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Electrical Engineering Materials

Pedagogical Handout

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Chapter 1

Fundamentals of Electrical Engineering Materials

2nd Year Engineering students

Contents

1.1. Introduction to Materials Science.....	4
1.2. Classification of Engineering Materials	5
1.3. Atomic Structure and Chemical Bonding	6
.A Atomic Structure	6
.B Valence Electrons.....	7
.C Chemical Bonding.....	7
1.4. Crystal Structure and Defects	9
.A Face-Centered Cubic (FCC) Structure.....	9
.B Body-Centered Cubic (BCC) Structure	9
.C Diamond Structure	10
.D Crystal Defects	10
.E Effect of Defects on Material Properties	10
1.5 Basic Material Properties	10
.A Electrical Properties	11
.B Magnetic Properties	11
.C Thermal Properties	11
.D Mechanical Properties	11
1.6 Materials in Electrical Engineering.....	11
1.7 Classification of Electrical Materials	12

Conductors:	13
Insulators:	13
Semiconductors:	13
Magnetic Materials:.....	13
Superconductors:	13
1.8. Fundamental Electrical Properties	14
A. Ohm's Law	14
B. Conductivity and Resistivity	15
C. Temperature Effects	15
D. Joule Effect.....	16
References	Error! Bookmark not defined.

1.1. Introduction to Materials Science

Materials are at the foundation of technology and the industrial world. A material is a substance of natural or artificial origin used in the manufacture of objects and products. Understanding materials is essential for any engineer, as the choice of material directly determines the performance, safety, and cost of any engineered system [1].

Consequently, materials science and engineering is the discipline that bridges fundamental discoveries in physics and chemistry with practical engineering applications. This field is grounded in a systematic framework known as the "Materials Science Tetrahedron," which explores the intricate relationships between four core elements: Processing, Structure, Properties, and Performance (Figure 1.1) [2].

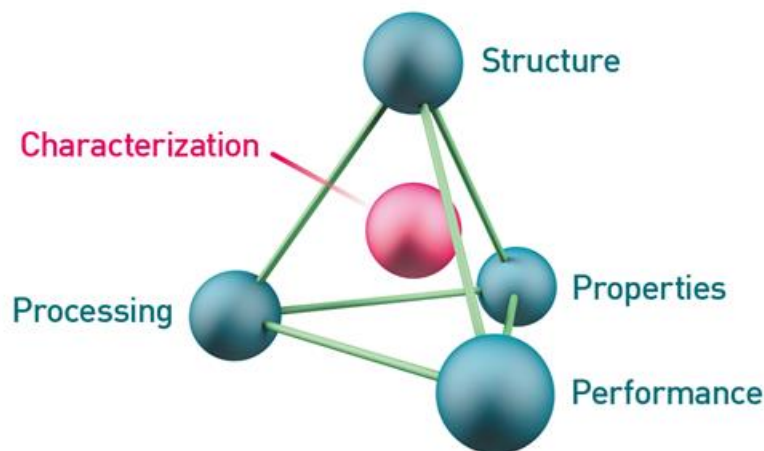


Figure 1.1 : Materials Science Tetrahedron

1.2. Classification of Engineering Materials

Scientifically and industrially, materials are generally grouped into main families (Figure 1.2): Metals, Ceramics, Polymers, and Composites. Additionally, there is a modern category known as Advanced Materials, which includes semiconductors and nanomaterials [3].

