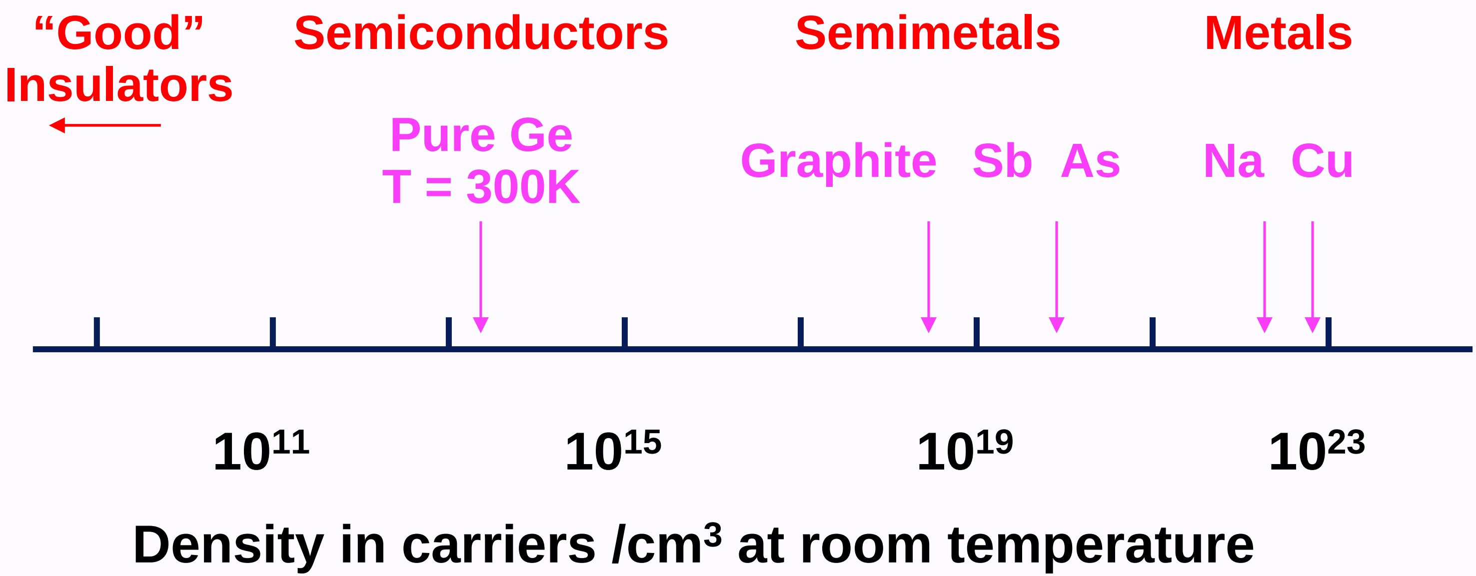
Lecture 16: Semiconductors
(Kittel Ch. 8)



Outline

- **What is a semiconductor?**

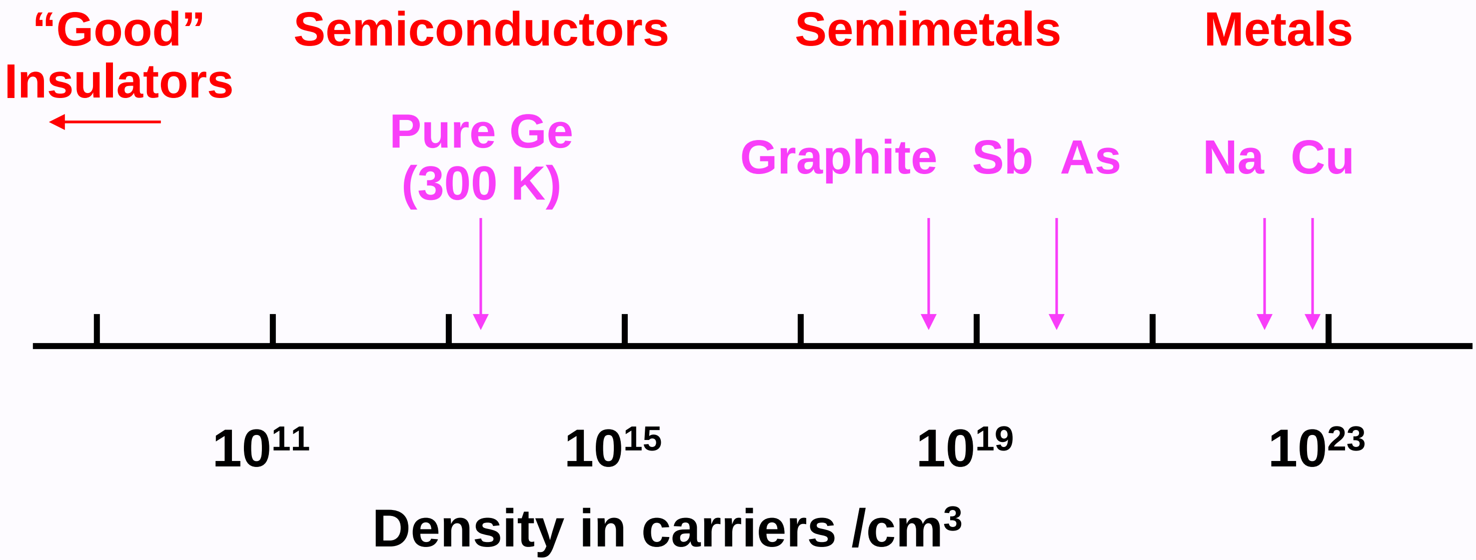
- **Bands in real semiconductors - Si, Ge, GaAs, ...**
  Starting point - Nearly free electrons!
  Energy gaps

- **Optical properties**
  Why is GaAs so different from Si and Ge?

- **(Read Kittel Ch 8)**

What is a semiconductor?

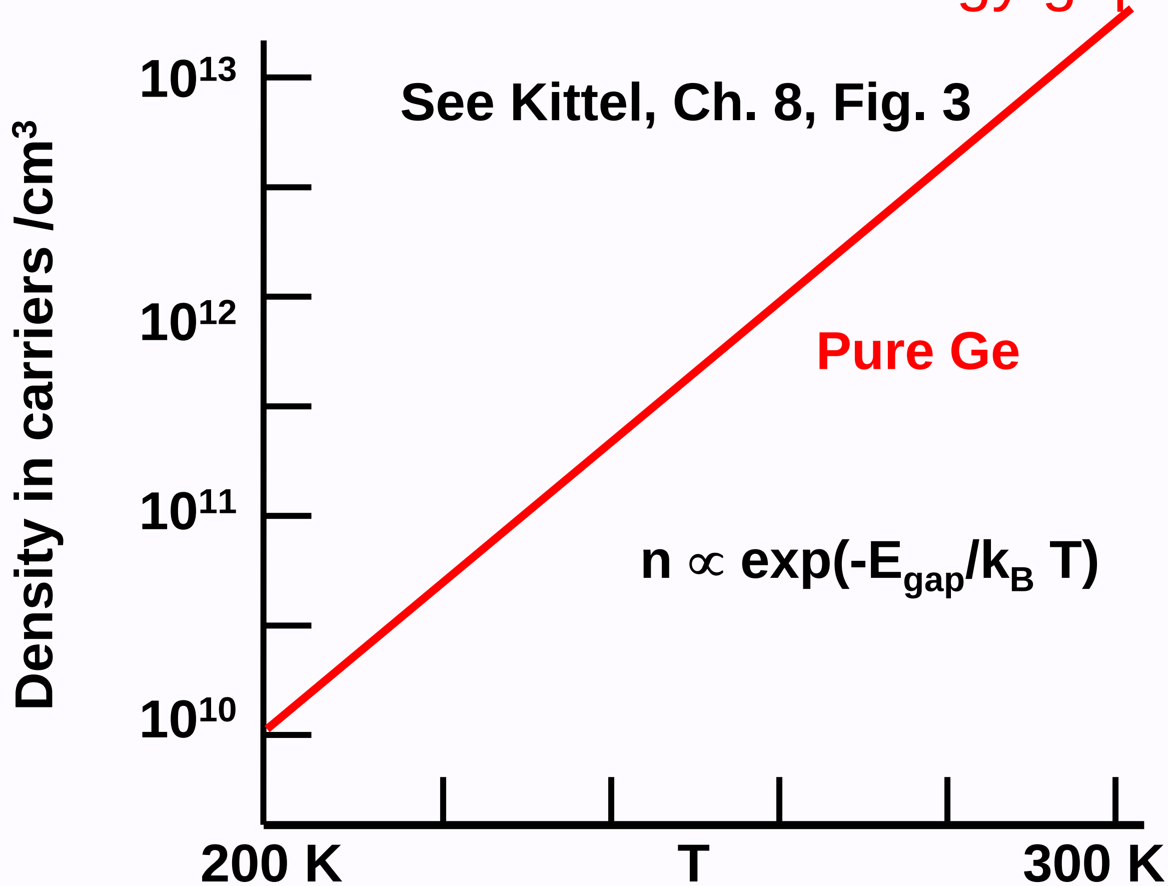
- Experimental facts - density of electrical carriers in different crystals at room temperature



