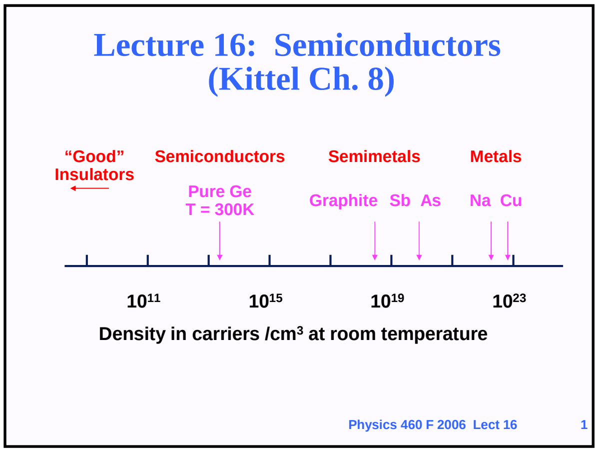
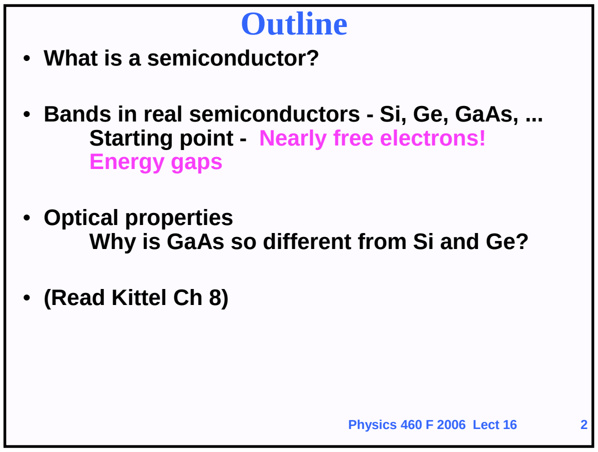
# Lecture 16 - Semiconductors



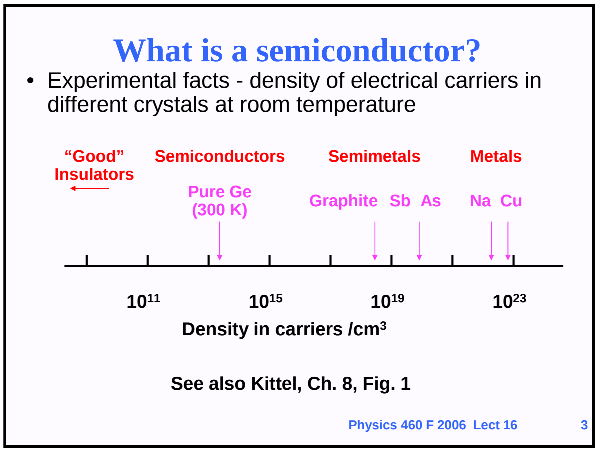
## Lecture 16: Semiconductors (Kittel Ch. 8)

