

University: University of Mohamed Kheider - Biskra

Faculty: Faculty of Science and Technology

Department: Common Core in Science and Technology

Electrical Engineering Materials

Pedagogical Handout

Dr.Toufik DJIMAOUI

Academic Year: 2025/2026

2nd Year Engineering students

Official Course Programs

SEMESTRE	Intitulé de la matière		Coefficient	crédits	Code
S3	Matériaux en Génie Electrique		1	1	IST 3.9
VHH	Cours	Travaux dirigés	Travaux Pratiques		
22h30	1h30		-		

Pré requis

- Des bases en physique générale : notions de mécanique, d'électricité, de magnétisme et de thermique.

Objectifs pédagogiques

- Expliquer le rôle et l'importance des matériaux en génie électrique.
- Classer les matériaux selon leur nature (conducteurs, isolants, magnétiques, semi-conducteurs, supraconducteurs).
- Relier les propriétés fondamentales (mécaniques, thermiques, électriques, magnétiques) à leur utilisation.

Contenu de la matière

Chapitre 1 – Introduction aux matériaux

- Rôle des matériaux en génie électrique
- Classification : conducteurs, isolants, magnétiques, semi-conducteurs, supraconducteurs
- Propriétés fondamentales : mécanique, thermique, électrique, magnétique
- Structure cristalline, défauts et influence sur les propriétés

Chapitre 2 – Matériaux conducteurs

- Métaux : cuivre, aluminium, alliages
- Résistivité, conductivité, température et effets secondaires (effet de peau)
- Applications : câbles, circuits imprimés, bobinages

Chapitre 3 – Matériaux isolants

- Solides (céramiques, polymères), liquides (huiles), gaz (SF₆)
- Permittivité, rigidité diélectrique, décharges partielles
- Vieillessement, conditions d'utilisation (température, humidité)

Chapitre 4 – Matériaux magnétiques

- Comportement magnétique : aimantation, hystérésis, pertes
- Matériaux doux : tôles Fe-Si, ferrites souples (transformateurs, moteurs)
- Matériaux durs (aimants) : ferrites, terres rares (NdFeB, SmCo)
- Focus sur les aimants permanents :
 - Propriétés (coercivité, énergie magnétique maximale)
 - Applications : moteurs brushless, capteurs, générateurs

Chapitre 5 – Semi-conducteurs

- Conduction dans les semi-conducteurs : n, p, dopage
- Matériaux : Si, GaAs, SiC
- Applications : électronique de puissance, photodétecteurs, diodes, transistors

Chapitre 6 – Supraconducteurs

- Principe de la supraconductivité (résistivité nulle, effet Meissner)
- Matériaux supraconducteurs : basse température (NbTi), haute température (YBCO)
- Applications : câbles HTS, électroaimants, IRM, trains à lévitation
- Contraintes technologiques : refroidissement, fragilité mécanique

Chapitre 7 – Critères de choix des matériaux

- Contraintes fonctionnelles, environnementales, économiques
- Compatibilité électromagnétique et thermique
- Durabilité et recyclabilité
- Études de cas (ex : choix de matériaux pour transformateur, moteur, isolateur)

Mode d'évaluation : Examen final : 100%

Références bibliographiques

- [1] P. Robert, "Matériaux de l'électrotechnique", Dunod.
- [2] F. Piriou, "Matériaux du génie électrique", MGE 2000, Germes.
- [3] Gérald Roosen, "Matériaux semi-conducteurs et nitrures pour l'optoélectronique", Hermès.
- [4] P. Tixador, "Matériaux supraconducteurs", Hermès.
- [5] G. LeRoy, C. Gary, B. Hutzler, J. Hamelin, J. Fontaine, "Les propriétés diélectriques de l'air et les très hautes tensions", Editions Eyrolles, 1984.
- [6] D. Kind, H. Kärner. "High voltage insulation technology: Textbook for Electrical Engineers", FriedrVieweg&Sohn, 1985.
- [7] André Faussurier, Robert Servan, "Matériaux en électrotechnique", Dunod Paris, 1971.
- [8] A. Chabloz, "Technologie des matériaux", Suisse 1980.
- [9] I.R. HARRS ET A.J. WILLIAMS, Material Science and engineering, Vol. II, Magnetic materials. Oxford: EOLSpublisher Co. L.td, 2009.
- [10] J. M. VEGA, Dielectric Materials for Electrical Engineering, John Wiley & Sons. 2010
- [11] Practical Handbook of Photovoltaics: Fundamentals and Applications, Luis Castaner and Tom Markvart, Edition: Elsevier Science Ltd, 2003.
- [12] F. Michael R. H David, "Matériaux : Propriétés, application et conception", Cours et exercices 4ème édition DUNOD, Octobre 2020.

General Introduction

Electrical materials are fundamental components in the design and operation of modern electrical and electronic systems. The performance, efficiency, reliability, and lifetime of electrical equipment depend strongly on the physical, electrical, magnetic, and thermal properties of the materials used [1], [2].

The behavior of an electrical material is mainly determined by its atomic structure, electronic configuration, and the type of bonding between atoms. These factors control important properties such as electrical conductivity, dielectric strength, magnetic response, and thermal stability [2], [4].

According to their electrical behavior, materials used in electrical engineering are generally classified into conductors, insulators, semiconductors, magnetic materials, and superconductors. Conductive materials allow efficient transport of electrical charges, while insulating materials prevent unwanted current flow and provide electrical protection. Semiconductor materials offer controllable electrical properties, enabling modern electronic devices. Magnetic and superconducting materials provide essential functions in energy conversion, storage, and advanced technological systems [4], [6].

The selection of suitable materials requires a balance between electrical performance, mechanical strength, thermal behavior, environmental resistance, reliability, and economic considerations. Therefore, understanding the relationship between material structure and engineering properties is essential for designing efficient and sustainable electrical systems [1], [21].

This course material presents the fundamental principles of electrical engineering materials, beginning with atomic structure and basic properties, followed by the study of conductive, insulating, magnetic, semiconductor, and superconducting materials. The final chapter focuses on material selection criteria and practical case studies to demonstrate how engineers choose appropriate materials for real electrical applications.

Contents

General Introduction.....	4
Chapter 1 : Fundamentals of Electrical Engineering Materials	12
1.1. Introduction to Materials Science.....	14
1.2. Classification of Engineering Materials	15
1.3. Atomic Structure and Chemical Bonding	16
.A Atomic Structure	16
.B Valence Electrons.....	17
.C Chemical Bonding.....	17
1.4. Crystal Structure and Defects	19
.A Face-Centered Cubic (FCC) Structure.....	19
.B Body-Centered Cubic (BCC) Structure	19
.C Diamond Structure	20
.D Crystal Defects	20
.E Effect of Defects on Material Properties	20
1.5 Basic Material Properties	20
.A Electrical Properties	21
.B Magnetic Properties	21
.C Thermal Properties	21
.D Mechanical Properties	21

1.6 Materials in Electrical Engineering.....	21
1.7 Classification of Electrical Materials	22
Conductors:	23
Insulators:	23
Semiconductors:	23
Magnetic Materials:.....	23
Superconductors:	23
1.8. Fundamental Electrical Properties	24
A. Ohm’s Law	24
B. Conductivity and Resistivity	25
C. Temperature Effects	25
D. Joule Effect.....	26
1.1 Introduction	28
2.2 Electrical Conduction in Metals.....	29
2.3 Conductive Metals (Copper, Aluminum, Alloys)	30
2.3.1 Copper (Cu).....	31
2.3.2 Aluminum (Al).....	31
2.3.3 Conductive Alloys.....	32
2.4 Resistivity, Temperature Effects, and Scattering.....	32
2.4.1 Temperature Effects	33
2.4.2 Electron Scattering	33
2.5 Applications: Cables, Circuit Boards, and Windings	34