See also Kittel, Ch. 8, Fig. 1

What is a semiconductor?

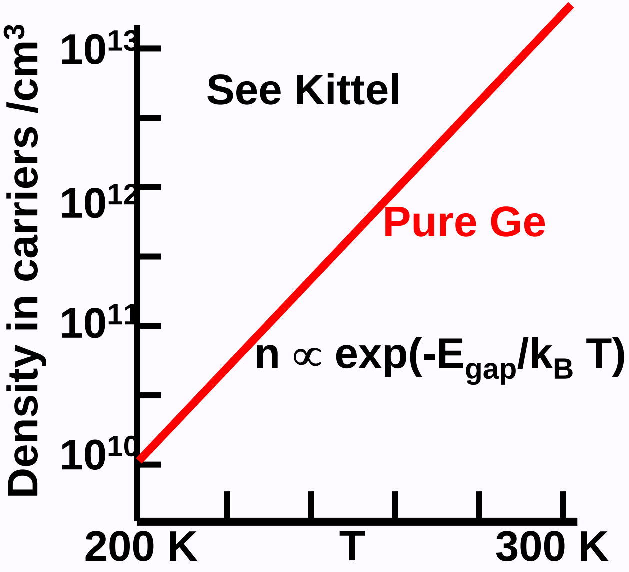
- Experimental facts - temperature dependence of carrier concentration indicates an energy gap



Typical Gaps

- Experimental values of energy gap

C	≈ 5.4 eV
Si	≈ 1.1 eV
Ge	≈ 0.7 eV
GaAs	≈ 1.5 eV
InAs	≈ 0.4 eV
GaP	≈ 2.3 eV
InP	≈ 1.4 eV
GaN	≈ 3.4 eV



What is a semiconductor?

- Experimental facts:

  Carrier concentration varies dramatically with purity (Can be changed or controlled - unlike a good metal like Cu)

  Carriers can have different signs! Positive and negative - as shown by Hall effect

- How can all this happen?

  Interpretation in terms of electron bands?

From last time

Metals vs Insulators

- A band holds two electrons per cell of the crystal
- Therefore an crystal with an odd number of electrons per cell MUST* be a metal!

  Partially filled bands lead to Fermi energy and "Fermi surface" in k space

  Conductivity because states can change and scatter when electric field is applied

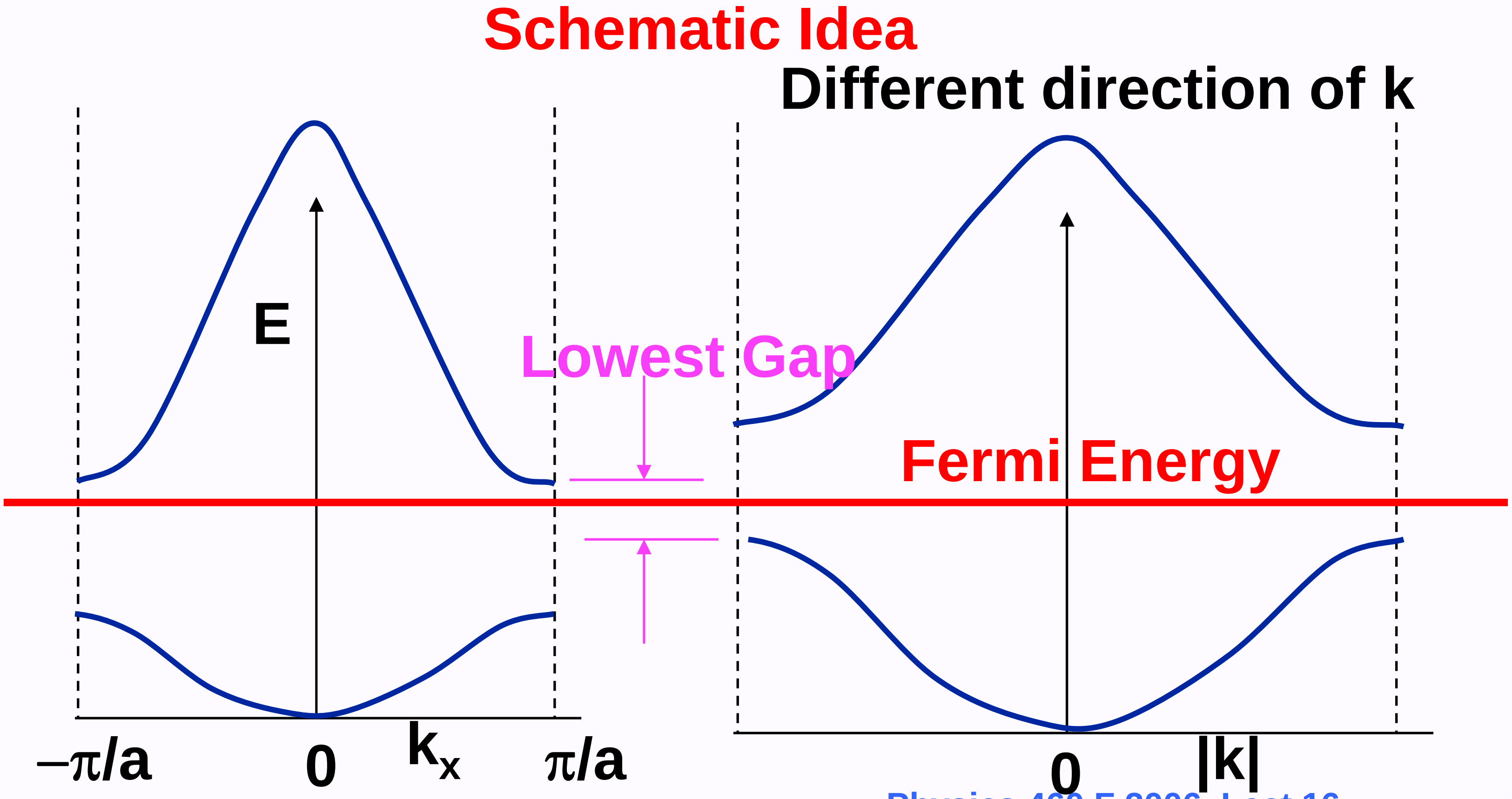
- A crystal with an even number of electrons per cell MAY be an insulator!