Density in carriers /cm$^3$ at room temperature



## 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)**

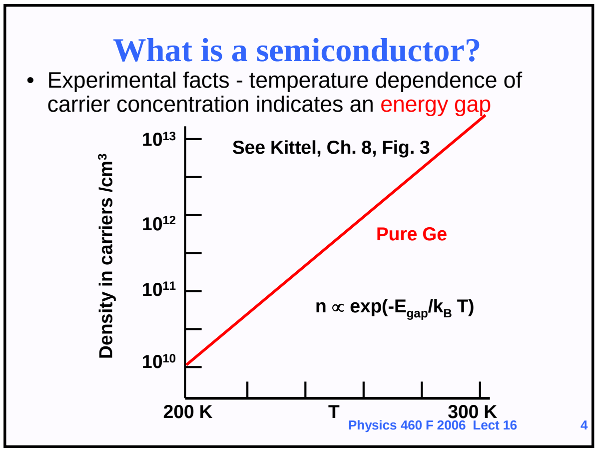


## What is a semiconductor?

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

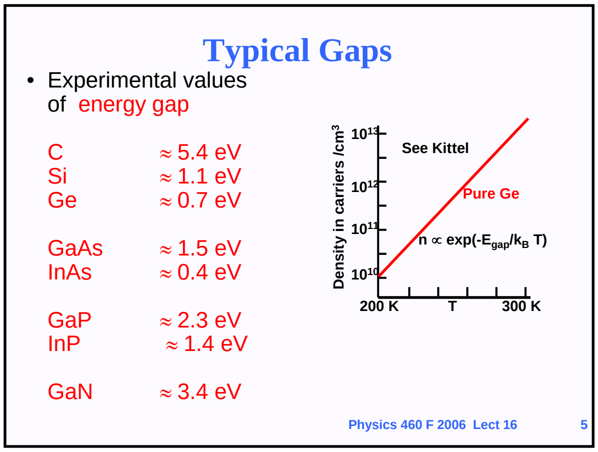
**Density in carriers /cm$^3$**

**See also Kittel, Ch. 8, Fig. 1**



## What is a semiconductor?

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



## Typical Gaps

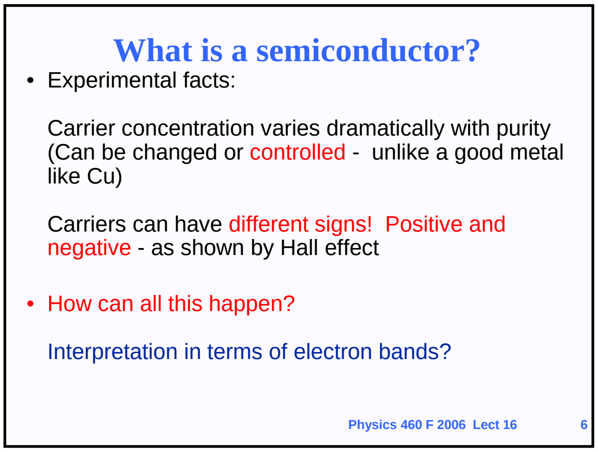
- Experimental values of energy gap

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?

# Lecture 16 - Semiconductors

## Metals vs Insulators

From last time

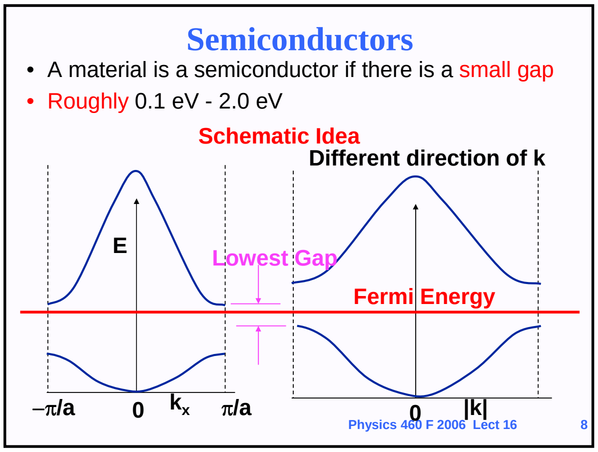
- A band holds two electrons per cell of the crystal
- Therefore an crystal with an odd number of electrons per cell MUST* be a metal!

  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!

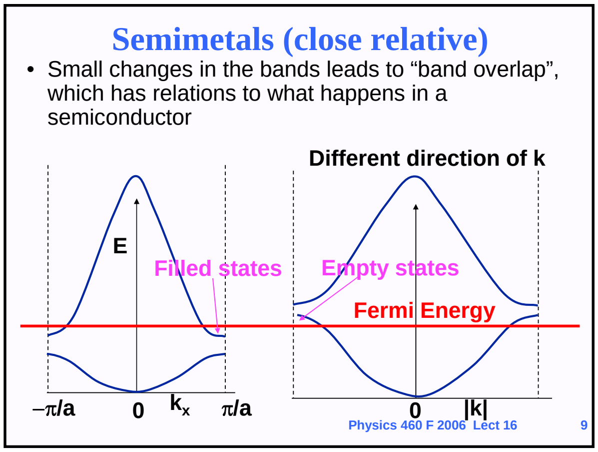
  Electrons "frozen"

