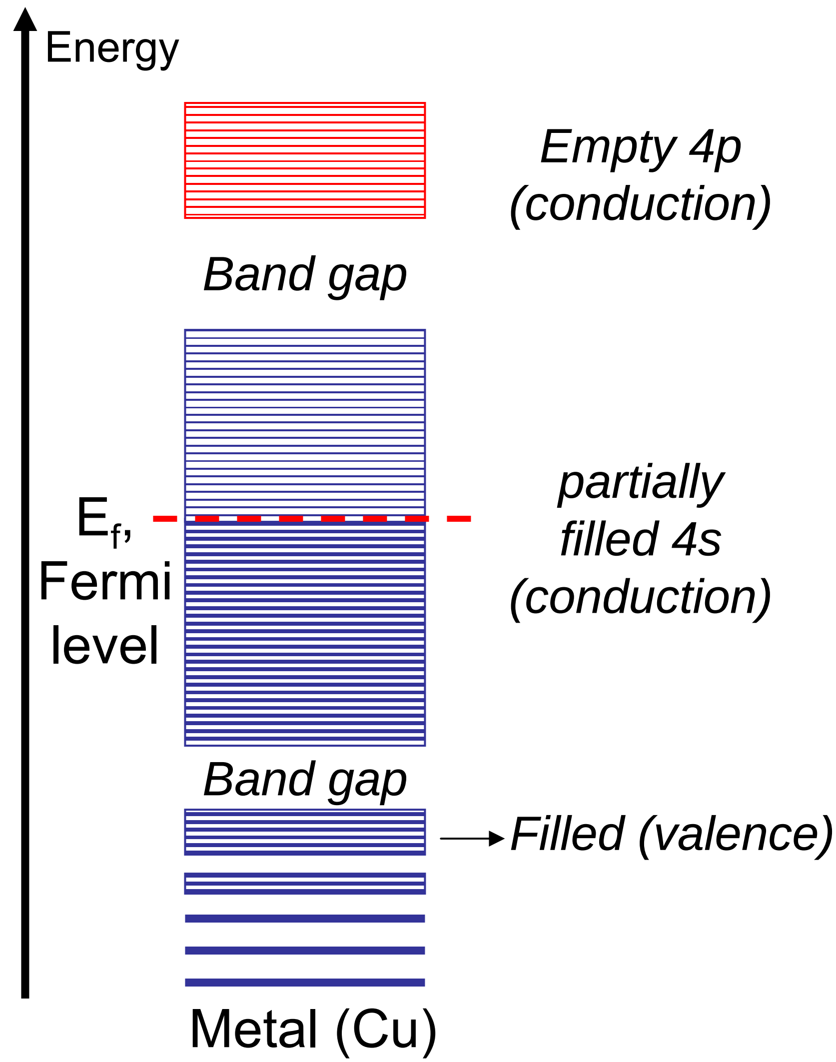
Band structures for semiconductors and insulators

- Semiconductors and Insulators have totally full valence bands and empty conduction bands with a bandgap between them. E_f exists in the bandgap.
  - The distinction between semiconducting and insulating materials is arbitrarily set to a bandgap of < or > 2-3 eV, respectively.



