Solid State Physics

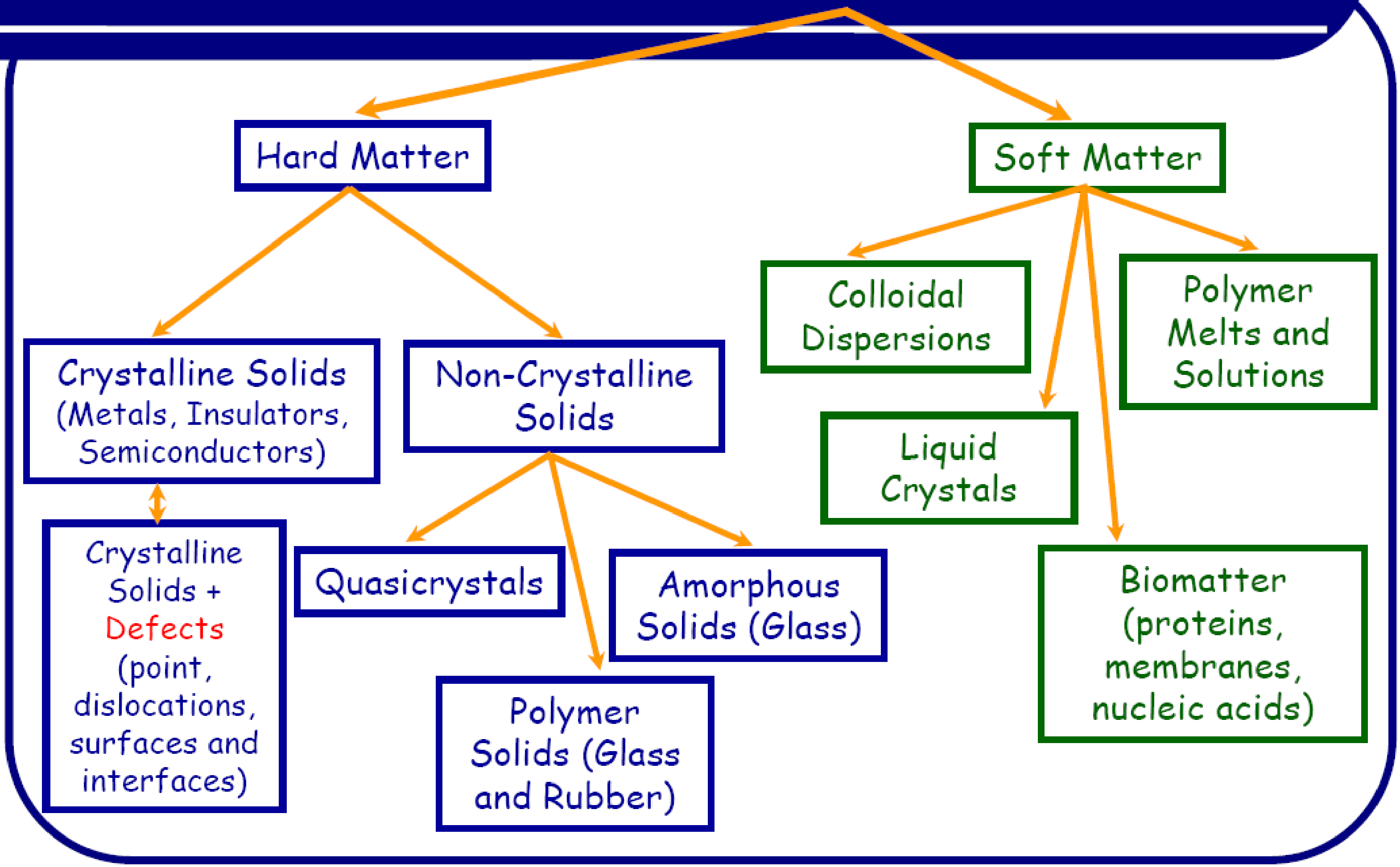
Structure of Matter

- Macroscopic Matter
- Molecules (~10^{23} cm^{-3})
- Atoms
- Electrons, protons, neutrons
- Quarks