2.5.1 Cables	34
2.5.2 Printed Circuit Boards (PCBs)	34
2.5.3 Windings	35
Chapter 3: Insulating Materials	36
1.1 Introduction	37
3.2 Types of Insulating Materials.....	38
A. Solid Insulators (Ceramics and Polymers)	38
B. Liquid Insulators (Oils)	38
C. Gaseous Insulators (Air and SF ₆)	39
3.3 Dielectric Properties	39
A. Permittivity	40
B. Dielectric Strength	40
C. Partial Discharges	41
3.4 Ageing and Operating Conditions.....	41
A. Temperature Effects	41
B. Humidity Effects.....	41
C. Electrical Ageing	41
3.5 Applications of Insulating Materials.....	42
A. Power Cables	42
B. Transformers.....	42
C. High-Voltage Equipment.....	42
Chapter 4: Magnetic Materials	43

4.1 Introduction	44
4.2 Fundamentals of Magnetism	45
A. Magnetic Moments and Domains	45
B. Magnetization and Hysteresis.....	45
C. Magnetic Losses	46
4.3 Soft Magnetic Materials	46
A. Fe–Si Electrical Steels.....	46
B. Soft Ferrites	47
4.4 Hard Magnetic Materials.....	47
A. Hard Ferrites.....	47
B. Rare-Earth Magnets.....	48
4.5 Applications of Magnetic Materials.....	48
Chapter 5: Semiconductors	50
5.1 Introduction	51
5.2 Semiconductor Fundamentals	52
A. Charge Carriers: Electrons and Holes.....	52
B. Intrinsic and Extrinsic Semiconductors	53
C. Doping: N-type and P-type	53
5.3 Semiconductor Materials.....	55
A. Silicon (Si)	55
B. Gallium Arsenide (GaAs)	55
C. Silicon Carbide (SiC).....	56

5.4 Electrical Properties of Semiconductors	56
5.5 Applications of Semiconductors	57
A. Diodes.....	57
B. Transistors	58
C. Power Electronics.....	58
D. Photodetectors and Optoelectronics.....	59
Chapter 6: Superconductors	60
6.1 Introduction	61
6.2 Fundamentals of Superconductivity.....	61
A. Zero Electrical Resistivity	61
B. Meissner Effect.....	62
C. Critical Parameters.....	62
6.3 Superconducting Materials.....	62
A. Low-Temperature Superconductors (NbTi).....	62
B. High-Temperature Superconductors (YBCO).....	63
6.4 Applications of Superconductors	64
.A HTS Power Cables	64
.B Superconducting Magnets.....	64
.C Magnetic Resonance Imaging (MRI).....	65
.D Maglev Trains	65
6.5 Technological Challenges	66
A. Cooling Requirements.....	66

B. Mechanical Limitations	66
Chapter 7: Material Selection Criteria	67
7.1 Introduction	68
7.2 Material Selection Criteria	69
A. Functional Requirements.....	69
B. Environmental Constraints	69
C. Economic Considerations	70
7.4 Durability and Sustainability.....	70
A. Service Life and Reliability.....	70
B. Recycling and Environmental Impact	71
7.5 Case Studies	71
A. Transformer Material Selection	71
B. Electric Motor Material Selection	72
C. High-Voltage Insulator Material Selection	72
References	74

Chapter 1 : Fundamentals of Electrical Engineering Materials

Contents

1.1. Introduction to Materials Science.....	14
1.2. Classification of Engineering Materials	15
1.3. Atomic Structure and Chemical Bonding	16
.A Atomic Structure	16
.B Valence Electrons.....	17
.C Chemical Bonding.....	17
1.4. Crystal Structure and Defects	19
.A Face-Centered Cubic (FCC) Structure.....	19
.B Body-Centered Cubic (BCC) Structure	19
.C Diamond Structure	20
.D Crystal Defects	20
.E Effect of Defects on Material Properties	20
1.5 Basic Material Properties	20
.A Electrical Properties	21
.B Magnetic Properties	21
.C Thermal Properties	21
.D Mechanical Properties	21

1.6 Materials in Electrical Engineering.....	21
1.7 Classification of Electrical Materials	22
Conductors:	23
Insulators:	23
Semiconductors:	23
Magnetic Materials:.....	23
Superconductors:	23
1.8. Fundamental Electrical Properties	24
A. Ohm's Law	24
B. Conductivity and Resistivity	25
C. Temperature Effects	25
D. Joule Effect.....	26

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].

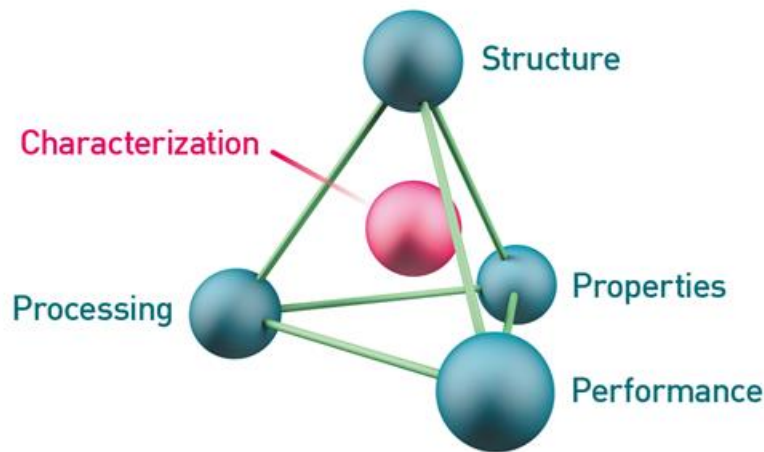


Figure 1.1 : Materials Science Tetrahedron

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].

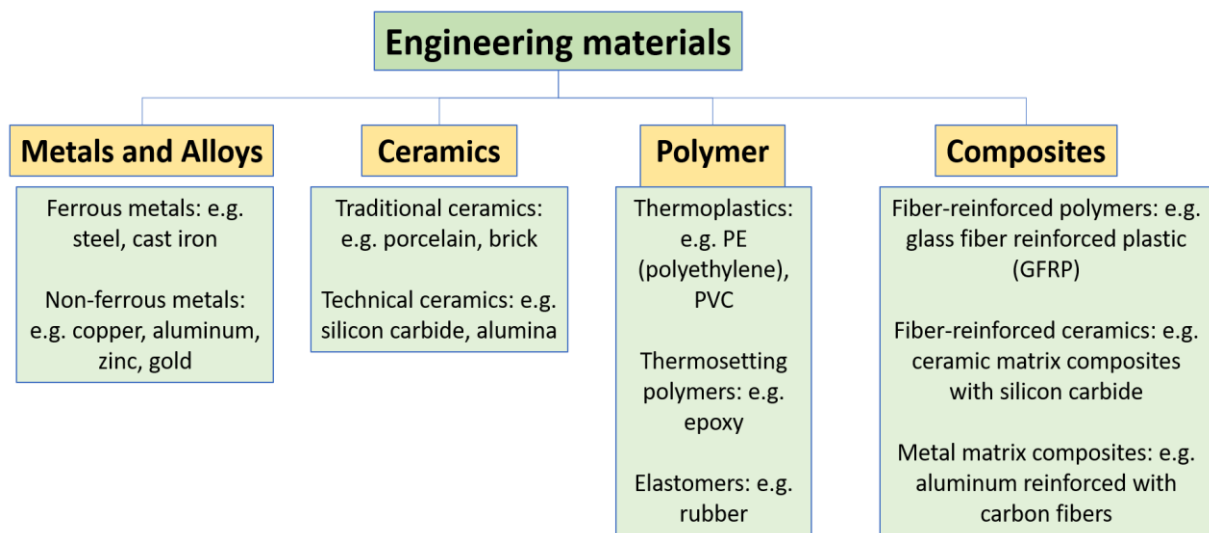


Figure 1.2 : Classification of Engineering Materials

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].