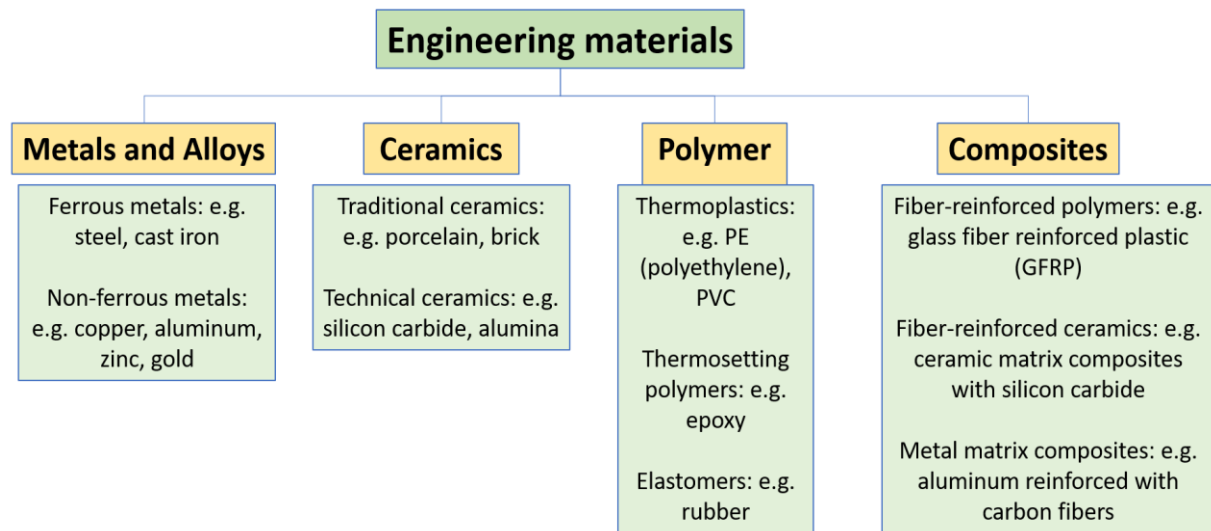


Figure 1.2 : Classification of Engineering Materials

Understanding the structure of a material at the atomic and microscopic levels equips engineers with the ability to predict how it will behave under different operating conditions. This knowledge is essential for designing materials tailored to meet precise technological requirements [2], [3].

1.3. Atomic Structure and Chemical Bonding

The properties of engineering materials are fundamentally determined by their atomic structure and the nature of the chemical bonds between atoms. Understanding these concepts is essential for explaining the electrical, thermal, and mechanical behavior of materials used in electrical engineering applications [2].

A. Atomic Structure

An atom consists of a positively charged nucleus containing protons and neutrons (Figure 1.3), surrounded by negatively charged electrons occupying discrete energy levels. The distribution of electrons around the nucleus governs the interactions between atoms and influences the properties of materials [2], [4].

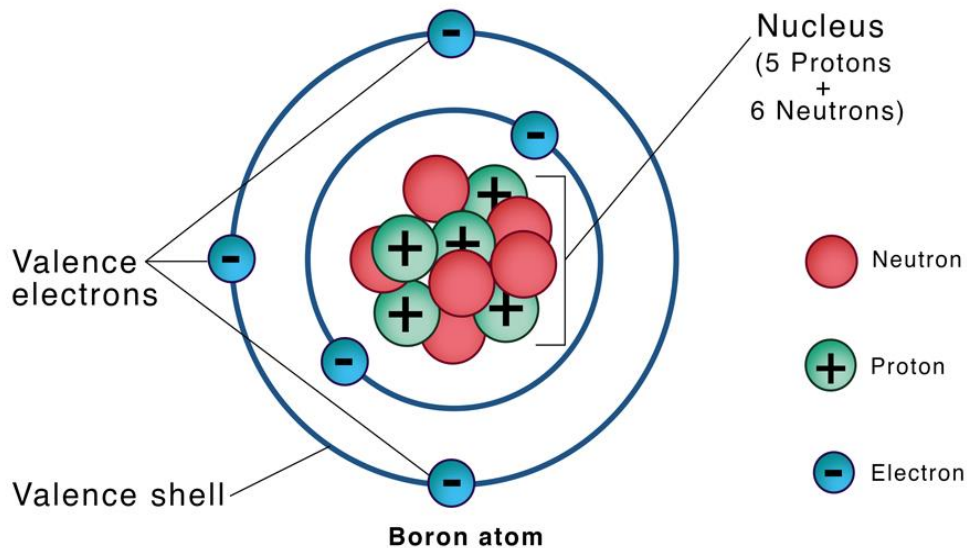


Figure 1.3 Atomic Structure

B. Valence Electrons

Valence electrons are the electrons located in the outermost energy level of an atom. They participate in chemical bonding and play a key role in determining the electrical conductivity and overall behavior of materials [4].

C. Chemical Bonding

Atoms bond together to achieve a more stable energy state. The primary chemical bonds found in engineering materials are:

Metallic Bonding: Occurs in metals, where valence electrons are shared collectively among atoms (Figure 1.4). The presence of free electrons gives metals their high electrical and thermal conductivity as well as their good ductility [2].