States of Matter

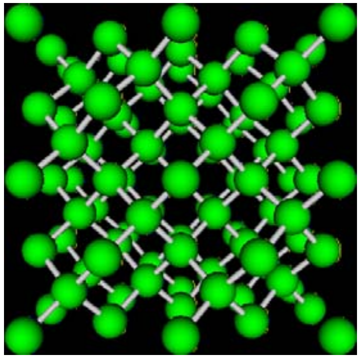
- Solid
  - Have definite shape, volume, strong interaction
- Liquid
  - Shapeless, intermediate interaction
- Gas
  - Free atoms or molecules, weak interaction
- Plasma
  - A collection of free, charged particles

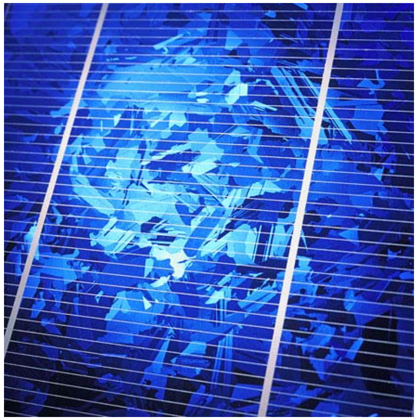
Condensed Matter Systems

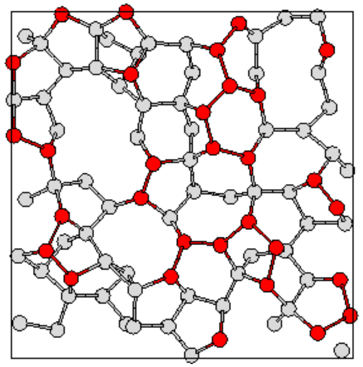


Arrangement of Atoms in Solids

- Crystalline
  - A regular arrangement of atoms with long-range order
- Polycrystalline
  - Short range order but no long range order
- Amorphous
  - Random arrangement of atoms





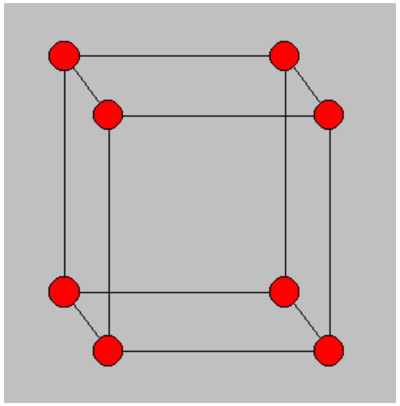


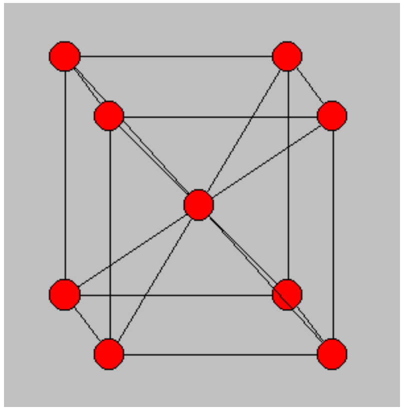
Crystalline Solids by Bond Types

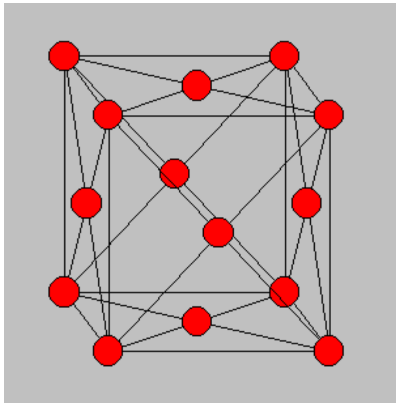
- Atomic crystals
  - Noble gases (He, Ne, Ar)
  - Chemically inert, soft, low melting point, poor thermal and electrical conduction
- Molecular crystals
  - Many polymers, molecular gases
  - Somewhat soft, moderate melting point, poor thermal and electrical conduction
- Ionic crystals
  - Crystal sites are occupied by positive and negative charged ions
  - Coulombic interactions dominate
  - Hard, high melting temperatures, poor thermal and electrical conduction
- Metallic crystals
  - Soft to hard, high melting temperatures, excellent thermal and electrical conductors
- Covalent crystals
  - Strong bonding
  - Hard, high melting temperatures, poor thermal and electrical conductors