Definition of Conductivity

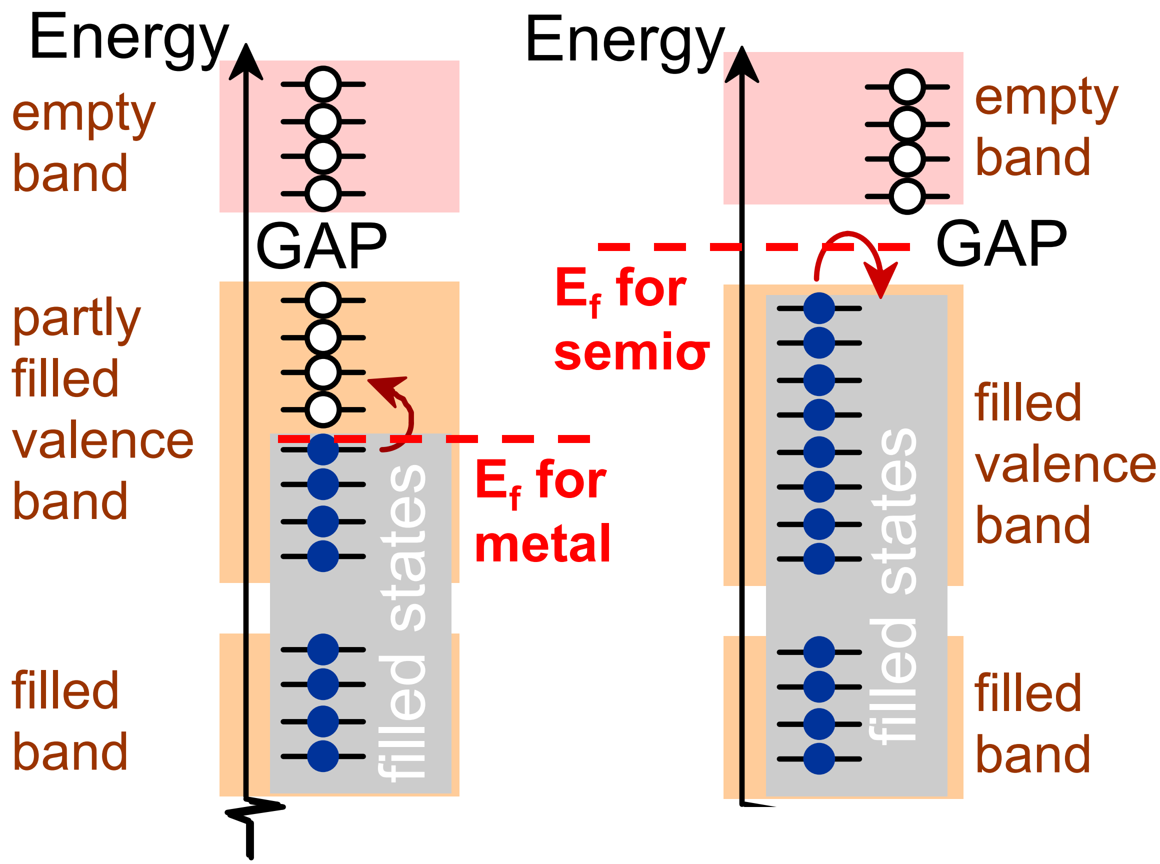
- The free-est electron (the electron with the highest energy) defines the position of '**E_f**,' the "Fermi level."
  - Above E_f, all electron states in the energy bands are empty
  - Below E_f, they are all filled.
- If there is **<u>no gap</u>** between filled and empty states (whether in a band or between bands), the material **<u>is conductive</u>**.
- If there is a gap, the material is a semiconductor or insulator.
- Essentially, conduction requires:
  - A) empty states
  - B) those empty states to be energetically accessible.



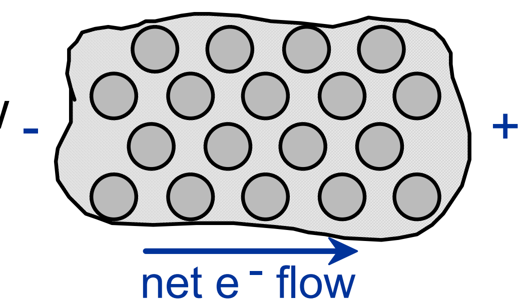
Depends on temperature, applied voltage, energy of light exposure, etc.

CONDUCTION & ELECTRON TRANSPORT

- At room temperature, atoms have kinetic energy = kT, which is approximately 25 meV.
- For most metals, this is sufficient to jump from a filled state to an empty state since the Fermi level (topmost electron) has empty states just above it.
- Once in the empty state, an electron can be swept away by an electric field, thus carrying current.