  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

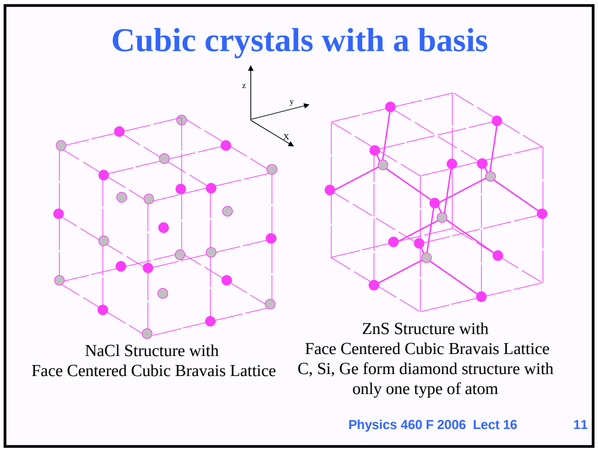


## Semimetals (close relative)

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

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

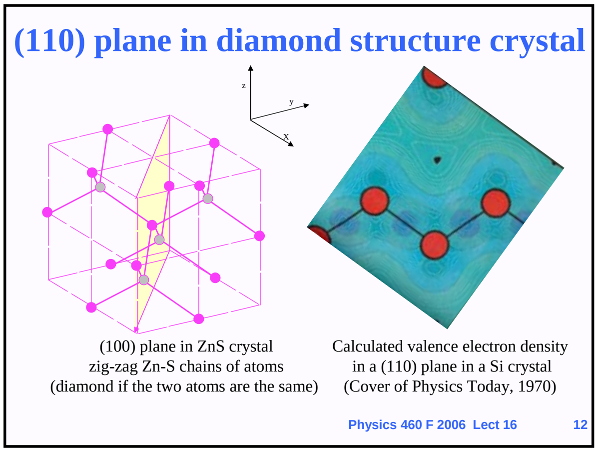
- All the common semiconductors in your electronics are diamond or zinc-blende structure - FCC - two atoms per primitive cell
- 8 valence electrons per cell
- Can be understood (roughly!) as nearly free electron-like



## 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

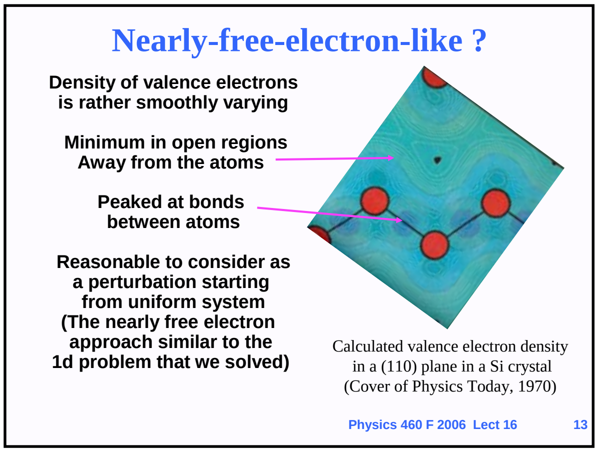


## (110) plane in diamond structure crystal

(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)

# Lecture 16 - Semiconductors



## Nearly-free-electron-like ?

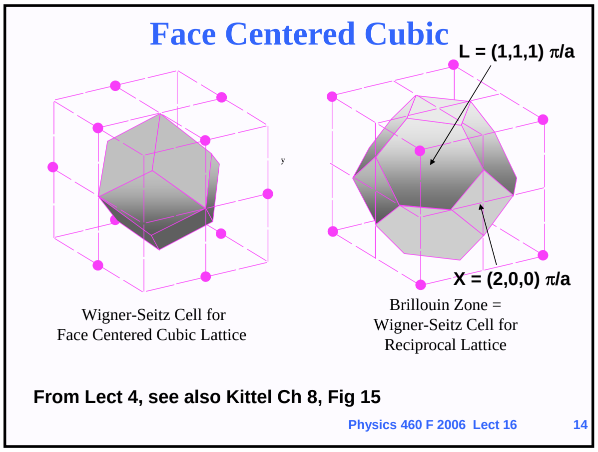
**Density of valence electrons is rather smoothly varying**