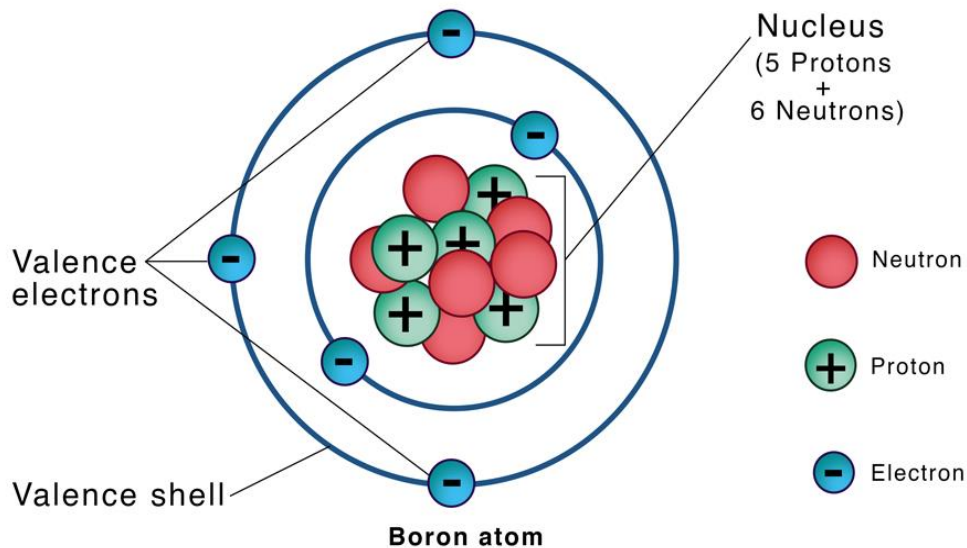


Figure 1.3 Atomic Structure

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].

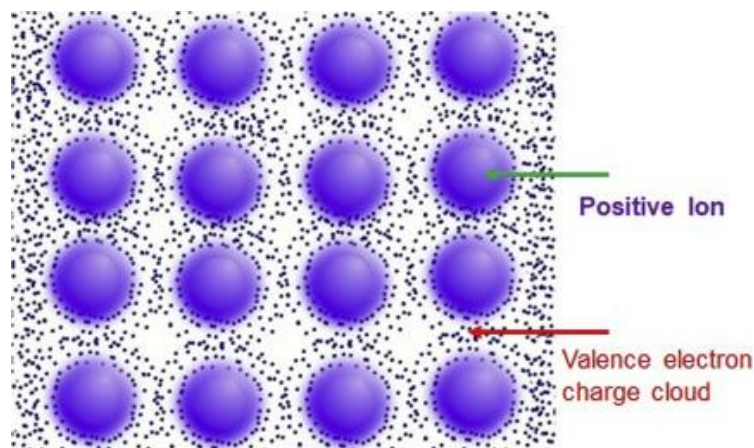


Figure 1.4 Metallic Bonding

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].

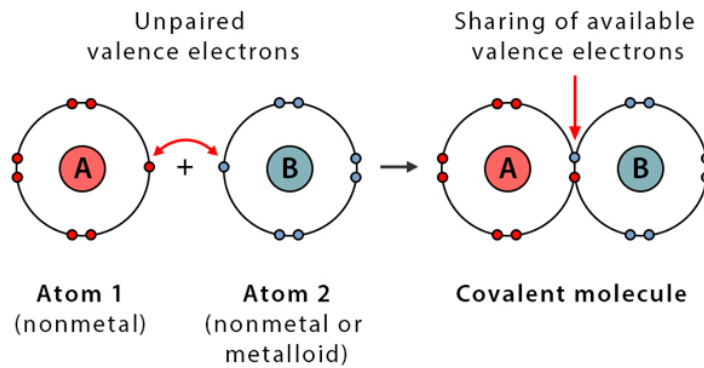


Figure 1.5 Covalent Bonding

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].

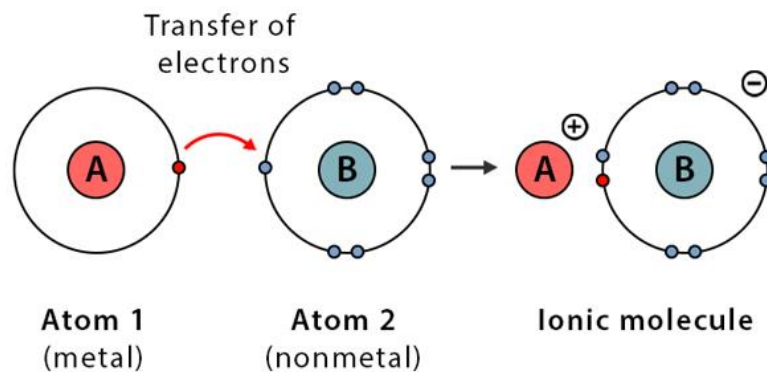


Figure 1.6 Ionic Bonding

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].

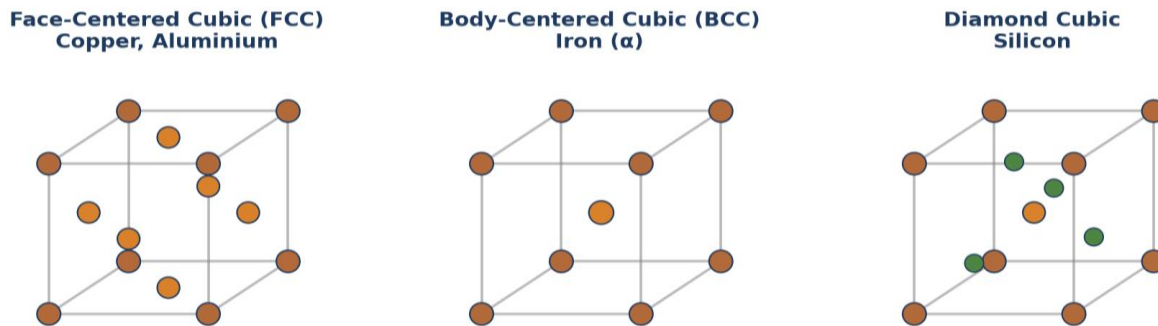


Figure 1.7 — Typical crystal

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].