  Electrons "frozen"

  Gap in energy for any excitations of electrons

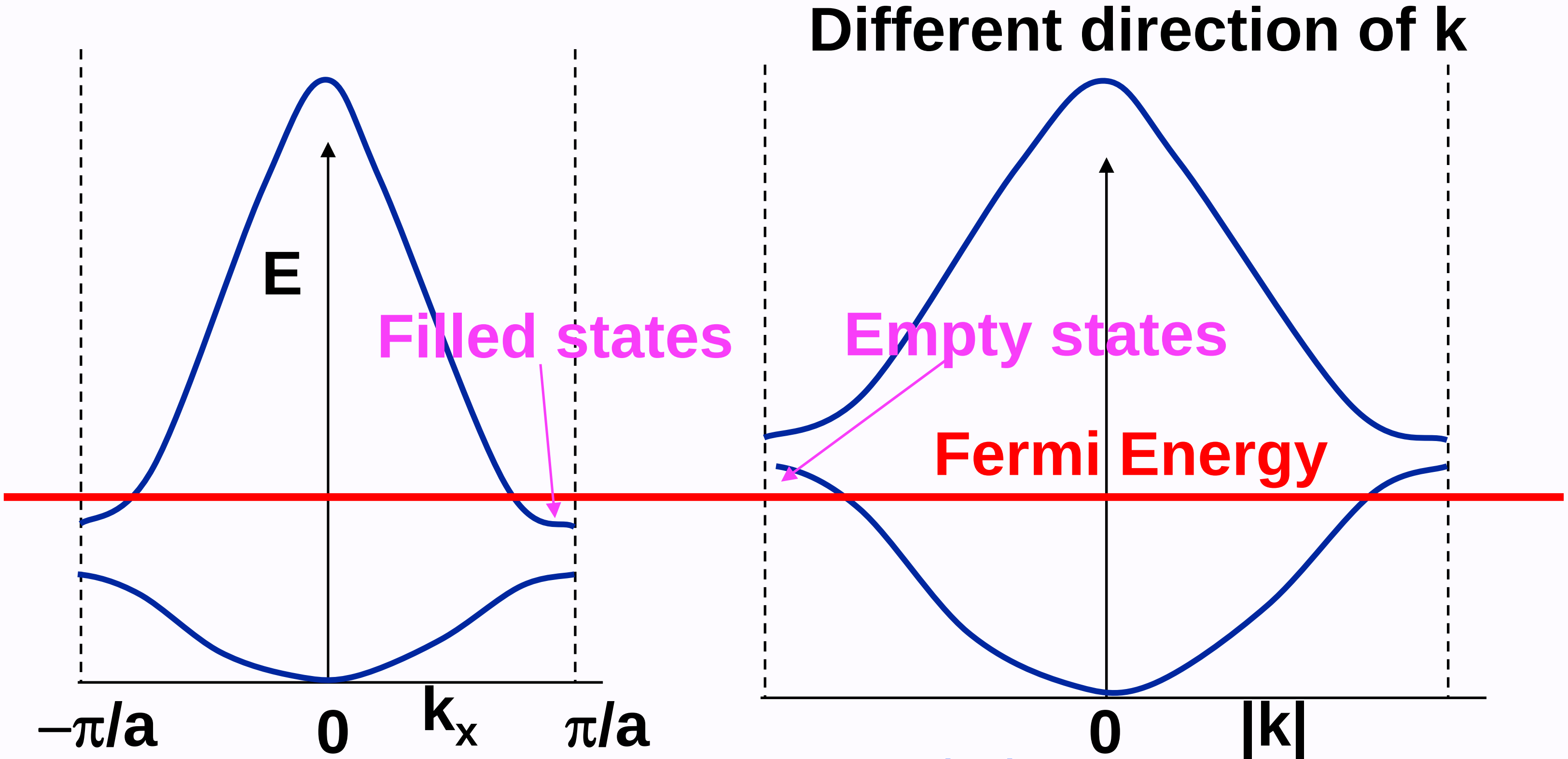
Semiconductors

- A material is a semiconductor if there is a small gap
- Roughly 0.1 eV - 2.0 eV



Semimetals (close relative)

- Small changes in the bands leads to “band overlap”, which has relations to what happens in a semiconductor



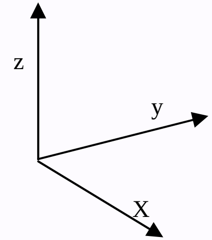
Real Semiconductors - Si, Ge, GaAs, ...

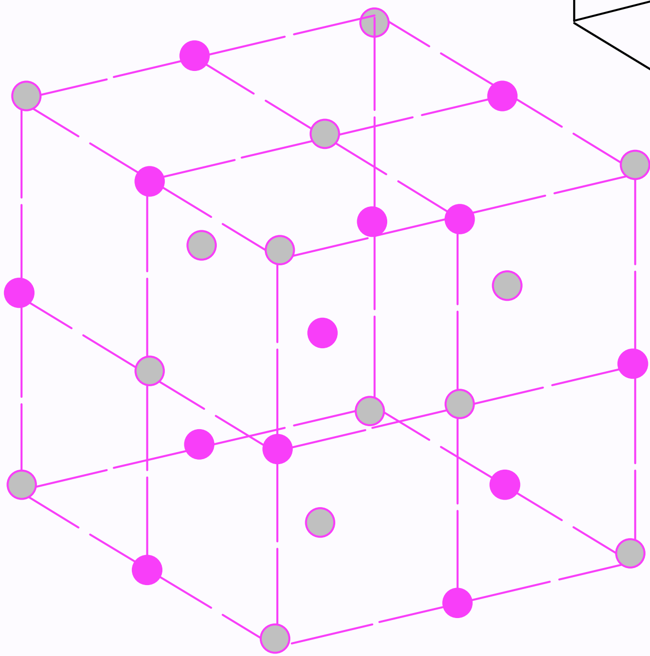
- All the common semiconductors in your electronics are diamond or zinc-blende structure - FCC - two atoms per primitive cell

- 8 valence electrons per cell

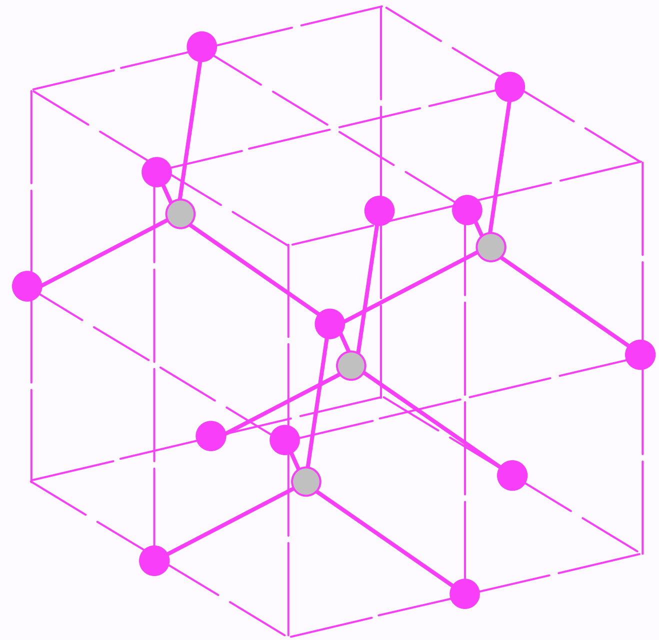
- Can be understood (roughly!) as nearly free electron-like