**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)

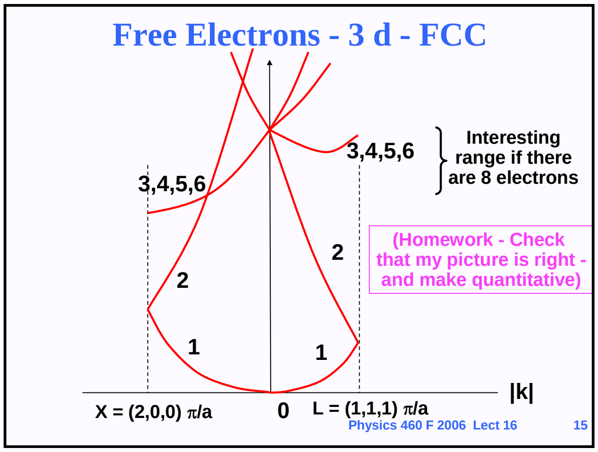


## Face Centered Cubic

Wigner-Seitz Cell for Face Centered Cubic Lattice

Brillouin Zone = Wigner-Seitz Cell for Reciprocal Lattice

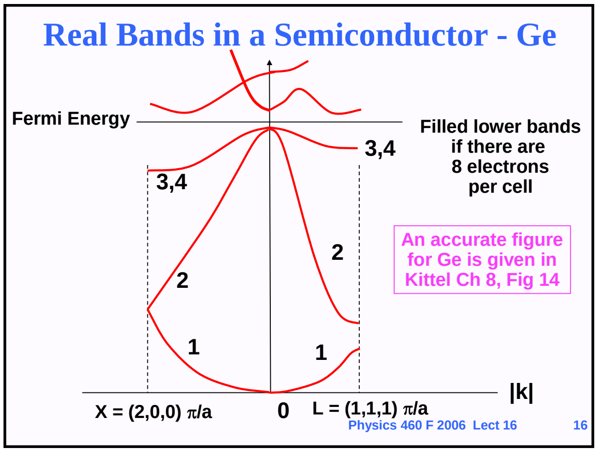
**From Lect 4, see also Kittel Ch 8, Fig 15**



## Free Electrons - 3 d - FCC

**Interesting range if there are 8 electrons**

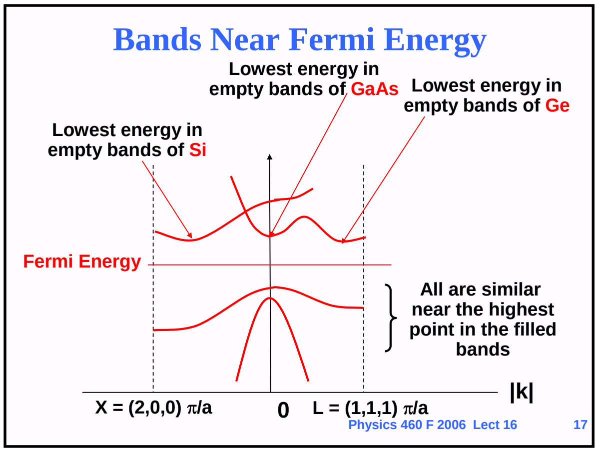
(Homework - Check that my picture is right - and make quantitative)