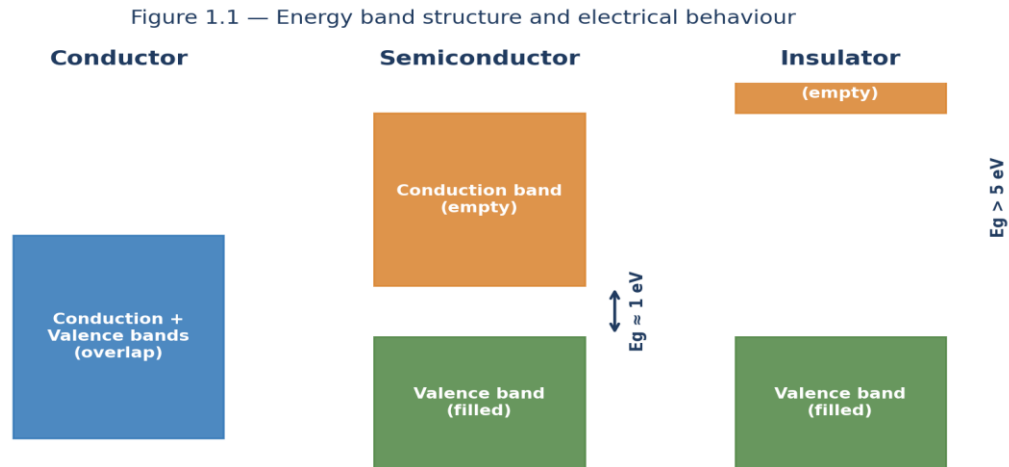


Figure 1.8 Energy band structure

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) [1]

Chapter 2: Conductive Materials

Contents

1.1 Introduction	28
2.2 Electrical Conduction in Metals	29
2.3 Conductive Metals (Copper, Aluminum, Alloys)	30
2.3.1 Copper (Cu)	31
2.3.2 Aluminum (Al)	31
2.3.3 Conductive Alloys	32
2.4 Resistivity, Temperature Effects, and Scattering	32
2.4.1 Temperature Effects	33
2.4.2 Electron Scattering	33
2.5 Applications: Cables, Circuit Boards, and Windings	34
2.5.1 Cables	34
2.5.2 Printed Circuit Boards (PCBs)	34
2.5.3 Windings	35

1.1 Introduction

Conductive materials are a fundamental class of engineering materials used to transport electrical energy and signals in a wide range of applications. Their performance directly influences the efficiency, reliability, and safety of electrical systems, from power transmission networks to electronic devices.

Metals constitute the primary group of conductive materials due to their high density of free charge carriers, which enables efficient current flow under the action of an electric field. Among them, copper and aluminum are the most widely used materials in electrical engineering because they offer an optimal balance between electrical conductivity, mechanical strength, thermal performance, and cost [4], [13].

In practical applications, pure metals are often supplemented or replaced by conductive alloys when additional mechanical strength, corrosion resistance, or thermal stability is required. Therefore, the selection of a conductive material is not based solely on electrical conductivity but on a compromise between multiple physical and economic factors [9].

This chapter discusses the physical basis of electrical conduction in metals, the main conductive materials used in engineering practice, and their most important industrial applications.

2.2 Electrical Conduction in Metals

Electrical conduction in metals is fundamentally explained by the presence of a large number of free electrons that originate from the outer (valence) shells of metal atoms (Figure 2.1). In most metallic elements used in electrical engineering, such as copper and aluminum, each atom contributes typically one to three valence electrons that become delocalized within the crystal lattice and are free to move under the influence of an electric field [4], [9].

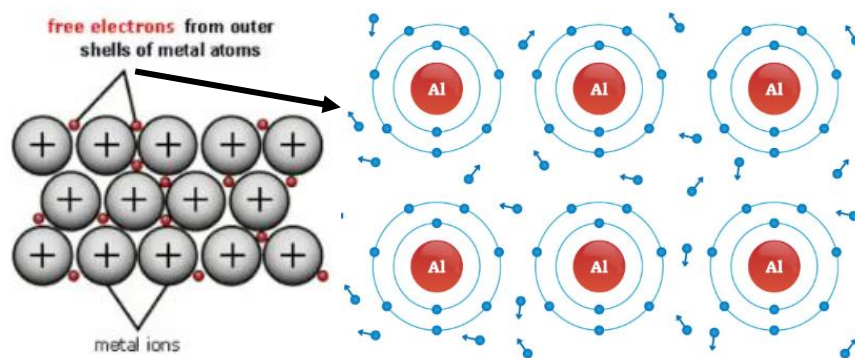


Figure 2.1 Free electron model

Unlike semiconductors and insulators, metals do not exhibit a forbidden energy gap (band gap) between the valence band and the conduction band. Instead, the valence band is partially filled or overlaps with the conduction band (Figure 2.2), allowing electrons to move freely without requiring external energy excitation. As a result, metals behave as excellent electrical conductors even at very low temperatures [9].

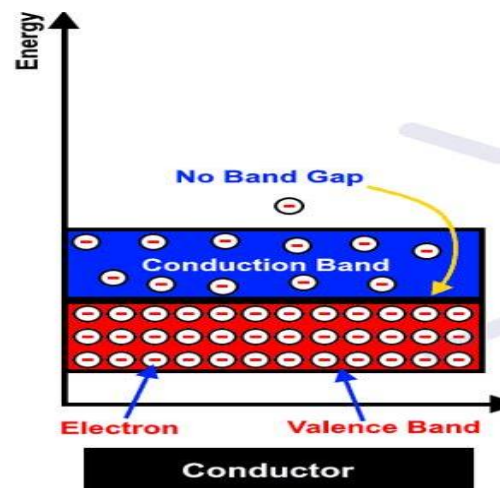


Figure.2 2 Energy band diagram for conductors

In the free electron model, these delocalized electrons are considered to form an electron gas that moves through a lattice of fixed positive ion cores. When an external electric field is applied, the electrons acquire a net drift velocity opposite to the direction of the field, producing an electric current [4].

The electrical conductivity of metals is therefore directly related to:

- The number of free electrons per atom (typically 1–3 in common conductors),
- The absence of a band gap (Figure 2.2) ,
- The ease of electron movement within the crystal lattice.

However, the motion of electrons is continuously interrupted by scattering processes caused by lattice vibrations (phonons), impurities, and crystal defects. These interactions limit electron mobility and give rise to the finite resistivity observed in real metallic materials [9].

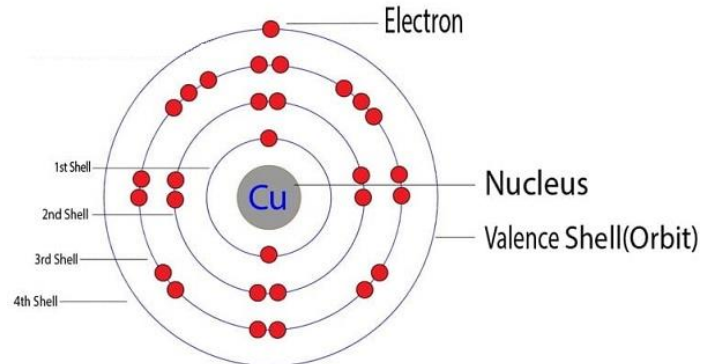
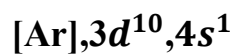
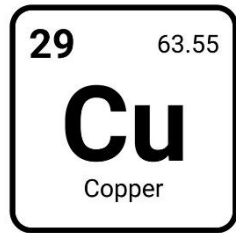
This microscopic description forms the physical basis for understanding why metals such as copper and aluminum are preferred in electrical engineering applications.

2.3 Conductive Metals (Copper, Aluminum, Alloys)

Conductive metals are characterized by the presence of a large number of free electrons originating from their outer atomic shells. These electrons are responsible for electrical conduction and are weakly bound to the atomic nucleus, allowing them to move freely under the influence of an applied electric field [4], [9].

2.3.1 Copper (Cu)

Copper has the electronic configuration:



Copper contributes **one free conduction electron per atom** (from the $4s^1$ orbital).

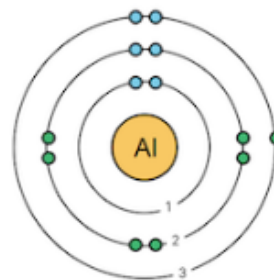
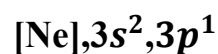
These electrons become delocalized within the metallic lattice, forming an electron gas responsible for its high conductivity.