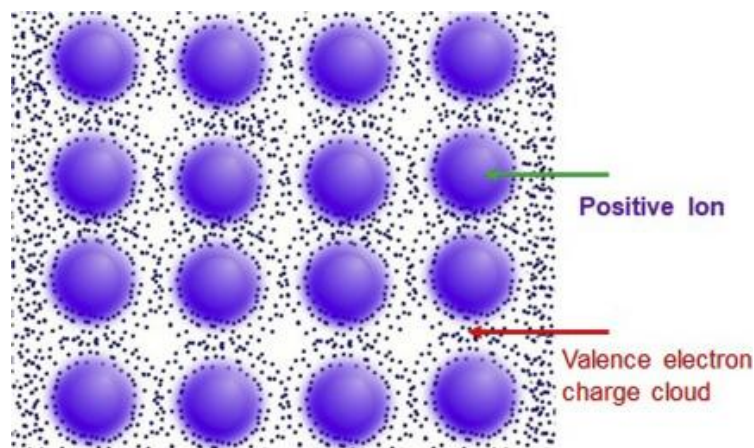


Figure 1.4 Metallic Bonding

Covalent Bonding: Results from the sharing of electrons between neighboring atoms (Figure 1.5). This type of bonding is common in semiconductors such as silicon and germanium and contributes to the high strength of materials such as diamond [4].

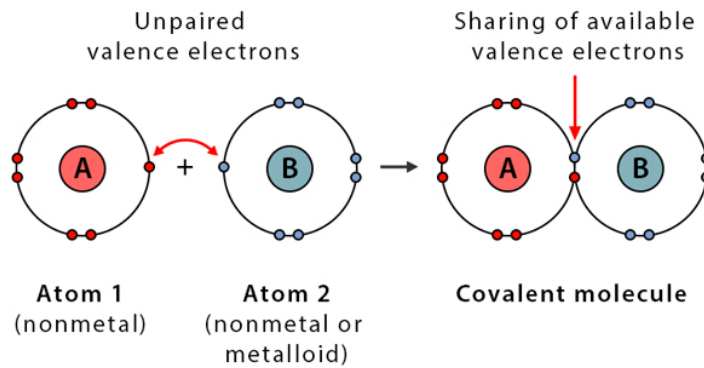


Figure 1.5 Covalent Bonding

Ionic Bonding: Occurs when electrons are transferred from one atom to another (Figure 1.6), producing positively and negatively charged ions held together by electrostatic attraction. Ionic materials are generally hard, brittle, and electrically insulating [2], [5].

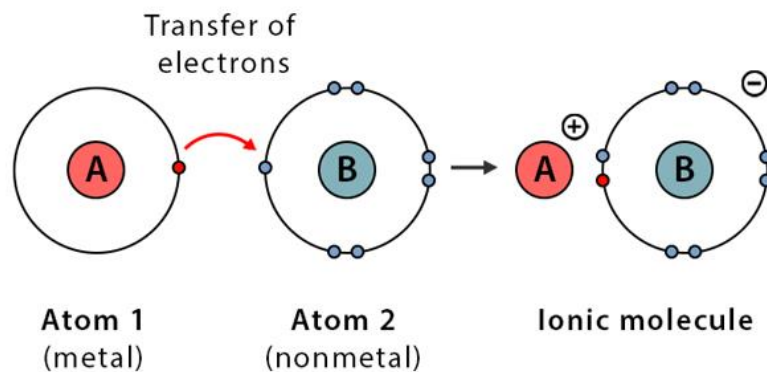


Figure 1.6 Ionic Bonding

1.4. Crystal Structure and Defects

The arrangement of atoms in a solid material significantly influences its electrical, thermal, and mechanical properties. In crystalline materials, atoms are organized in a regular and repeating three-dimensional pattern known as a crystal lattice (Figure 1.7) [2].

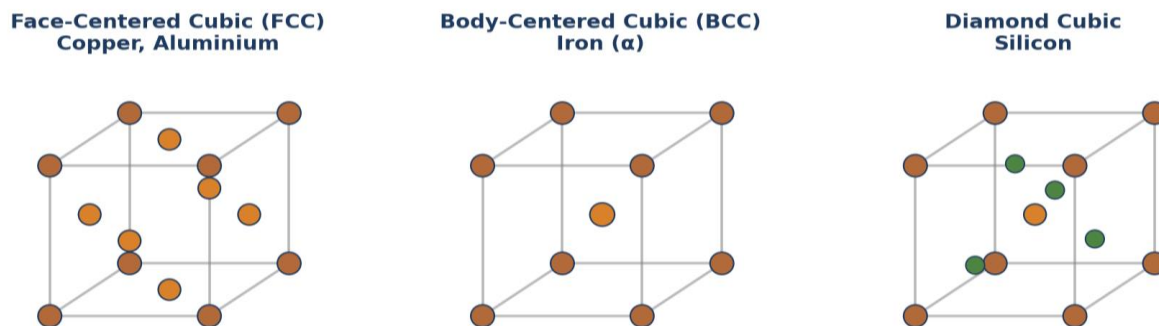


Figure 1.7 — Typical crystal

A. Face-Centered Cubic (FCC) Structure

In the FCC structure, atoms are located at the corners and the centers of all cube faces. This arrangement provides high atomic packing density and contributes to the excellent ductility and electrical conductivity of metals such as copper and aluminum, which are widely used in electrical engineering applications [2].

