

Introduction to Solid State Physics

What are solids? Which solids are of interest?

As we know, any material can exist as a solid, liquid, or gas. Liquids and gases do not have a fixed shape, whereas solids are characterized by having a definite shape.

Thus, a solid is any material with a fixed shape, such as wood, metals (silver, aluminum), semiconductors, and insulators.

The solids of interest in this course are materials with technological importance, specifically:

- **Metals:** characterized by high electrical conductivity.
- **Semiconductors:** used in computers and lasers.
- **Insulators:** used in applications such as space shelters.

What does solid state physics study?

Solid-state physics is concerned with the study and understanding of the special properties of solids.

Electronic properties (conductivity):

Why do some materials, such as copper (Cu), conduct electricity while others, such as glass, do not? Why can semiconductors be used in computer technology?

Band gap; Band structure; Density of state

Optical properties:

Why do some semiconductors emit blue light (as in lasers), while others emit red light?

Typical optical quantities include: dielectric function, refractive index, reflectivity, and absorption.

Mechanical properties:

These properties describe the mechanical strength (hardness) of materials. For example, why is diamond extremely hard?

Mechanical properties include elastic constants, hardness, softness, and bulk modulus.

The effect of applied stress or strain on the properties of solids is also studied.

Why do we need solid-state physics?

Solid-state physics has numerous technological applications. Semiconductors are the basic components of many advanced modern technologies. For example, silicon (Si) is used in electronic circuits and computer components, and GaAs/AlAs compounds are used in lasers.

Key questions include:

1. Can we find cheaper and more efficient materials?
2. How can we improve the efficiency of currently used materials?

The key to answering these questions is understanding the properties of solids.

What determines the properties of solids?

In general, the properties of materials are determined by atoms and electrons.

More specifically:

- Electrons determine the electrical and optical properties.
- Atoms together with electrons determine the mechanical properties.

Solid State Theory

The physical laws used to understand the properties of solids are the same laws used to study atoms and molecules, including:

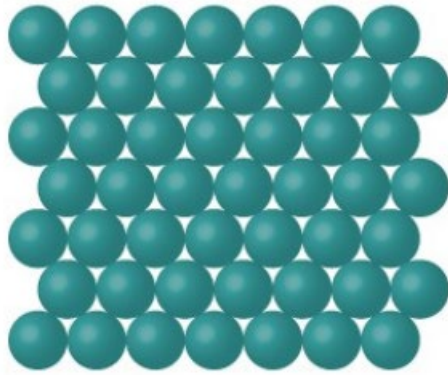
- Maxwell's equations
- Schrödinger's equation
- Laws of thermodynamics
- Statistical laws

Background Information

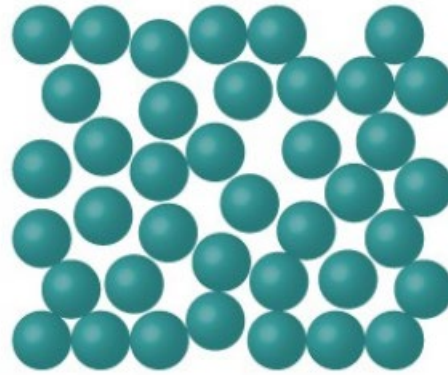
Atoms in solids are not stationary; instead, they vibrate about their equilibrium positions. The fixed equilibrium positions of atoms give solids their definite shape, which distinguishes them from liquids and gases.

Solids are classified into:

1. **Crystalline solids:** atoms are arranged in a periodic geometric pattern, such as in the NaCl crystal. This is the main focus of this course.
2. **Non-crystalline (amorphous) solids:** atoms are arranged randomly.



Crystalline



Amorphous

There is also a distinction between crystalline, polycrystalline, and amorphous solids.

Electrons obey the Pauli exclusion principle: only one electron can occupy a given quantum state, but two electrons may occupy the same state if they have opposite spin ($m_s = \pm 1/2$).

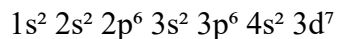
Valence (external) electrons are affected by external forces and fields and therefore determine the properties of materials. Core (inner) electrons are not significantly affected by external fields and contribute very little to material properties.

Example

Example: What are the core and valence electrons in cobalt (Co)?

Solution:

Cobalt has atomic number 27. Its electron configuration is:



The two electrons in the 4s orbital and the seven electrons in the 3d orbital are valence electrons. All other electrons are core electrons.

Extra Notes:

Quantum Description of Solids: Kinetic and Potential Energy

At the most fundamental level, any solid is a quantum-mechanical system consisting of electrons and ions. Therefore, its behavior is governed by the Schrödinger equation, whose Hamiltonian can always be written as the sum of kinetic energy and potential energy:

$$H = T + V$$

1. Kinetic Energy

The kinetic energy consists of two contributions:

$$T = T_e + T_i$$

where:

- T_e is the kinetic energy of the electrons
- T_i is the kinetic energy of the ions (nuclei)

This term describes the quantum motion of particles in the solid.

2. Potential Energy

The potential energy arises from Coulomb interactions between charged particles. It can be written as:

$$V = V_{ee} + V_{ei} + V_{ii}$$

where:

- V_{ee} represents electron–electron interactions
- V_{ei} represents electron–ion interactions
- V_{ii} represents ion–ion interactions

These interactions determine how particles bind together to form a solid.

3. Total Hamiltonian of a Solid

Combining all terms, the Hamiltonian of a solid can be written as:

$$H = T_e + T_i + V_{ee} + V_{ei} + V_{ii}$$

This Hamiltonian contains all the physics of a solid. However, solving it exactly is impossible for real materials because it involves a very large number of interacting particles.

4. From Quantum Mechanics to Solid State Physics

Because of this complexity, we introduce approximations and effective Hamiltonians that capture the essential physics. Using this approach, we can explain:

- Electrical conductivity
- Band structure
- Phonons and lattice vibrations
- Optical and mechanical properties

Thus, solid-state physics can be viewed as quantum mechanics applied to many-particle systems, where the competition between kinetic and potential energy determines the properties of materials.