- Free electrons per atom: ≈ 1 **electron/atom**
- Electron distribution: valence electron ($4s^1$) $\rightarrow$ delocalized conduction band

This single free electron per atom, combined with high atomic density, results in excellent electrical and thermal conductivity [4].

2.3.2 Aluminum (Al)

Aluminum has the electronic configuration:



Aluminum contributes **three valence electrons per atom**, which become free conduction electrons in the metallic state.

- Free electrons per atom: ≈ 3 electrons/atom
- Electron distribution: $3s^2 + 3p^1 \rightarrow$ delocalized conduction band

Although aluminum provides more free electrons per atom than copper, its overall conductivity is lower due to higher scattering effects and lower electron mobility [9].

2.3.3 Conductive Alloys

In conductive alloys, the situation becomes more complex. Alloying introduces impurity atoms into the metallic lattice, which affects the movement of free electrons:

- The number of free electrons per atom depends on the base metal.
- Alloying elements create scattering centers.
- Electron mobility decreases, leading to higher resistivity.

Therefore, conductive alloys are designed as a compromise between electrical conductivity and mechanical performance rather than maximizing free electron concentration [4].

2.4 Resistivity, Temperature Effects, and Scattering

The electrical behavior of conductive materials is mainly characterized by conductivity (σ) and resistivity (ρ), which are inversely related:

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

Materials with high conductivity and low resistivity are preferred for electrical applications because they allow current to flow with minimal energy losses [4], [9].

2.4.1 Temperature Effects

The resistivity of metallic conductors generally increases with temperature. As temperature rises, atomic vibrations become more intense, causing more frequent collisions between electrons and the crystal lattice. This reduces electron mobility and increases electrical resistance [4].

The variation of resistivity with temperature can be approximated by:

$$\rho_T = \rho_0 [1 + \alpha (T - T_0)]$$

where (α) is the temperature coefficient of resistivity [9].

2.4.2 Electron Scattering

The movement of free electrons is affected by several factors, including:

- Thermal vibrations of atoms (phonons),
- Impurities and alloying elements,
- Crystal defects.

These scattering mechanisms hinder electron motion and increase the resistivity of the material. Consequently, pure metals generally exhibit higher conductivity than alloys [2], [4].

2.5 Applications: Cables, Circuit Boards, and Windings

The choice of conductive materials depends on the electrical, mechanical, and economic requirements of the application. Copper and aluminum are the most widely used conductors in electrical engineering due to their high conductivity and availability [4], [10].

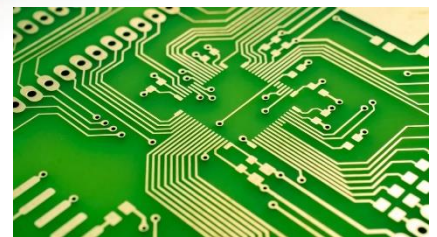
2.5.1 Cables

Electrical cables are used for power transmission and distribution. Copper is commonly employed in domestic and industrial wiring because of its high conductivity and flexibility. Aluminum is preferred for overhead transmission lines due to its low density and reduced cost, especially for long-distance power transmission [10].



2.5.2 Printed Circuit Boards (PCBs)

In electronic circuits, conductive paths are formed by thin copper tracks deposited on an insulating substrate. Copper is selected because it combines high conductivity, good solderability, and excellent reliability, allowing efficient transmission of electrical signals between electronic components [4].



2.5.3 Windings



Windings are essential components of electrical machines, transformers, and inductors. They are generally manufactured from insulated copper wire because of its high conductivity and good mechanical properties. In large power equipment, aluminum windings may also be used to reduce weight and cost [10].

These applications illustrate the importance of conductive materials in ensuring efficient transport of electrical energy and signals in modern electrical and electronic systems.

Chapter 3: Insulating Materials

Contents

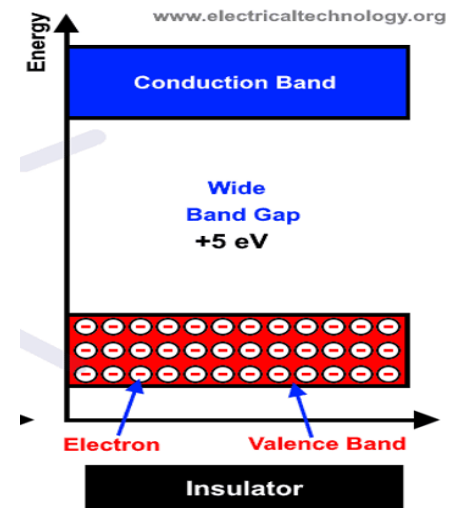
1.1 Introduction	37
3.2 Types of Insulating Materials.....	38
A. Solid Insulators (Ceramics and Polymers)	38
B. Liquid Insulators (Oils)	38
C. Gaseous Insulators (Air and SF ₆)	39
3.3 Dielectric Properties	39
A. Permittivity	40
B. Dielectric Strength.....	40
C. Partial Discharges	41
3.4 Ageing and Operating Conditions.....	41
A. Temperature Effects	41
B. Humidity Effects.....	41
C. Electrical Ageing	41
3.5 Applications of Insulating Materials.....	42
A. Power Cables	42
B. Transformers.....	42
C. High-Voltage Equipment.....	42

1.1 Introduction

Insulating materials, also known as dielectrics, are essential components of electrical and electronic systems. Their primary function is to prevent unwanted current flow, electrically separate conductive parts, and withstand high electric fields without breakdown. They also play an important role in energy storage, particularly in capacitors [4], [10].

The electrical behavior of insulating materials is fundamentally different from that of conductors. In metals, a large number of free electrons are available for charge transport. In contrast, the valence electrons in insulating materials are strongly bound to their atoms and cannot move freely under normal operating conditions. As a result, the concentration of free charge carriers is extremely low, leading to very high electrical resistivity [4], [12].

According to band theory, insulators possess a wide energy gap (band gap) between the valence band and the conduction band, typically greater than 3 eV. Because electrons cannot easily gain sufficient energy to cross this gap, electrical conduction is strongly restricted. This electronic structure explains the excellent insulating properties of dielectric materials [4], [12].



Insulating materials are commonly classified into solid, liquid, and gaseous dielectrics. The choice of an insulating material depends on its dielectric properties, operating conditions, and intended electrical application

3.2 Types of Insulating Materials

Electrical insulating materials are classified according to their physical state into solid, liquid, and gaseous insulators. Each category possesses specific dielectric, thermal, and mechanical properties that determine its suitability for electrical applications [10].

A. Solid Insulators (Ceramics and Polymers)

Solid insulators are the most widely used dielectric materials because they provide both electrical insulation and mechanical support.

Ceramics are inorganic materials characterized by high dielectric strength, excellent thermal stability, and resistance to environmental conditions. Typical applications include overhead line insulators, transformer bushings, and high-voltage equipment [5], [10].

Polymers are organic insulating materials valued for their low weight, flexibility, and ease of processing. Polyvinyl chloride (PVC) is commonly used in low-voltage cable insulation, while cross-linked polyethylene (XLPE) is widely employed in medium- and high-voltage power cables because of its superior thermal and dielectric performance [2].

B. Liquid Insulators (Oils)

Liquid dielectrics are mainly used in high-voltage equipment where insulation and cooling are required simultaneously.

Mineral oils are the most common insulating liquids in power transformers. They provide good dielectric properties and efficiently remove heat generated during operation [10].

Synthetic and natural ester oils are increasingly used as environmentally friendly alternatives to mineral oils due to their higher biodegradability and improved fire safety characteristics.