B. Body-Centered Cubic (BCC) Structure

The BCC structure consists of atoms positioned at the cube corners and one atom at its center. Metals with this structure, such as iron and tungsten, generally exhibit higher strength but lower ductility compared with FCC metals [2], [4].

C. Diamond Structure

The diamond crystal structure is formed by covalent bonding between atoms arranged in a tetrahedral configuration. Silicon and germanium, the most important semiconductor materials, crystallize in this structure, making it fundamental to modern electronic devices [4].

D. Crystal Defects

Real crystalline materials are never perfectly ordered. They contain imperfections known as crystal defects, including vacancies, interstitial atoms, impurities, and dislocations. These defects modify the arrangement of atoms within the crystal lattice [2].

E. Effect of Defects on Material Properties

Crystal defects strongly influence material behavior. They can increase mechanical strength, alter electrical conductivity, and affect semiconductor performance. In electronic materials, controlled introduction of impurities (doping) is essential for tailoring electrical properties and enabling the operation of semiconductor devices [4], [6].

1.5 Basic Material Properties

The behavior and performance of engineering materials are determined by a set of physical and mechanical properties. Understanding these properties is essential for selecting suitable materials for various engineering applications [7], [8].

A. Electrical Properties

Electrical properties describe the ability of a material to conduct or resist the flow of electric charge. These properties are commonly characterized by electrical conductivity and resistivity, which vary from one material to another [9].

B. Magnetic Properties

Magnetic properties define the response of a material to an applied magnetic field. Materials may exhibit different magnetic behaviors depending on their atomic structure and composition [9].

C. Thermal Properties

Thermal properties describe how a material responds to heat. Important characteristics include thermal conductivity, specific heat capacity, and thermal expansion, which influence the transfer and storage of thermal energy [7].

D. Mechanical Properties

Mechanical properties determine the ability of a material to withstand external forces without failure. Common mechanical properties include strength, hardness, ductility, and toughness [8].

The combination of these properties determines the suitability of a material for a particular engineering application.

1.6 Materials in Electrical Engineering

Materials form the cornerstone of electrical engineering, which relies on the manipulation, transport, and conversion of electrical energy and signals. Every device, ranging from a simple cable to a power transformer or microprocessor,

depends entirely on the physical behavior of its constituent materials. Consequently, the performance, energy efficiency, and cost of any electrical system are not determined solely by circuits and mathematical equations, but are directly linked to the limitations and properties (electrical, thermal, mechanical, and chemical) of the materials used in its construction [11].

In electrical engineering, materials are utilized to perform four primary functions:

Conduction Optimization: Transmitting electrical current with minimal losses and reducing Joule losses in power transmission networks.

Isolation and Safety: Safely isolating components and withstanding extremely high voltages without electrical breakdown.

Energy Storage and Conversion: Guiding and storing magnetic flux, maximizing energy density in capacitors, and optimizing magnetic fluxes in rotating machinery [10].

Electronic Control: Precisely controlling electron transport within semiconductor devices.

Given that these multiple functions frequently converge and overlap within the same final product, the design and development of modern electrical systems necessitate a broad and comprehensive understanding of materials science and its diverse properties.

1.7 Classification of Electrical Materials

In the field of electrical and electronic engineering, materials are classified into five main categories based on their ability to conduct electrical current and their response to magnetic fields [11]:

Conductors: Materials that allow electrical current to flow easily with low resistance (e.g., copper and aluminum).

Insulators: Materials that prevent the flow of electrical current, used for insulation and protection in circuits (e.g., ceramics and polymers).

Semiconductors: Materials that possess a controllable conductivity falling between that of conductors and insulators; they form the foundation of modern electronics (e.g., silicon and germanium).

Magnetic Materials: Materials that interact strongly with magnetic fields, used to guide and store magnetic flux (e.g., iron and cobalt).

Superconductors: Materials that exhibit absolutely zero electrical resistance when cooled below a specific critical temperature.