Crystal Lattices

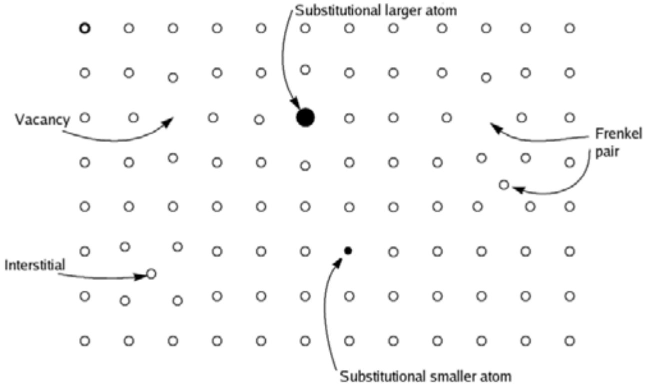
- A unit cell is the smallest arrangement of atoms that has all the information necessary to build the lattice.
- Simple, body centered , face centered cubic lattices.





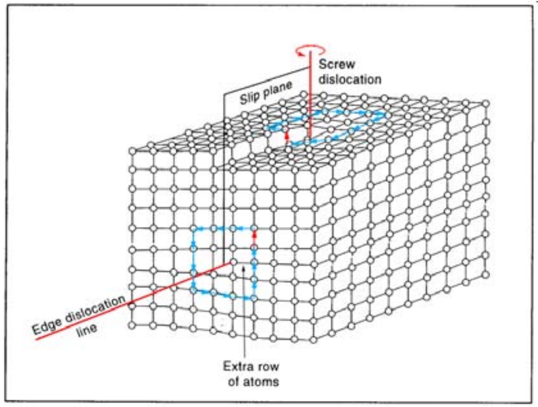


Defects in Solids

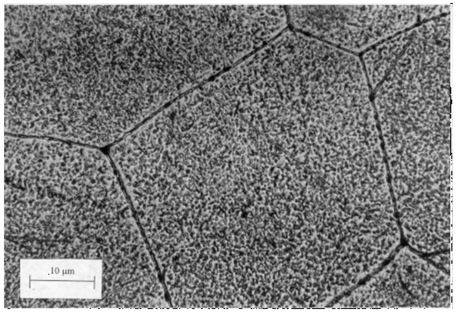


- Vacancies

- Dislocations
  - Edge dislocations
  - Screw dislocations



- Grain Boundaries



Vacancies

- Also called point defects.
- Mainly arise from the absence of an atom from its regular site in the crystal.
- The fraction of vacant sites follows the typical thermodynamic form: $f = \exp\left(-E_f / k_B T\right)$
- Presence of a foreign atom in a site is also possible.

Dislocations (Line defects)