C. Gaseous Insulators (Air and SF₆)

Gaseous dielectrics are widely used in electrical insulation systems because they can fill large volumes and recover their insulating properties after electrical discharges.

Air is the most economical insulating medium and is naturally used in overhead transmission lines and outdoor substations [10].

Sulfur hexafluoride (SF₆) possesses a dielectric strength significantly higher than that of air, making it suitable for gas-insulated substations (GIS) and high-voltage circuit breakers. Its excellent insulating performance allows substantial reduction in equipment size [6].

The selection of an insulating material depends on the required dielectric strength, thermal performance, environmental conditions, and economic considerations.

3.3 Dielectric Properties

The performance of an insulating material is primarily determined by its dielectric properties. These properties describe the behavior of the material when subjected to an electric field and are essential for the design of electrical equipment and insulation systems [13], [15].

A. Permittivity

When an insulating material is placed in an electric field, its bound charges experience a slight displacement, producing a phenomenon known as polarization. The ability of a dielectric to store electrical energy is characterized by its permittivity (ϵ) [14].

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

where:

- (ϵ): permittivity of the material,
- (ϵ)₀: permittivity of free space.

Materials with high permittivity can store more electrical energy and are therefore used in capacitors, whereas insulating supports generally require moderate permittivity values to limit unwanted capacitive effects [14].

B. Dielectric Strength

Dielectric strength is the maximum electric field that an insulating material can withstand without electrical breakdown. It is usually expressed in kilovolts per millimeter (kV/mm) [13].

When the applied electric field exceeds this critical value, the material loses its insulating capability and becomes conductive, resulting in dielectric breakdown. This phenomenon may cause permanent damage to solid insulators and failure of electrical equipment [15].

C. Partial Discharges

Partial discharges (PD) are localized electrical discharges that occur within a portion of an insulating system without completely bridging the space between conductors [13].

They are generally initiated by defects such as voids, cracks, or impurities where the local electric field becomes excessively high. Although each discharge releases only a small amount of energy, repeated PD activity progressively degrades the insulation and may eventually lead to complete breakdown [15].

For this reason, partial discharge monitoring is widely used as a diagnostic tool for assessing the condition of high-voltage insulation systems.

3.4 Ageing and Operating Conditions

The performance of insulating materials gradually degrades under thermal, electrical, and environmental stresses. These ageing mechanisms reduce dielectric strength and may eventually lead to insulation failure [13], [15].

A. Temperature Effects

High temperatures accelerate the degradation of insulating materials, reducing their mechanical and dielectric properties and shortening their service life [10].

B. Humidity Effects

Moisture decreases insulation resistance and dielectric strength. In outdoor equipment, humidity may also promote leakage currents and surface flashover [13].

C. Electrical Ageing

Long-term exposure to electric fields can create defects within the insulation. Over time, these defects may develop into partial discharges and eventually cause dielectric breakdown [15].

Proper material selection and operating conditions are therefore essential to ensure reliable insulation performance.

3.5 Applications of Insulating Materials

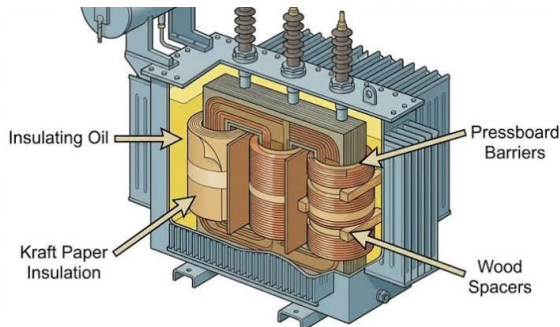
Insulating materials are essential components of electrical equipment, ensuring safe operation, electrical isolation, and long-term reliability. Their selection depends on the operating voltage, temperature, and environmental conditions [10].

A. Power Cables

Polymeric insulators such as PVC and XLPE are widely used in power cables to electrically isolate conductors and prevent current leakage. XLPE is particularly preferred in medium- and high-voltage cables because of its excellent dielectric and thermal properties [10].



B. Transformers

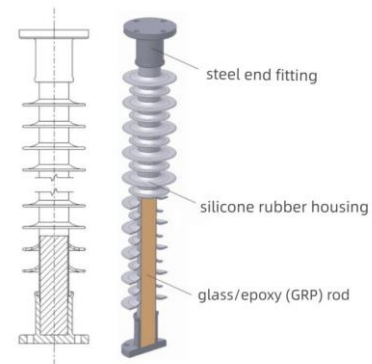


Liquid and solid insulating materials are used in power transformers. Mineral oils provide both electrical insulation and cooling, while cellulose paper is employed to insulate windings [13].

C. High-Voltage Equipment

Ceramics, composite insulators, air, and SF₆ are commonly used in high-voltage transmission systems, substations, and circuit breakers. These materials ensure adequate insulation and prevent electrical breakdown under high electric fields [15].

The reliability and efficiency of electrical systems depend strongly on the proper selection and maintenance of insulating materials.



Chapter 4: Magnetic Materials

Contents

4.1 Introduction	44
4.2 Fundamentals of Magnetism	45
A. Magnetic Moments and Domains	45
B. Magnetization and Hysteresis.....	45
C. Magnetic Losses	46
4.3 Soft Magnetic Materials	46
A. Fe–Si Electrical Steels.....	46
B. Soft Ferrites	47
4.4 Hard Magnetic Materials.....	47
A. Hard Ferrites	47
B. Rare-Earth Magnets	48
4.5 Applications of Magnetic Materials.....	48

4.1 Introduction

Magnetic materials play a fundamental role in electrical engineering, particularly in devices that generate, convert, or control electrical energy, such as transformers, motors, generators, and inductors [10]. Their ability to guide and concentrate magnetic flux makes them essential for efficient energy conversion and electromagnetic operation.

The magnetic behavior of materials originates from the motion and spin of electrons. In most materials, the magnetic moments associated with electrons cancel each other. However, in ferromagnetic materials, some magnetic moments remain aligned, producing a net magnetization under the influence of an external magnetic field [4], [12].

Magnetic materials are generally classified into two main categories:

- **soft magnetic materials**, which are easily magnetized and demagnetized,
- **hard magnetic materials**, which retain their magnetization and are used as permanent magnets.

Understanding their magnetic properties is essential for selecting appropriate materials in electrical and electronic applications.

4.2 Fundamentals of Magnetism

The magnetic properties of materials originate from the magnetic moments associated with the orbital motion and spin of electrons. In ferromagnetic materials, these magnetic moments interact and align within microscopic regions called magnetic domains (Weiss domains), giving rise to strong magnetic behavior [4], [12].

A. Magnetic Moments and Domains

In the absence of an external magnetic field, magnetic domains are randomly oriented, resulting in zero net magnetization. When a magnetic field is applied, the domains gradually align with the field, increasing the magnetization of the material [2].

B. Magnetization and Hysteresis

The relationship between the magnetic flux density (B) and the magnetic field intensity (H) is expressed by:

$$B = \mu H$$

where (μ) is the magnetic permeability of the material.

For ferromagnetic materials, the magnetization process is not completely reversible. When the magnetic field is cycled, the material exhibits a hysteresis loop characterized by:

- **Remanence (B_r):** the residual magnetic flux density remaining after the external field is removed.

- **Coercivity (H_c)**: the reverse magnetic field required to cancel the residual magnetization [2], [16].

C. Magnetic Losses

Under alternating magnetic fields, part of the energy is dissipated as heat within the magnetic material. The main sources of magnetic losses are:

- **Hysteresis losses**, caused by repeated magnetization and demagnetization cycles.
- **Eddy current losses**, generated by currents induced inside conductive magnetic materials [16].