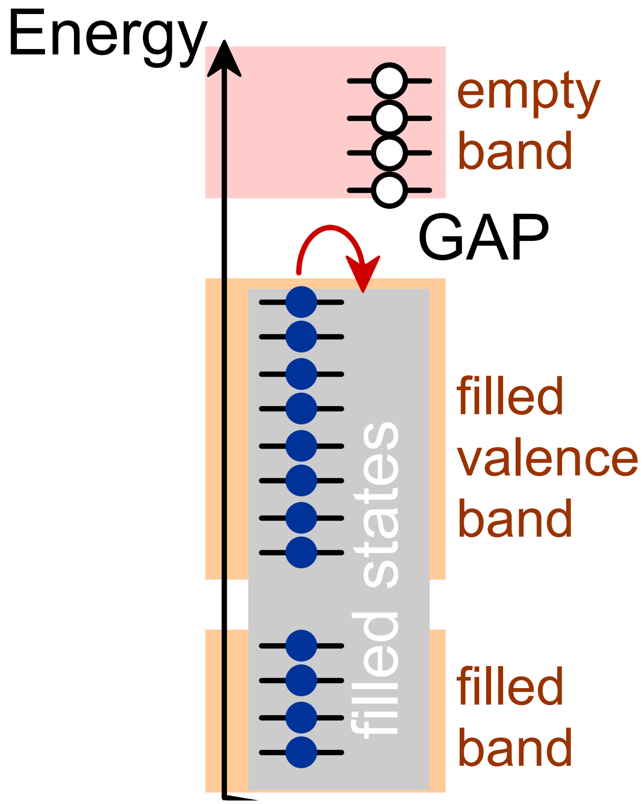


- BUT, for most semiconductors/insulators, there are few electrons able to get to an empty state (ie into the conduction band)
  - the gap to the next available state is >> 25 meV

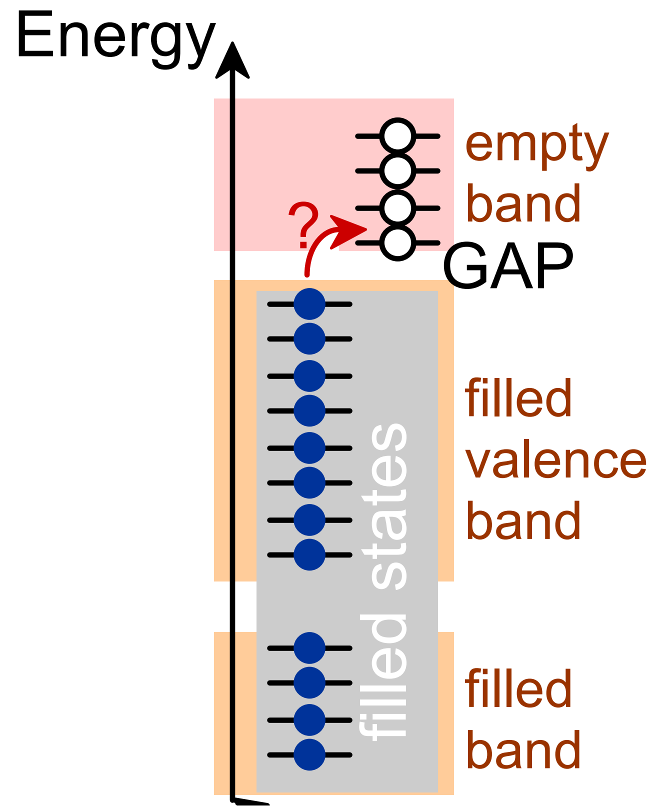


Conduction in insulators/semiconductors

- Insulators:
  --Higher energy states *not accessible* due to gap.



- Semiconductors:
  --Higher energy states *possibly accessible* due to smaller gap.



Note: Conductivity can sometimes be enhanced by adding:

1. Dopants to generate excess charges
2. Impurities, vacancies, or insterstitials that create states or bands within the gap.