Cubic crystals with a basis



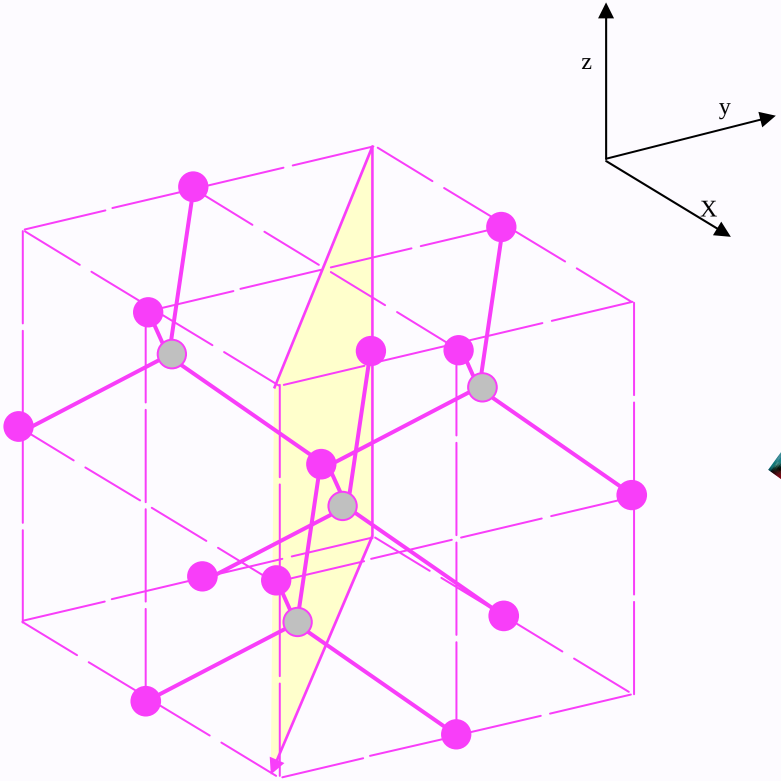


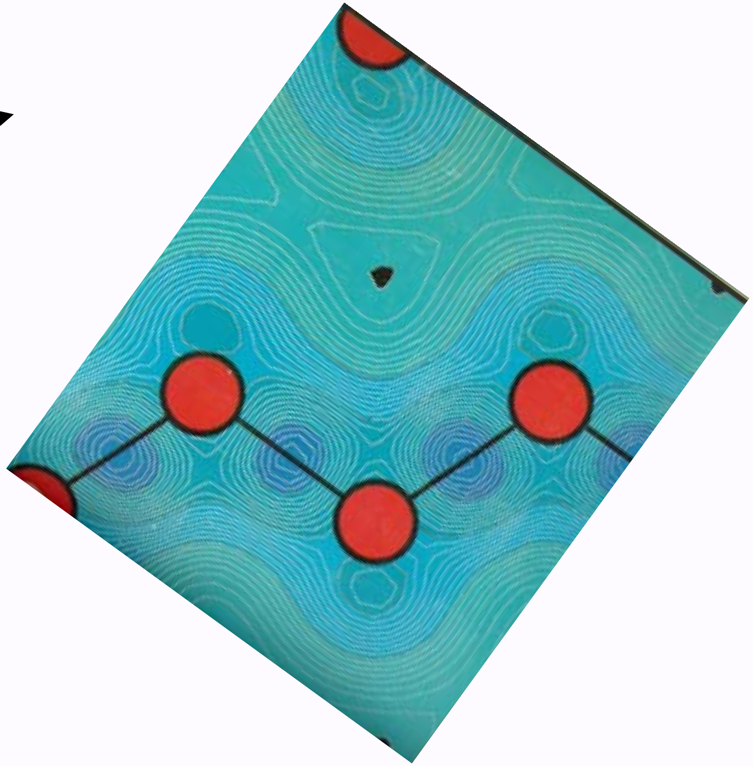
NaCl Structure with
Face Centered Cubic Bravais Lattice



ZnS Structure with
Face Centered Cubic Bravais Lattice
C, Si, Ge form diamond structure with
only one type of atom

(110) plane in diamond structure crystal





(100) plane in ZnS crystal
zig-zag Zn-S chains of atoms
(diamond if the two atoms are the same)

Calculated valence electron density
in a (110) plane in a Si crystal
(Cover of Physics Today, 1970)

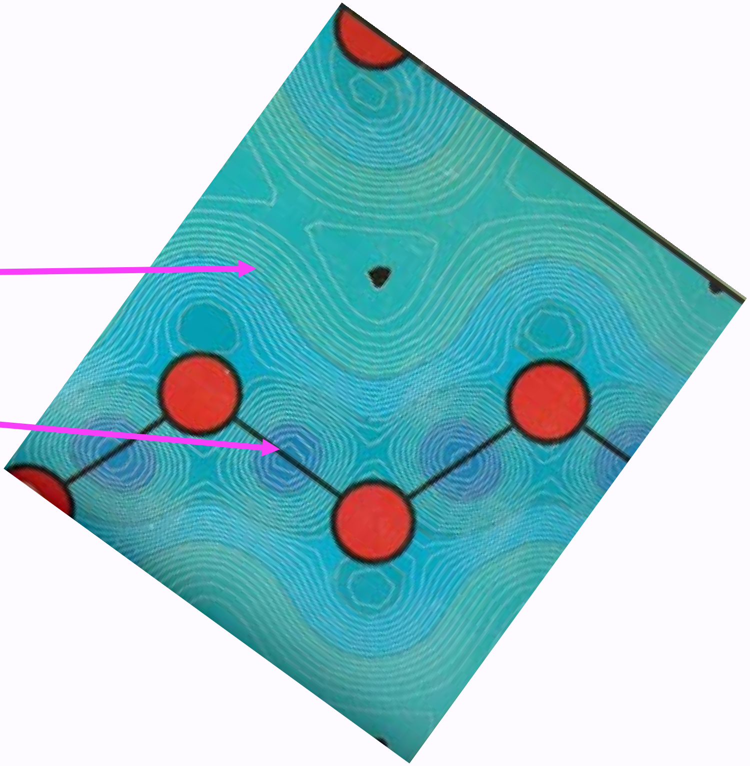
Nearly-free-electron-like ?

Density of valence electrons is rather smoothly varying

Minimum in open regions Away from the atoms

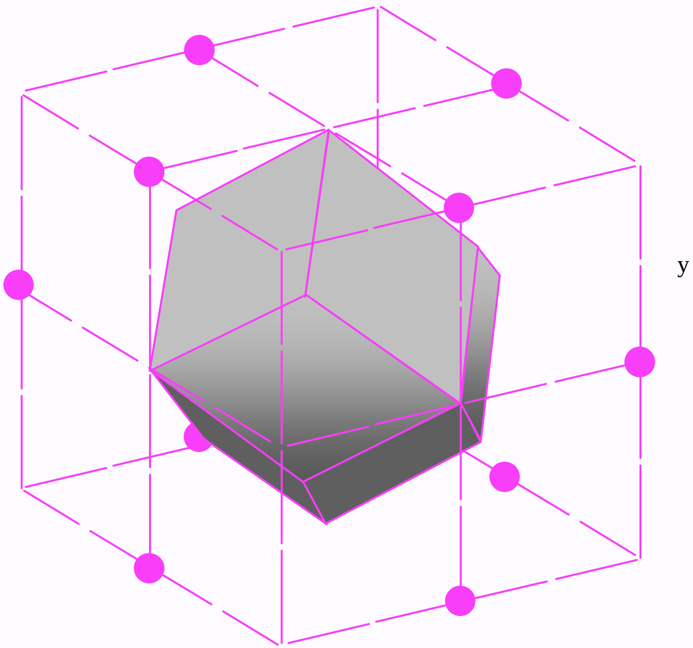
Peaked at bonds between atoms

Reasonable to consider as a perturbation starting from uniform system (The nearly free electron approach similar to the 1d problem that we solved)