## 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



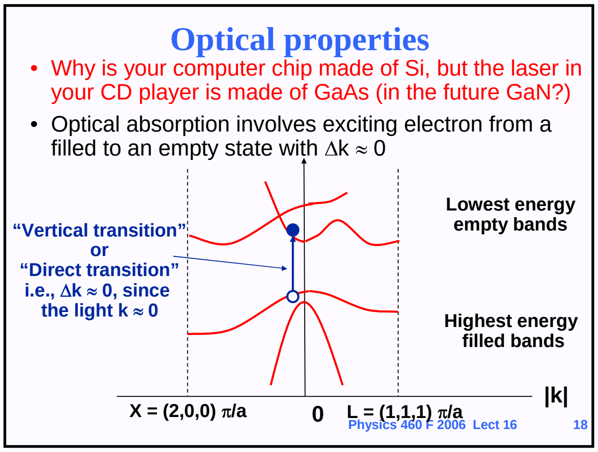
## Bands Near Fermi Energy

**Lowest energy in empty bands of GaAs**

**Lowest energy in empty bands of Ge**

**Lowest energy in empty bands of Si**

**All are similar near the highest point in the filled bands**



## 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 Δk ≈ 0

**"Vertical transition" or "Direct transition" i.e., Δk ≈ 0, since the light k ≈ 0**

**Lowest energy empty bands**

**Highest energy filled bands**

# Lecture 16 - Semiconductors

## 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

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

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

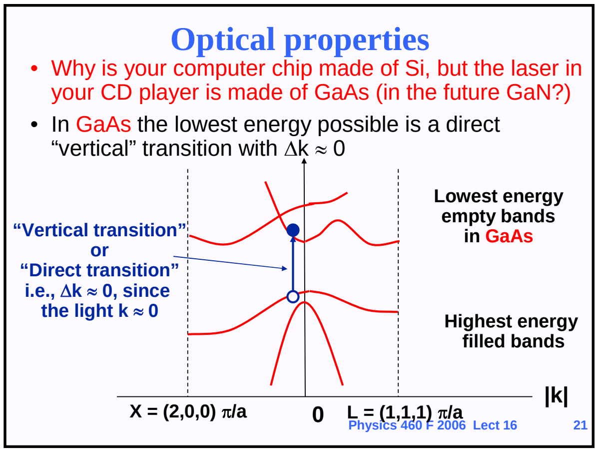
- Emission is the same with "initial" and "final" reversed

## 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 $\lambda_{photon}$ >> atoms size

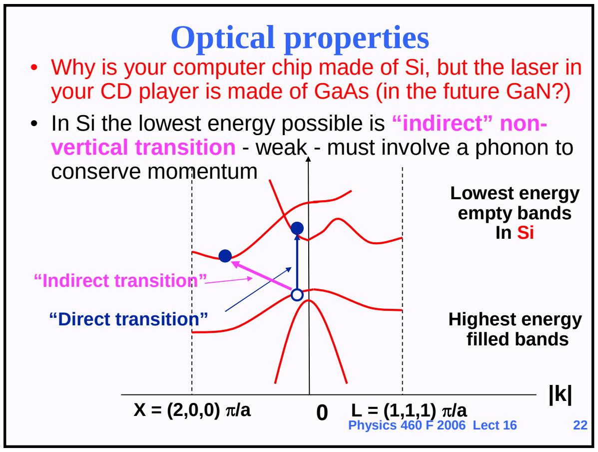
  $\lambda_{photon}$ ~ 100-500 nm  atomic size ~ a ~ 0.1-1 nm

- 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



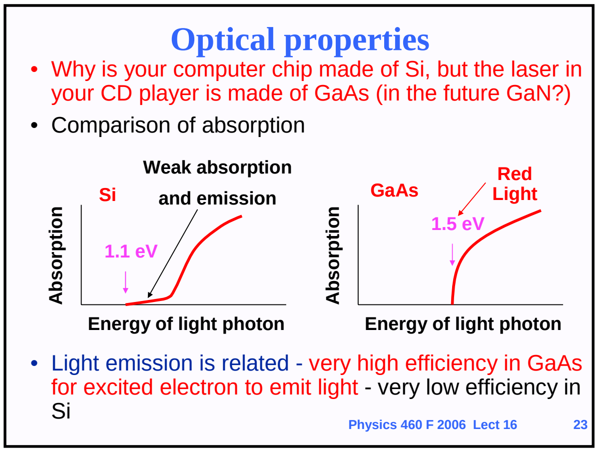
## Optical properties

- 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

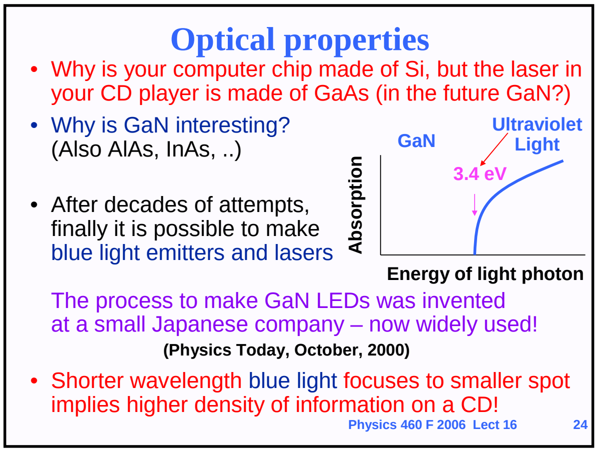
- Why is your computer chip made of Si, but the laser in your CD player is made of GaAs (in the future GaN?)
- In Si the lowest energy possible is "indirect" non-vertical transition - weak - must involve a phonon to conserve momentum



## 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)