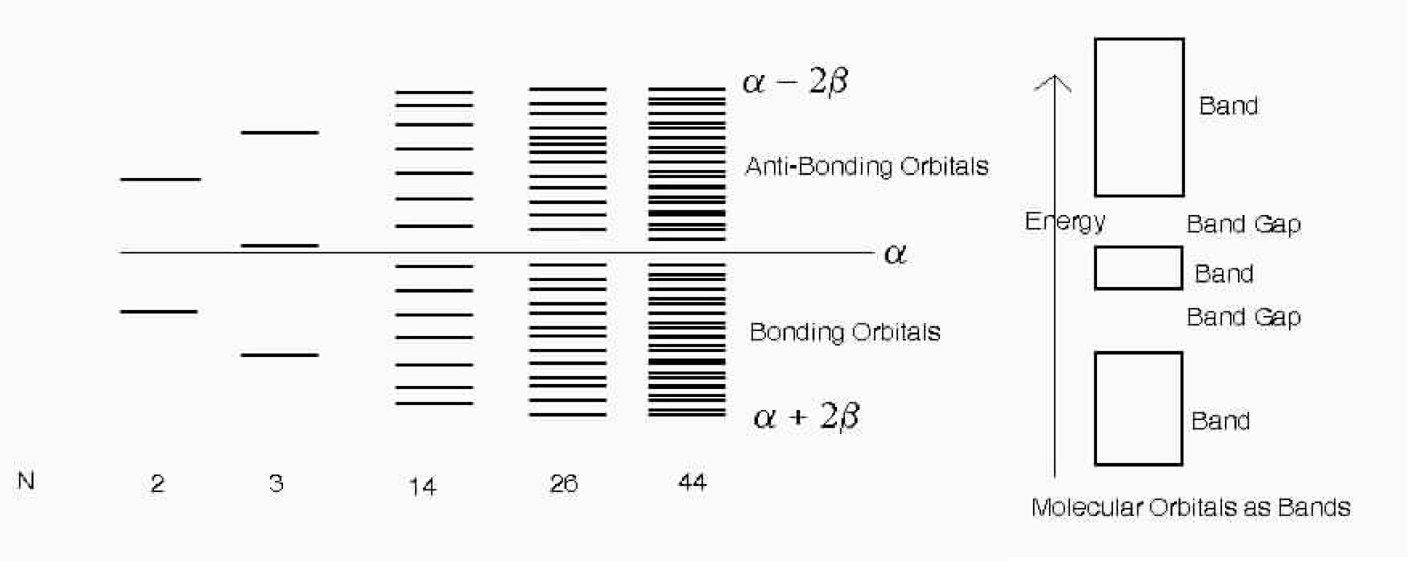
- Not thermodyamical in nature.
- Seen in thin film growth due to lattice-substrate mismatch.
- Edge Dislocations
  - Can be generated by wedging an extra row of atoms into a lattice due to stress or strain.
- Screw Dislocations
  - One plane of sites is cut and sheared with respect to another.

Grain Boundaries

- Surface defects existing between two single grain crystals of different orientation.
- A heterogeneous region exists in the boundary region.
- Will effect electrical and mechanical properties.

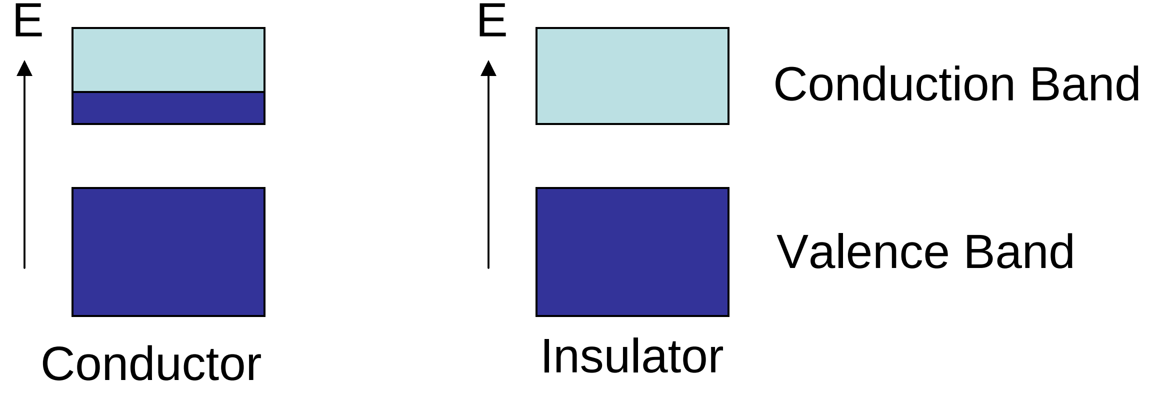
Band Structure

- Single molecules (or atoms) have their electrons in discrete energy levels.
- As molecules get closer, the energy levels will split into multiple levels.
- When many molecules come together to form a crystal, the multiple levels merge into continuous energy bands separated by forbidden zones (band gaps).



Band Filling

- In the ground state, electrons fill the available energy levels from the bottom.
- If highest occupied band is only partially filled, the electrons are energetically allowed to move about the crystal and the material is a conductor.
- If the highest band is fully occupied, then the electrons are energetically bound and the material is an insulator.