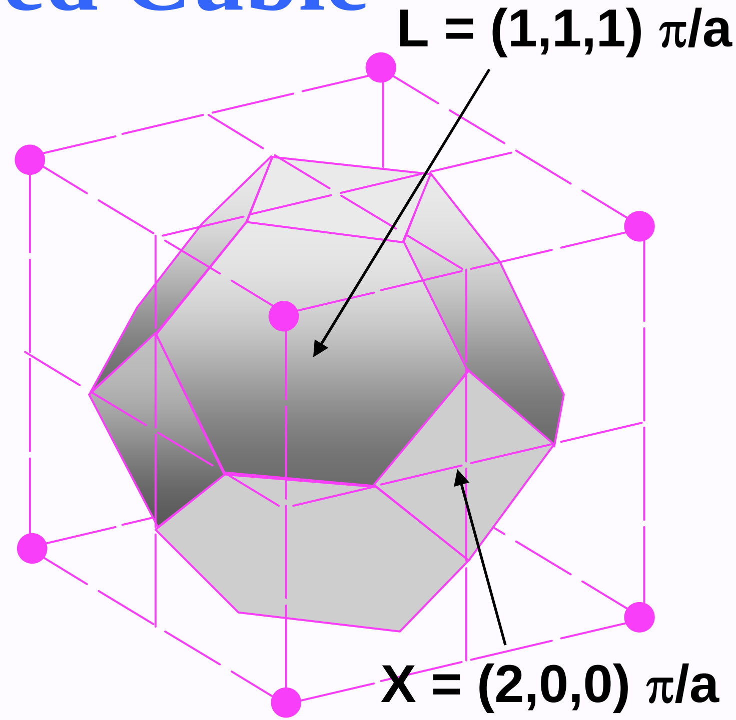


Calculated valence electron density in a (110) plane in a Si crystal (Cover of Physics Today, 1970)

Face Centered Cubic



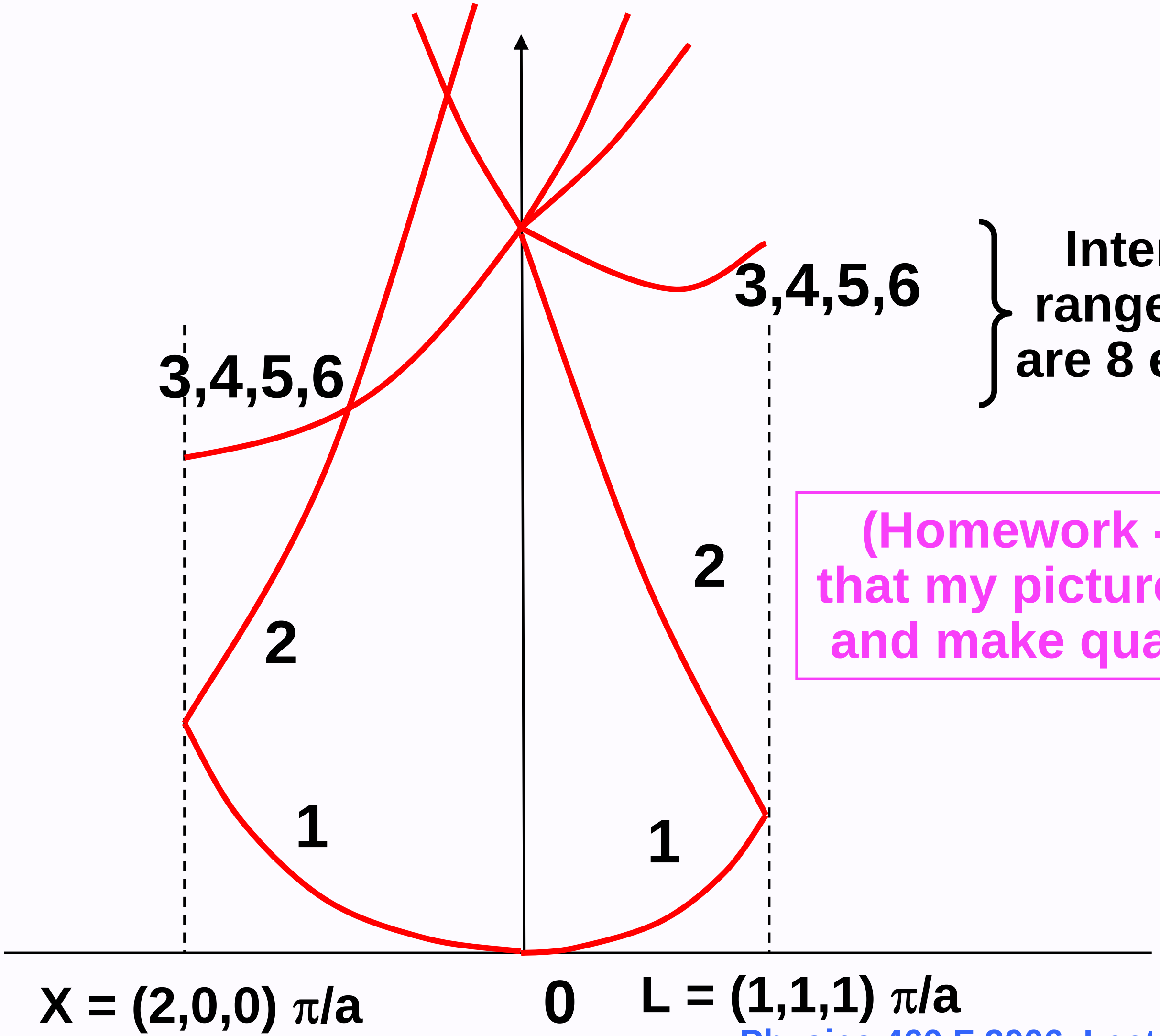
Wigner-Seitz Cell for
Face Centered Cubic Lattice