Reducing these losses is essential for improving the efficiency of transformers, motors, and other electromagnetic devices.

4.3 Soft Magnetic Materials

Soft magnetic materials are materials that are easily magnetized and demagnetized. They are characterized by high magnetic permeability, low coercivity, and a narrow hysteresis loop, which makes them ideal for applications where magnetic fields vary with time, such as transformers and electrical machines [4], [16].

A. Fe–Si Electrical Steels

Iron-silicon (Fe–Si) alloys are the most widely used soft magnetic materials in power engineering applications operating at industrial frequencies (50/60 Hz).

The addition of silicon (typically 2–4%) increases the electrical resistivity of iron, which significantly reduces eddy current losses. In practical applications, Fe–Si cores

are manufactured in the form of thin laminated sheets separated by an insulating layer to further minimize induced currents [2], [16].

These materials are mainly used in transformer cores, electric motors, and generators due to their good magnetic performance and relatively low cost.

B. Soft Ferrites

Soft ferrites are ceramic magnetic materials composed of iron oxides combined with elements such as manganese, zinc, or nickel.

Unlike metallic materials, ferrites have very high electrical resistivity, which almost eliminates eddy current losses, especially at high frequencies. However, they exhibit lower magnetic saturation compared to Fe–Si steels [4].

Because of these properties, soft ferrites are mainly used in high-frequency applications such as switching power supplies, inductors, and electromagnetic interference (EMI) filters.

4.4 Hard Magnetic Materials

Hard magnetic materials are characterized by a wide hysteresis loop, high coercivity, and high remanent magnetization. Once magnetized, they retain their magnetic state for a long time, which makes them suitable for permanent magnet applications [4], [16].

A. Hard Ferrites

Hard ferrites are ceramic-based permanent magnets composed mainly of iron oxides combined with barium or strontium. They are relatively inexpensive, chemically stable, and resistant to corrosion. However, their magnetic energy density is moderate compared to advanced alloys [2].

B. Rare-Earth Magnets

Rare-earth magnets represent the most powerful class of permanent magnets currently available.

- **Neodymium–Iron–Boron (NdFeB):**

These magnets exhibit very high energy density, allowing the design of compact and efficient electrical machines. However, they are sensitive to temperature and corrosion [12].

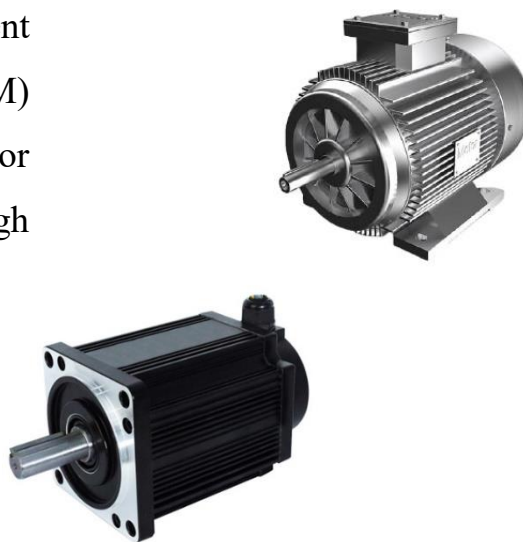
- **Samarium–Cobalt (SmCo):**

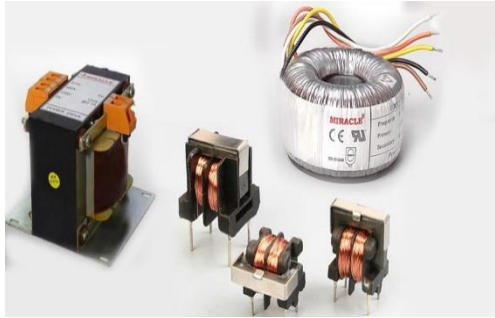
These magnets offer slightly lower magnetic strength than NdFeB but provide excellent thermal stability and can operate at high temperatures without significant performance loss [12].

4.5 Applications of Magnetic Materials

Magnetic materials are widely used in electrical and electronic systems where energy conversion and electromagnetic control are required.

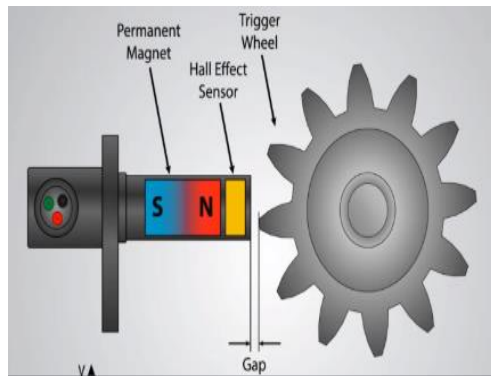
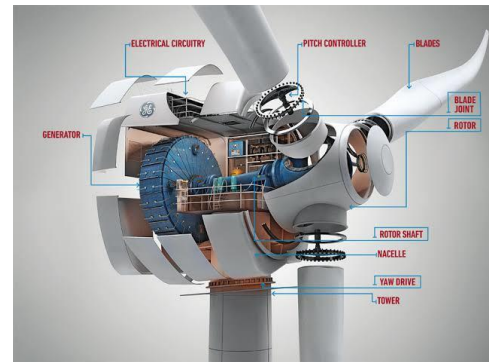
Electrical Machines: Permanent magnet synchronous motors (PMSM) and brushless DC motors use NdFeB or SmCo magnets to achieve high efficiency and power density





Transformers and Inductors: Soft magnetic materials such as Fe–Si steels and ferrites are used to guide magnetic flux and minimize losses.

Energy Generation: Wind turbines and generators use magnetic materials to convert mechanical energy into electrical energy efficiently



Sensors: Magnetic sensors (e.g., Hall effect sensors) are used in position detection, speed measurement, and automotive systems [10], [12].

The performance and efficiency of these systems strongly depend on the appropriate selection of magnetic materials based on their magnetic properties and operating conditions.

Chapter 5: Semiconductors

Contents

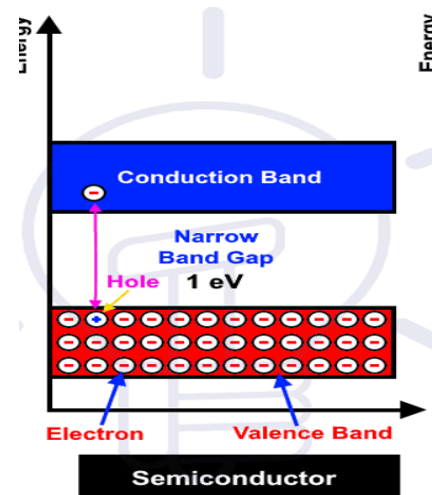
5.1 Introduction	51
5.2 Semiconductor Fundamentals	52
A. Charge Carriers: Electrons and Holes	52
B. Intrinsic and Extrinsic Semiconductors	53
C. Doping: N-type and P-type	53
5.3 Semiconductor Materials.....	55
A. Silicon (Si)	55
B. Gallium Arsenide (GaAs)	55
C. Silicon Carbide (SiC)	56
5.4 Electrical Properties of Semiconductors	56
5.5 Applications of Semiconductors	57
A. Diodes.....	57
B. Transistors	58
C. Power Electronics.....	58
D. Photodetectors and Optoelectronics.....	59

5.1 Introduction

Semiconductors are a class of materials whose electrical conductivity is between that of conductors and insulators. Their unique property is the ability to control the concentration of charge carriers, making them essential materials for modern electrical and electronic systems [4], [6].