Electron Conductivity

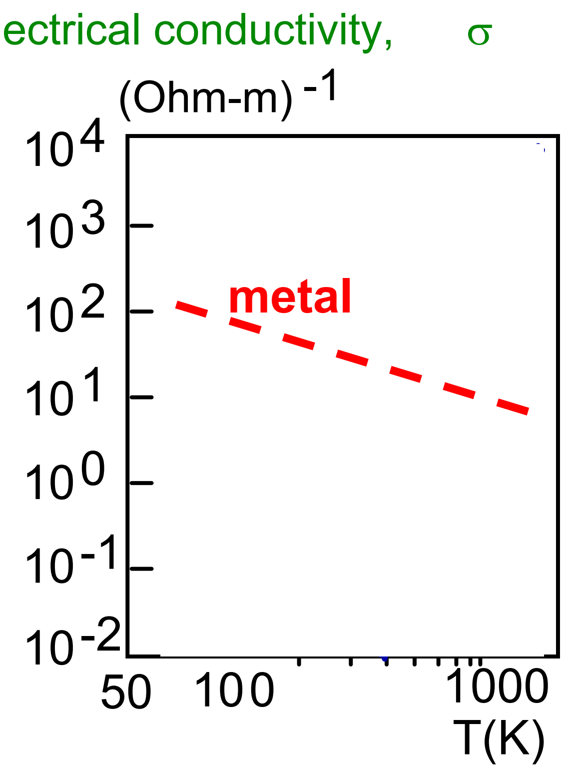
- Metals $$\sigma_e = n|e|\mu_e = \frac{1}{\rho}$$
  - Dominated by mobility, which decreases with increasing Temperature due to increased probability of scattering at higher T.

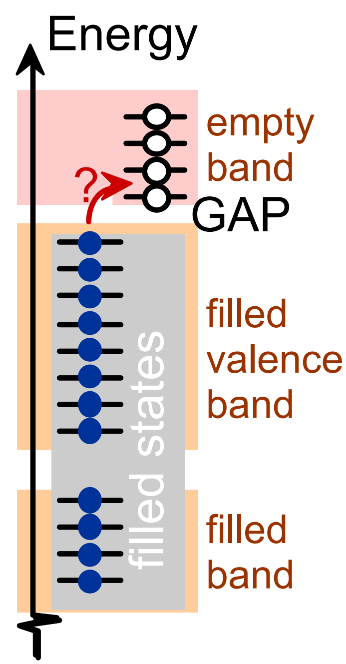
$$\mu_e \propto 1/T$$

- Insulators and Intrinsic Semiconductors (ie semiconductors with **NO** dopants or impurities).
  - Scattering still increases with T.
  - BUT, number of carriers is **very** sensitive to T.
  - n increases exponentially due to increased probability of electrons having enough energy to jump across the band gap.

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

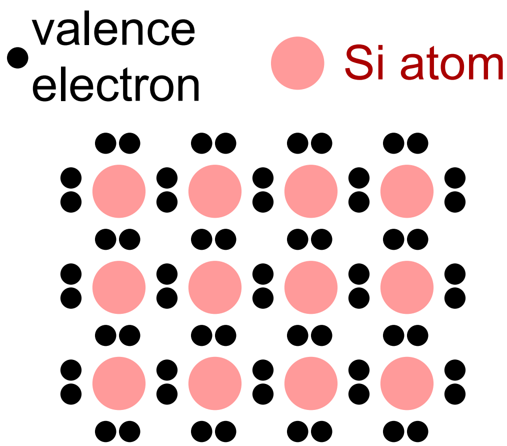
  - Thus, conductivity increases exponentially with T.





Electron and hole conductivity

- In a semiconductor, there can be electrons ***and*** holes:



no applied electric field

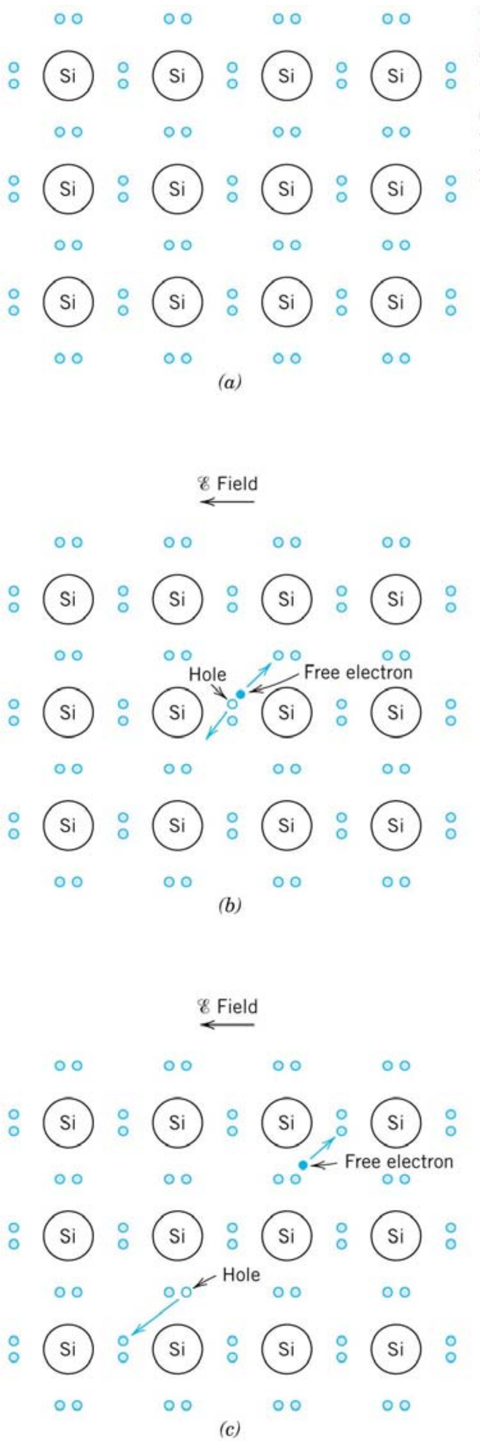
- Total Electrical Conductivity thus given by:

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

n: # electrons/m^3; μ_e: electron mobility; p: # holes/m^3; μ_h: hole mobility

***n*=electrons/m^3**
(10^{16} for pure Si at room T)

Intrinsic carriers



- With intrinsic systems (***only***), for every free electron, there is also a free hole.

electrons = n = # holes = p = n_i

--true for pure Si, or Ge, etc.

$$\sigma = n|e|\mu_e + p|e|\mu_h = n_i|e|(\mu_e + \mu_h)$$

μ_h is ~20% of μ_e

- Holes don't move as easily (mobility of holes is always less than for electrons), but still there are so many that they will contribute at least an extra 10-20% to the intrinsic conductivity.

Conductivity review

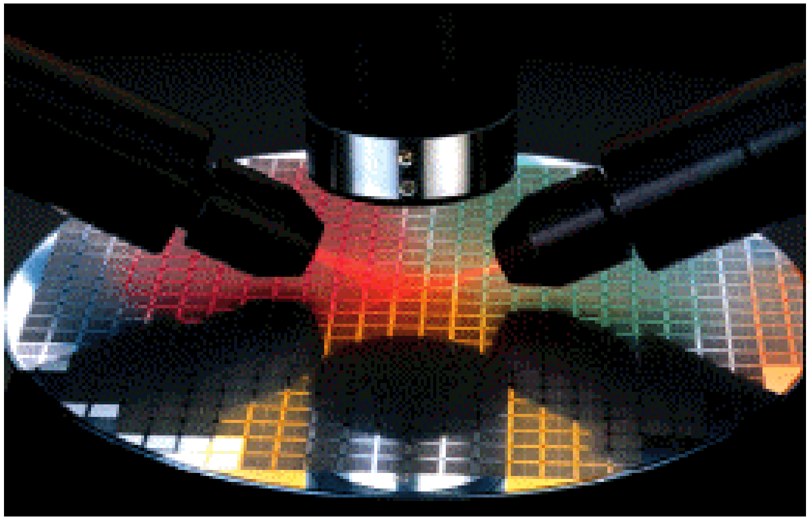
- As a general rule, as temperature increases, scattering also increases. This *decreases conductivity* for metals.
- The mobility for an intrinsic semiconductor *will also diminish* with increasing temperature due to increased scattering.
- Still, the extra temperature provides lots of extra electrons and holes in the conduction band for intrinsic semiconductors. This causes n to increase exponentially with Temperature.

$$\sigma = n|e|\mu_e + p|e|\mu_h = n_i|e|(\mu_e + \mu_h) = e^{-E_{gap}/kT}|e|(\mu_e + \mu_h)$$