Brillouin Zone =
Wigner-Seitz Cell for
Reciprocal Lattice

From Lect 4, see also Kittel Ch 8, Fig 15

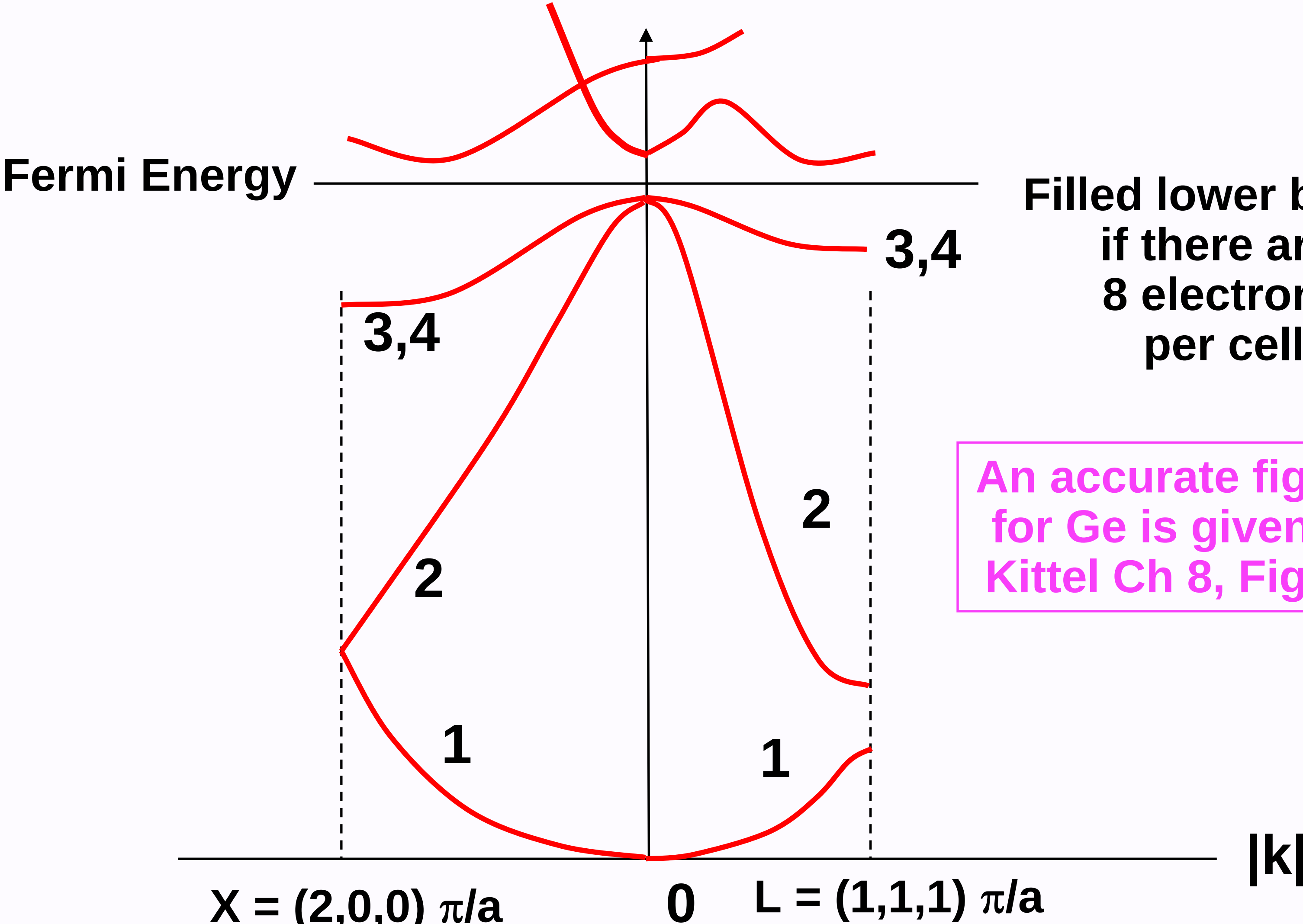
Free Electrons - 3 d - FCC



Interesting range if there are 8 electrons

(Homework - Check that my picture is right - and make quantitative)

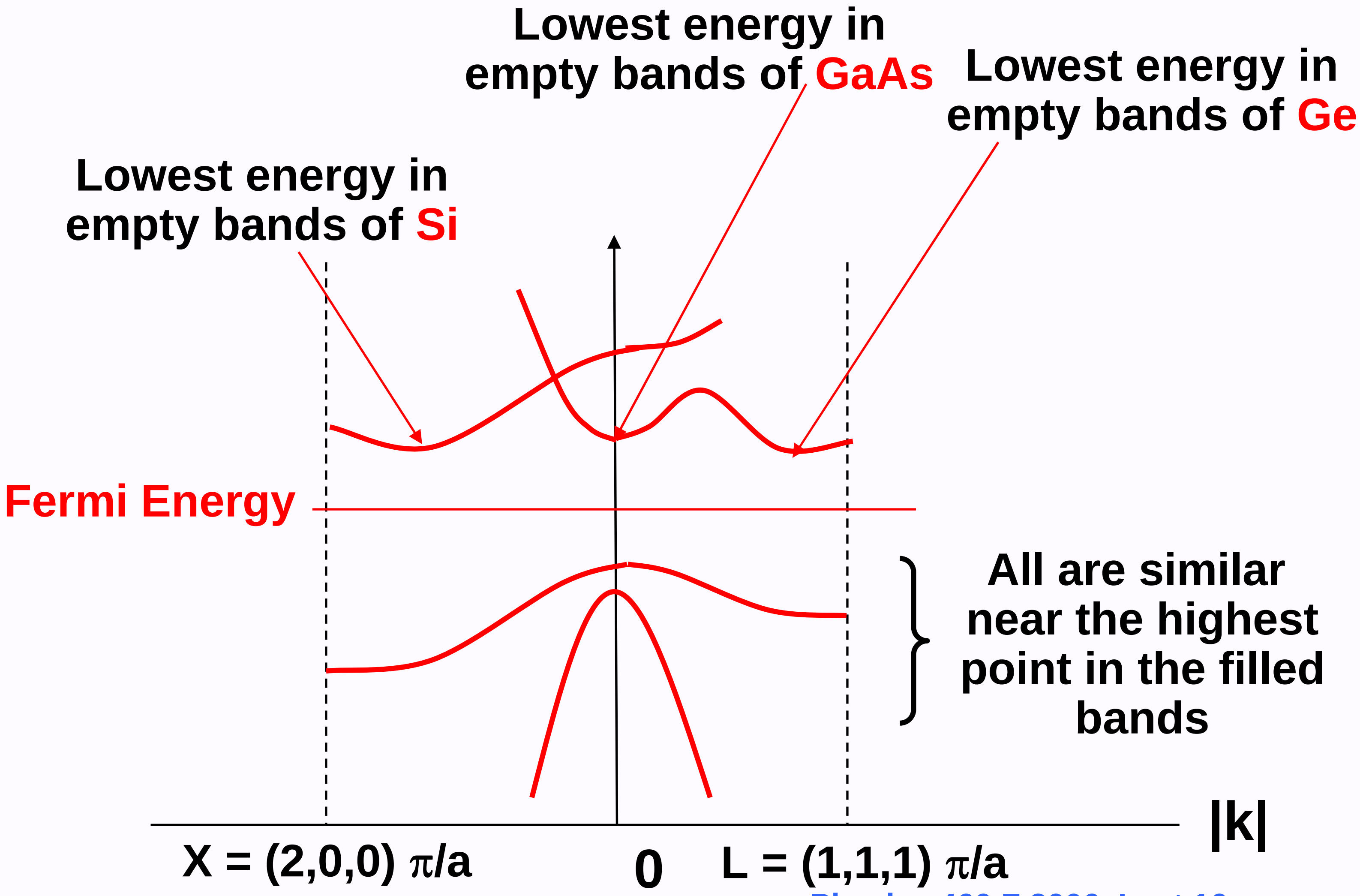
Real Bands in a Semiconductor - Ge



Filled lower bands if there are 8 electrons per cell

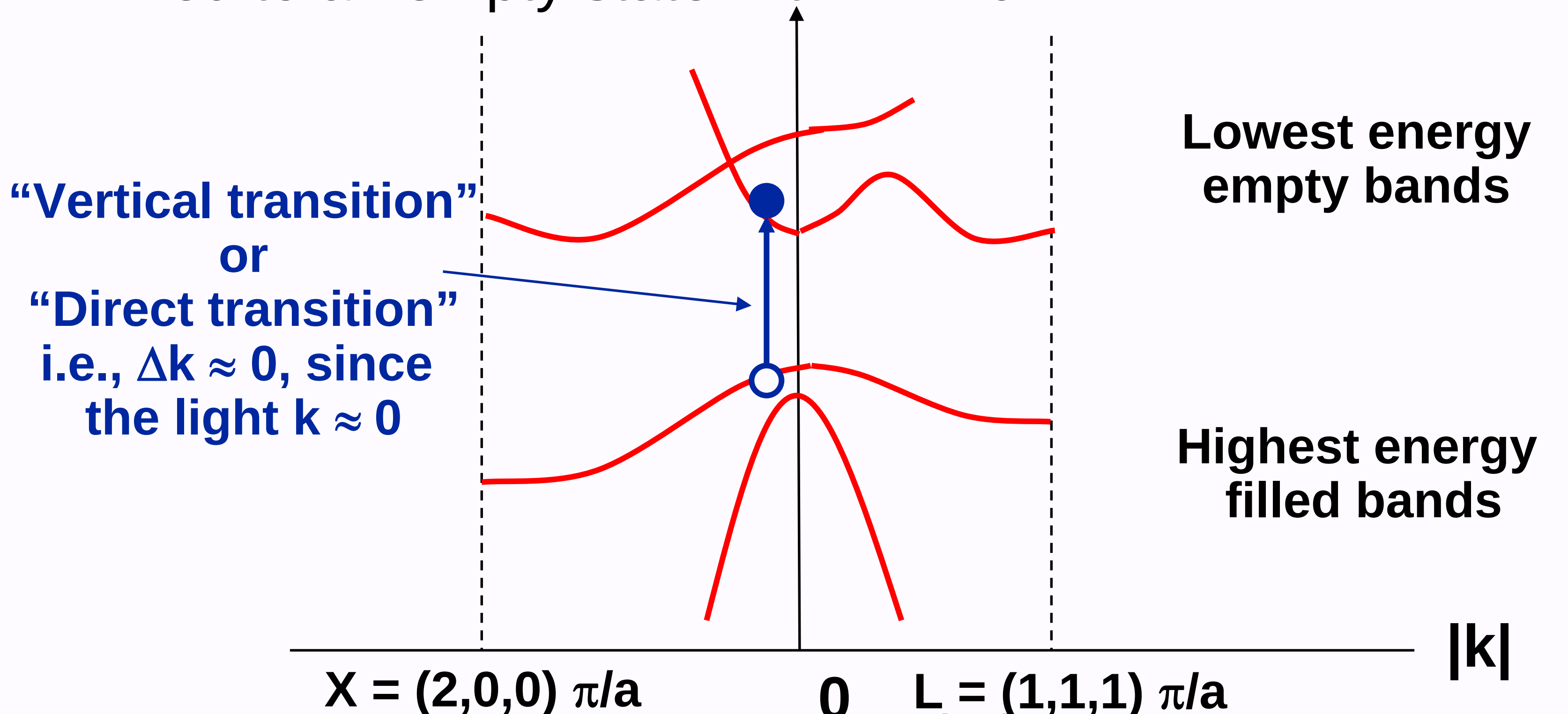
An accurate figure for Ge is given in Kittel Ch 8, Fig 14