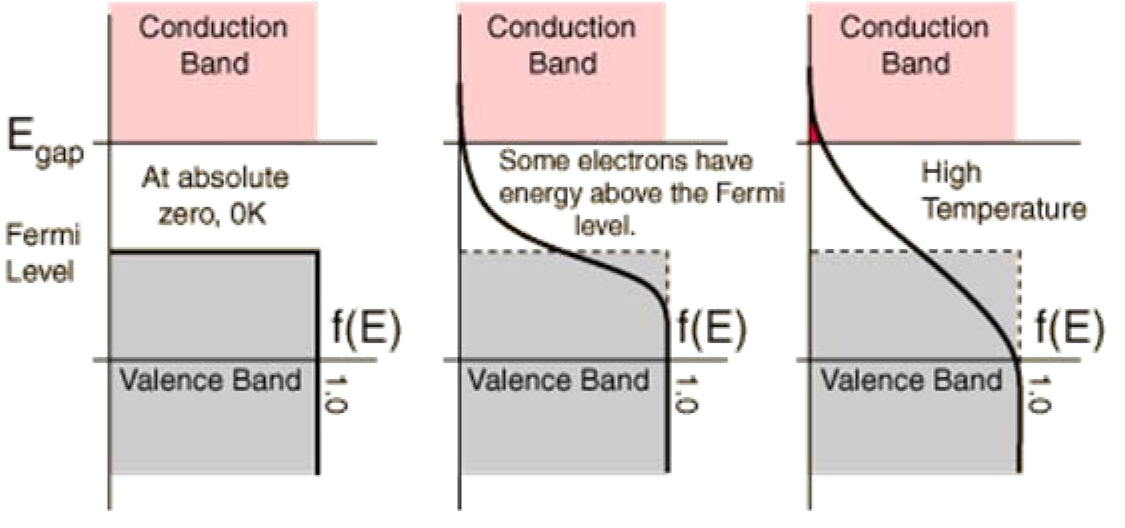


Electrons and Holes

- If an electron somehow gets excited to a higher energy level and moves away from its parent atom, it leaves behind an empty orbital which acts as a positively charged particle – a hole.
- Together, free electrons and holes are called carriers.
- The density of free electrons is called n, and holes, p.
- Electrons and holes can get attracted to each other and form a neutral particle called an exciton.
- The electron can return to its ground state, ie. recombine with a hole and release its extra energy, either as light (photon), a lattice vibration (phonon) or transfer it to another electron.

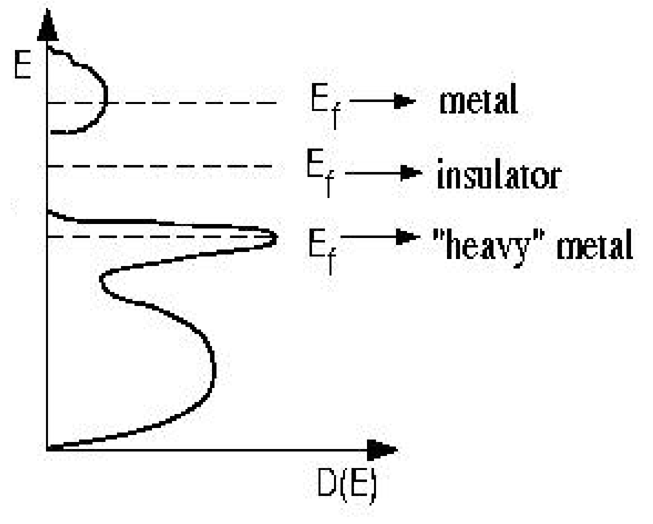
Fermi Level

- The Fermi level is the energy of the highest occupied level at 0 K.
- As the temperature is increased, there is a finite possibility of higher levels being occupied.



Density of States

- It is an integrated measure of the available energy levels and the possible number of electrons in them.