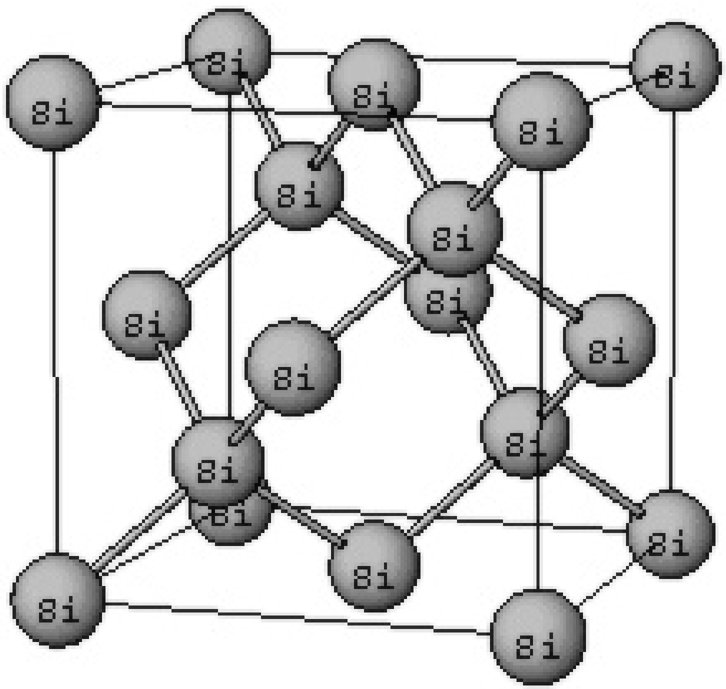
- n goes up so fast w/r to mobility that the excess electrons totally wash out the diminishing effect of extra scattering.
  - ***Thus, conductivity almost always increases with temperature for a semiconductor, but the opposite happens for a metal.***

Semiconductor Industry in 2003

- The semiconductor business: >$200B per year.
  - Roughly 10^{20} transistors produced annually.
- US semiconductor industry: $80B.
  - $20B reinvested in research.
  - $20B reinvested in equipment.
  - 250 000 jobs in US alone.



http://www.infras.com/Tutorial/sld001.htm



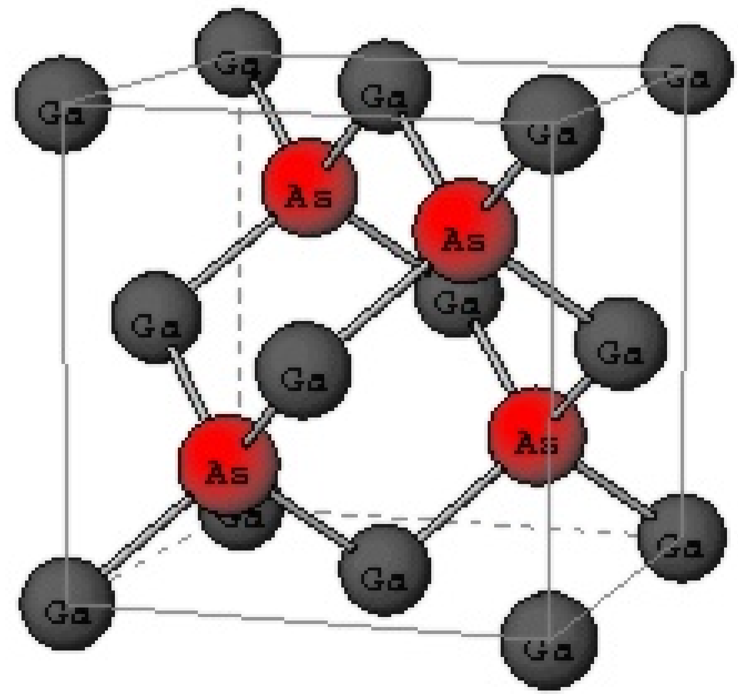
Silicon

Diamond Cubic Structure

4 atoms at (0,0,0)+ FCC translations

4 atoms at (¼,¼,¼)+FCC translations

Bonding: covalent



GaAs

ZnS (Zinc Blende) Structure

4 Ga atoms at (0,0,0)+ FCC translations

4 As atoms at (¼,¼,¼)+FCC translations

Bonding: covalent, partially ionic

SUMMARY

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Reading for next class

Semiconductors and Integrated Circuits

Chapter sections: 18.10-15