Bands Near Fermi Energy



Optical properties

- Why is your computer chip made of Si, but the laser in your CD player is made of GaAs (in the future GaN?)
- Optical absorption involves exciting electron from a filled to an empty state with $\Delta k \approx 0$



Interaction of light with solids

- Why is the absorption (or emission of light) a "vertical transition" (also called a "direct transition") ?
- Recall what a band structure is:
  - The energy of electron states in a crystal $E^n(k)$, where k is the wavevector inside the Brillouin Zone and n labels the bands, n=1,2, … .
- Absorption of a photon with energy $E_{photon} = \hbar\,\omega_{photon}$ and wavevector $k_{photon} = 2\pi/\lambda_{photon}$ causes an electron to change from initial to final states:

$$k_i \Rightarrow k_f \text{ and } n_i \Rightarrow n_f$$

where

$$k_f - k_i = k_{photon} \quad \text{and} \quad E^{n_f}(k_f) - E^{n_i}(k_i) = E_{photon}$$

(conservation of energy E and "crystal momentum" k)

- Emission is the same with "initial" and "final" reversed

Interaction of light with solids

- Why is the absorption (or emission of light) a "vertical transition" (also called a "direct transition") ?

- What is special about light?

- The wavelength λ_{photon} >> atoms size

  λ_{photon} ~ 100-500 nm   atomic size ~ a ~ 0.1-1 nm

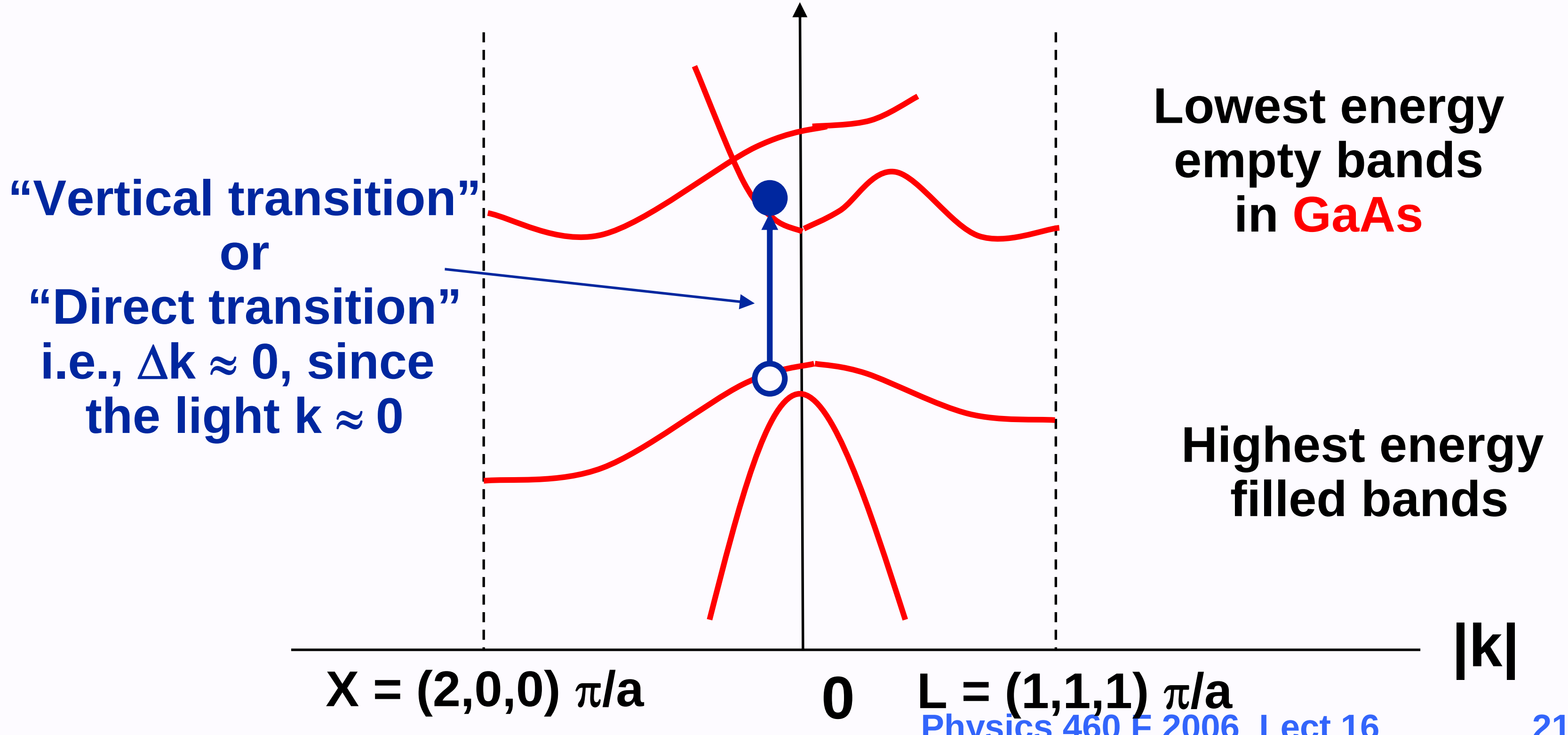
- Thus $k_{photon} << k_{BZ} \sim 2\pi/a$
  where k_{BZ} is the size of the Brillouin zone

- The change in k for the electron $k_f - k_i = k_{photon}$ is very small compared the the scale of the Brilloiun Zone