This classification relies fundamentally on the material's behavior when exposed to electrical and magnetic fields—specifically, the physical and electrical properties that determine its function within electrical and electronic systems. The most important of these principles include [1], [11]:

Electrical Conductivity (σ): The ability of a material to allow the flow of an electrical current. Based on the value of conductivity or resistivity, materials are differentiated into conductors, semiconductors, and insulators [11].

Electronic Structure: This is explained through Band Theory. Materials possessing a conduction band that overlaps with the valence band are conductive. In contrast, insulators have a wide band gap that prevents electron transfer, while semiconductors lie between them with a narrow band gap that electrons can overcome when excited Figure 1.8 [2].

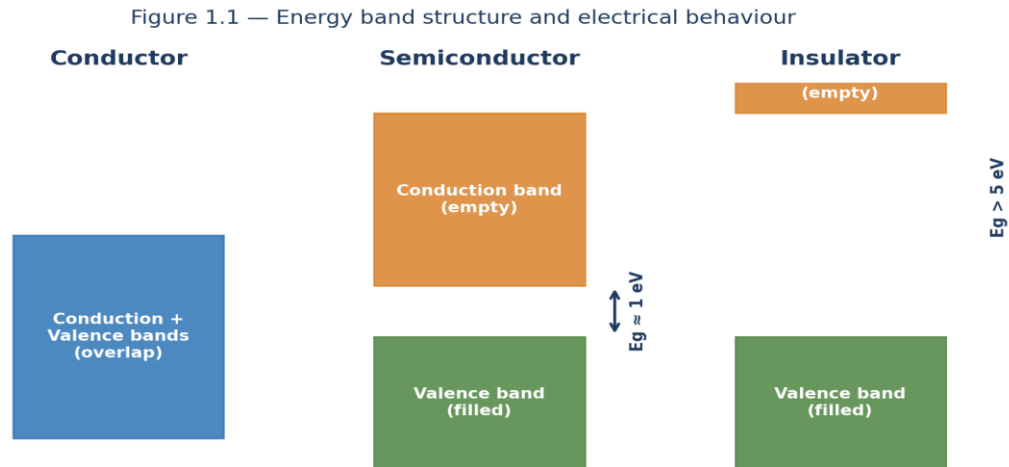


Figure 1.8 Energy band structure

Magnetic Response: This is determined by magnetic permeability and the material's susceptibility to magnetization. Accordingly, materials are classified into magnetic materials—which are used in transformers and electrical machines—and non-magnetic materials [11].

1.8. Fundamental Electrical Properties

The classification and selection of electrical materials are primarily based on their electrical behavior. Among the most important electrical properties are conductivity, resistivity, temperature dependence, and energy losses associated with current flow [9], [4].

A. Ohm's Law

Ohm's law is the fundamental empirical relationship governing electrical conduction in most metallic and ohmic materials. It states that the voltage V (in volts, V) across a conductor is directly proportional to the current I (in amperes, A) flowing through it, provided the temperature remains constant:

$$V = I \times R$$

where R is the electrical resistance of the conductor, measured in ohms (Ω). The resistance depends on the material's resistivity ρ , the conductor length L , and its cross-sectional area A , according to:

$$R = \rho \times L / A$$

This expression establishes the critical link between a macroscopic circuit parameter (R) and an intrinsic material property (ρ), and serves as the basis for the discussion of conductivity and resistivity that follows [9], [12].

B. Conductivity and Resistivity

Electrical conductivity σ (S/m) describes the ability of a material to conduct electric current, whereas electrical resistivity ρ ($\Omega\cdot\text{m}$) represents its opposition to current flow. These properties are related by:

$$\rho = \frac{1}{\sigma}$$

Materials with high conductivity, such as metals, are widely used for current transmission, while materials with high resistivity are commonly used as electrical insulators [9].

C. Temperature Effects

The electrical properties of materials vary with temperature. In metallic conductors, resistivity generally increases as temperature rises due to enhanced atomic vibrations that hinder electron motion. In contrast, semiconductors exhibit increased conductivity with increasing temperature because of the higher concentration of charge carriers [4].

D. Joule Effect

When an electric current flows through a material with finite resistance, part of the electrical energy is converted into heat. This phenomenon, known as the Joule effect, is responsible for power losses and temperature rise in electrical systems.

The generated heat is expressed by:

$$P=I^2R$$

where (P) is the dissipated power in Watts (**W**), (I) is the current in Amperes (**A**), and (R) is the electrical resistance in Ohms (Ω) [12].

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