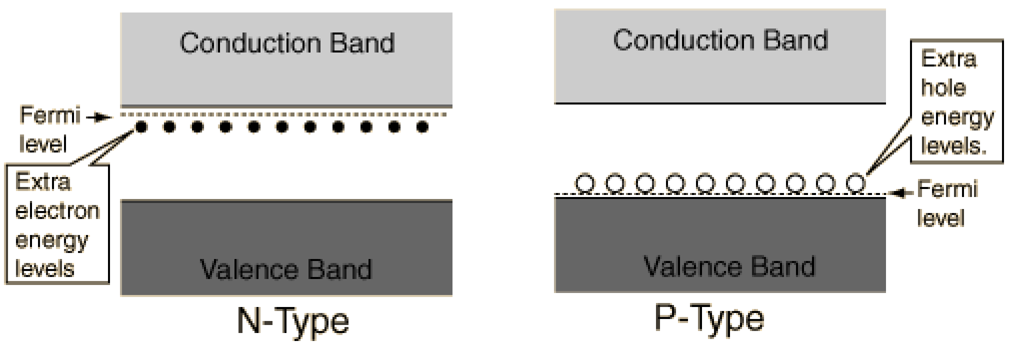


Semiconductors

- A semiconductor is really an insulator with a smaller band gap.
- A perfect semiconductor has no free electrons, the valence band is completely filled and the conduction band is completely empty.
- At finite temperatures, some electrons are thermally excited and break their bonds to become free leaving behind holes.
- In thermal equilibrium, np = constant
- For a pure (intrinsic) semiconductor, $n=p=n_i$
  – for Si, $n = p \sim 10^{10}\ cm^{-3}$

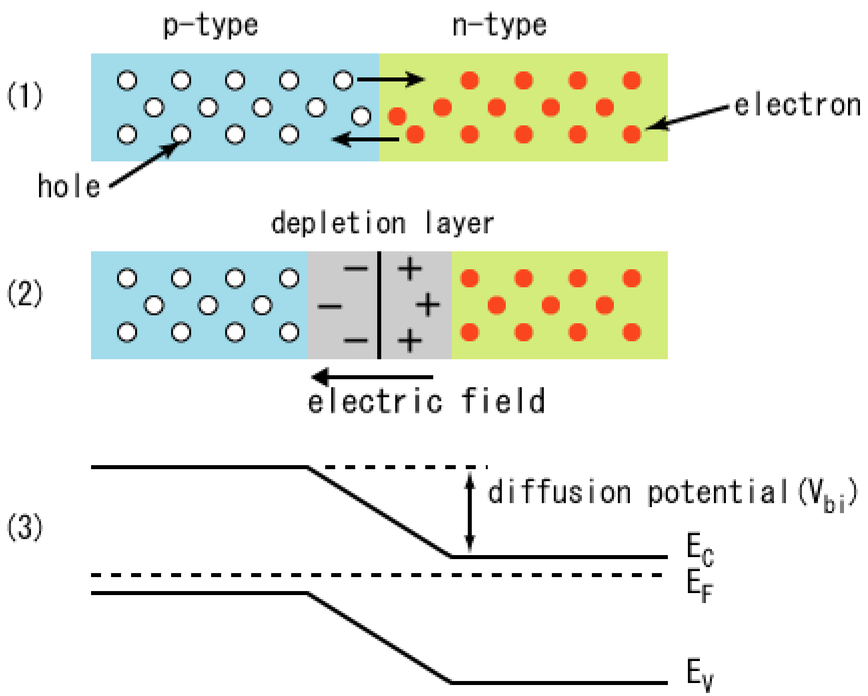
Doping

- Doping is the controlled addition of impurity atoms to a host material.
- If the impurity has an extra electron to supply to the host, it is called a donor.
- If the impurity receives an electron from the host, it is an acceptor.
- Donors create extra energy levels near the conduction band.
- Acceptors create extra energy levels near the valence band.
- Once the doping level exceeds the intrinsic carrier concentration, the semiconductor is said to be doped.



p-n Junctions

- In equilibrium, the Fermi level has to be constant throughout the material.
- This results in a built-in electric field which acts as an energy barrier to charge flow.
- Externally applied voltages or incident light can alter the barrier and regulate charge flow enabling modern semiconductor devices.



X-Ray Diffraction

- Send x-rays to the crystal.
- The rays scatter off of atomic layers and interfere with each other.
- Record the pattern as a function of angle of incidence.

$$\lambda = 2 d_{hkl} \sin\theta$$