- We can approximate $k_f = k_i$, i.e., a vertical (direct) transition

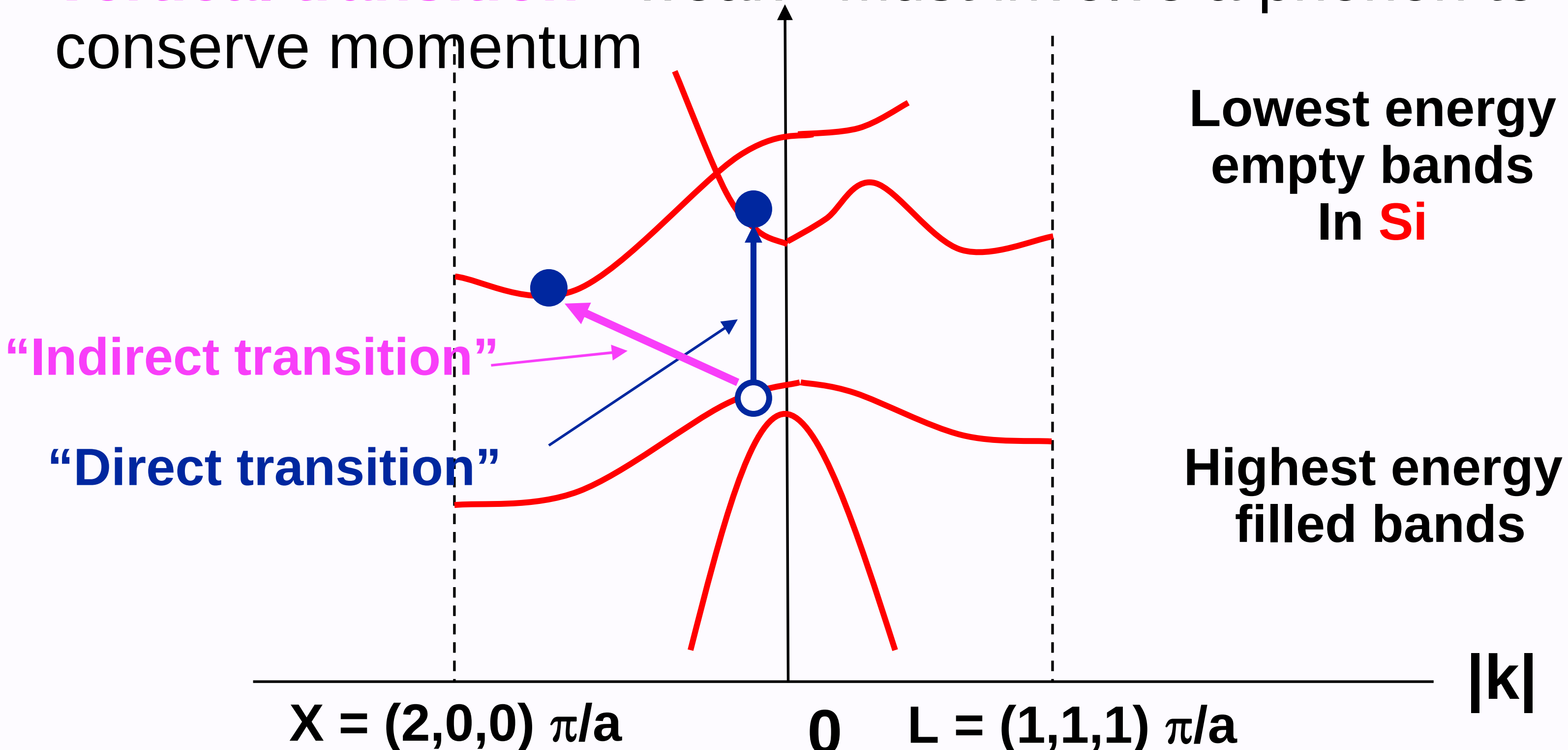
Optical properties

- Why is your computer chip made of Si, but the laser in your CD player is made of GaAs (in the future GaN?)
- In GaAs the lowest energy possible is a direct "vertical" transition with $\Delta k \approx 0$



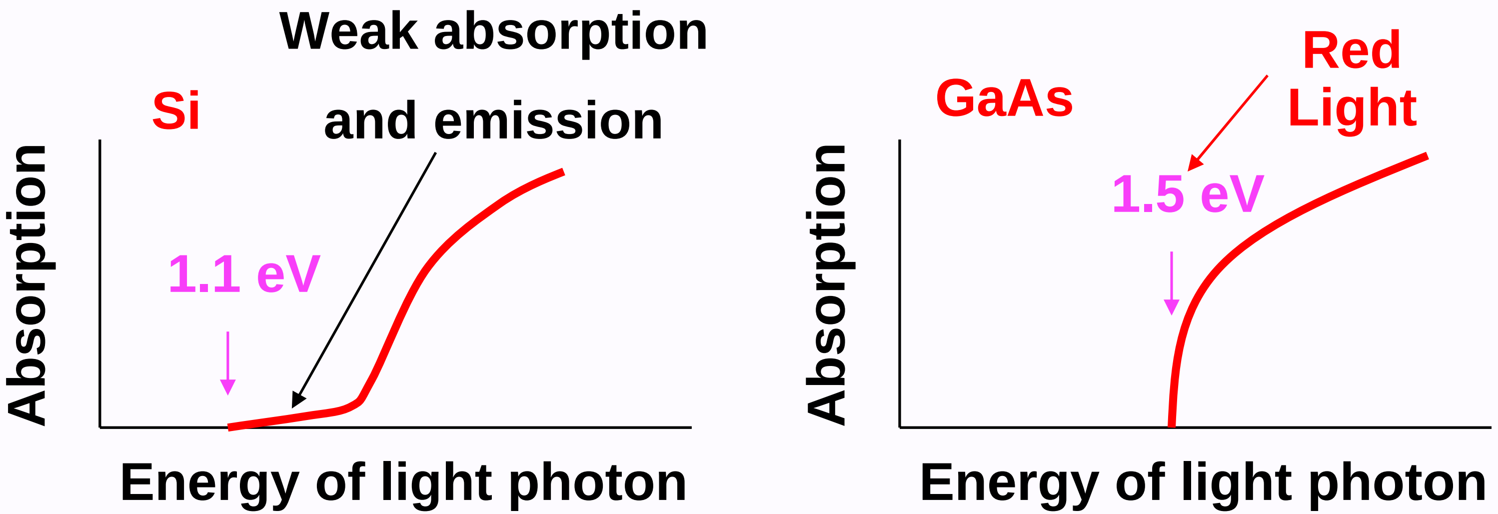
Optical properties

- Why is your computer chip made of Si, but the laser in your CD player is made of GaAs (in the future GaN?)
- In Si the lowest energy possible is **“indirect” non-vertical transition** - weak - must involve a phonon to conserve momentum



Optical properties

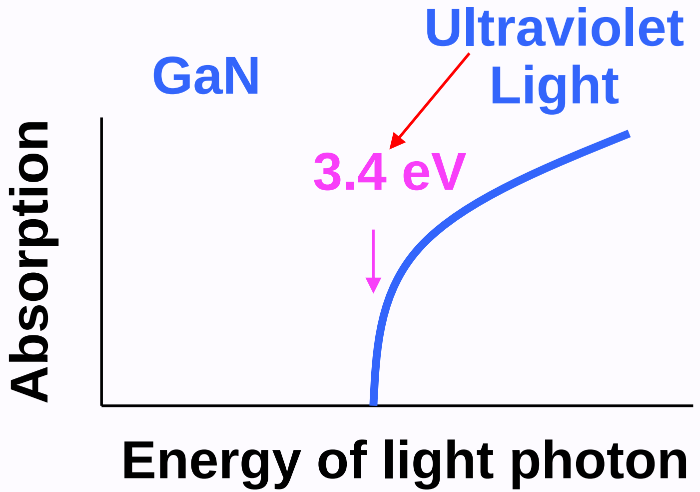
- Why is your computer chip made of Si, but the laser in your CD player is made of GaAs (in the future GaN?)
- Comparison of absorption



- Light emission is related - very high efficiency in GaAs for excited electron to emit light - very low efficiency in Si

Optical properties

- Why is your computer chip made of Si, but the laser in your CD player is made of GaAs (in the future GaN?)
- Why is GaN interesting?
  (Also AlAs, InAs, ..)



- After decades of attempts, finally it is possible to make blue light emitters and lasers

The process to make GaN LEDs was invented at a small Japanese company – now widely used!

(Physics Today, October, 2000)

- Shorter wavelength blue light focuses to smaller spot implies higher density of information on a CD!

Summary

- What is a semiconductor?
    - Defined by density of carriers
        - High enough for interesting conductivity
        - Low enough to be controlled by temperature and other factors
- Bands in real semiconductors - Si, Ge, GaAs, ...
    - Starting point - Nearly free electrons!
    - Analysis for FCC
        - (applies to all the common semiconductors)
    - Energy bands and gaps
- Optical properties
    - Why is GaAs so different from Si and Ge?
    - Recent developments with GaN
    - Very recent developments with nanostructures --- later
- (Read Kittel Ch 8)

Next time

- More en electrons in Semiconductors
  - Effective mass
  - Electrons and holes
- Intrinsic effects in a pure material
- Control of conductivity by doping (impurities)
- (Read Kittel Ch 8)