Unlike metals, where a large number of free electrons are available for electrical conduction, and insulating materials, where electrons are strongly bound to atoms, semiconductors have a limited number of charge carriers that can be controlled by temperature and impurity addition (doping).

From the energy band perspective, semiconductors have a relatively small band gap between the valence band and the conduction band. This allows electrons to gain sufficient energy to become free carriers, creating both electrons and holes that contribute to electrical conduction [6].



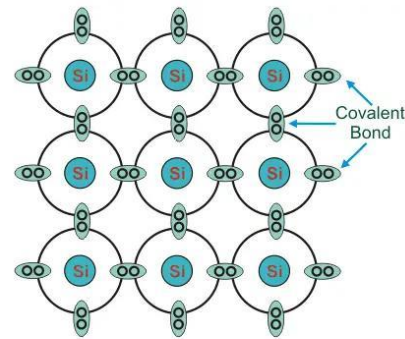
The electrical properties of semiconductors can be modified by introducing controlled impurities, which enables the fabrication of electronic devices such as diodes, transistors, integrated circuits, and power semiconductor components.

5.2 Semiconductor Fundamentals

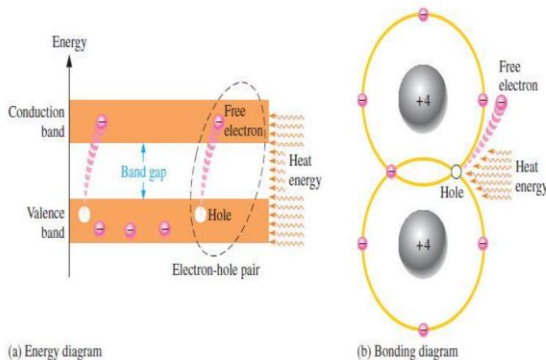
Electrical conduction in semiconductors is based on the movement of **charge carriers** within the crystal lattice. Unlike metals, where electrical conduction results from a large number of free electrons, semiconductors use a dual conduction mechanism involving two types of carriers: **electrons and holes** [4], [6].

A. Charge Carriers: Electrons and Holes

In a pure semiconductor crystal such as silicon, atoms are connected through strong covalent bonds. At low temperatures, these bonds keep electrons strongly bound, limiting electrical conduction. However, at room temperature, thermal energy can provide enough energy to break some covalent bonds [6].



Pure Silicon Crystal Structure



When an electron gains sufficient energy, it moves from the valence band to the conduction band, becoming a **free electron** and acting as a negative charge carrier. The empty position left behind by this electron is called a **hole**. Although a hole is not a real particle, the movement of neighboring electrons to fill this vacancy makes the hole appear to move in the opposite direction; therefore, it behaves as a positive charge carrier [4], [6].

Electrical current in semiconductors is produced by the combined movement of electrons and holes.

For intrinsic silicon at room temperature (300 K), each generated electron creates one corresponding hole, therefore:

$$n = p \approx 1.5 \times 10^{10} \text{ cm}^{-3}$$

where (n) is the electron concentration and (p) is the hole concentration. This carrier concentration is extremely low compared with metals, which explains the limited conductivity of pure semiconductors [6].

B. Intrinsic and Extrinsic Semiconductors

An **intrinsic semiconductor** is a pure semiconductor material where charge carriers are generated only by thermal energy. In this state, the number of electrons and holes is naturally equal:

$$n = p$$

However, the conductivity of intrinsic semiconductors is relatively low and cannot be easily controlled for practical applications [4].

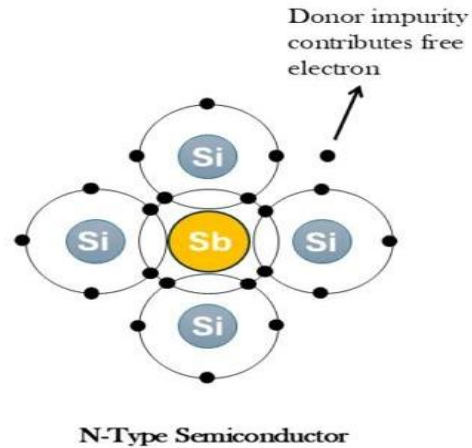
To improve and control electrical conductivity, controlled impurity atoms are intentionally introduced into the crystal lattice. This process is known as **doping**, and the resulting material is called an **extrinsic semiconductor** [4], [6].

C. Doping: N-type and P-type

Doping is the controlled addition of impurity atoms to modify the concentration of charge carriers in a semiconductor [6].

1. N-type Semiconductor

N-type semiconductors are formed by adding donor atoms such as phosphorus (P) or arsenic (As). These atoms contain five valence electrons. Four electrons form covalent bonds with silicon atoms, while the fifth electron remains weakly bound and becomes a free electron [4].

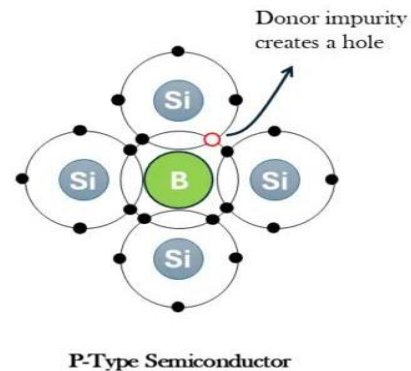


As a result:

- Free electron concentration increases.
- Electrons become the **majority carriers**.
- Holes become the **minority carriers**.

2. P-type Semiconductor

P-type semiconductors are formed by adding acceptor atoms such as boron (B), which contain three valence electrons. The missing electron in the fourth covalent bond creates a hole that can move through the crystal structure [6].



As a result:

- Hole concentration increases.
- Holes become the **majority carriers**.
- Electrons become the **minority carriers**.

The ability to control carrier concentration through doping is the fundamental principle behind semiconductor devices such as diodes, transistors, and integrated circuits [4], [6].

5.3 Semiconductor Materials

The selection of semiconductor materials depends on their electrical properties, especially band gap energy, carrier mobility, thermal stability, and ability to operate under specific conditions. The most important semiconductor materials used in electrical engineering are Silicon (Si), Gallium Arsenide (GaAs), and Silicon Carbide (SiC) [4], [6].

A. Silicon (Si)

Silicon is the most widely used semiconductor material due to its low cost, availability, and excellent technological maturity.

It has a band gap:

$$E_g \approx 1.12 \text{ eV}$$

Its covalent crystal structure allows controlled electrical conduction through doping. Silicon is mainly used in integrated circuits, diodes, transistors, and power electronic devices [4], [6].

B. Gallium Arsenide (GaAs)

Gallium Arsenide is a compound semiconductor with a direct band gap:

$$E_g \approx 1.42 \text{ eV}$$

It provides higher electron mobility than silicon, making it suitable for high-frequency and optoelectronic applications such as LEDs, laser diodes, and photodetectors [4].

C. Silicon Carbide (SiC)

Silicon Carbide is a wide band gap semiconductor:

$$E_g \approx 3.26 \text{ eV}$$

Its high breakdown voltage, thermal stability, and high operating temperature capability make it suitable for power electronics applications, including electric vehicles, converters, and high-voltage switching systems [6].

The choice of semiconductor material depends on the required balance between electrical performance, thermal behavior, and application constraints [4], [6].

5.4 Electrical Properties of Semiconductors

The electrical properties of semiconductors are mainly determined by the concentration and mobility of charge carriers. Unlike metals, their conductivity can be controlled and varies significantly with temperature and impurity concentration [4], [6].

The electrical conductivity is expressed as:

$$\sigma = q(n\mu_n + p\mu_p)$$

where:

(σ): electrical conductivity

(q): electron charge

(n, p): electron and hole concentrations

(μ_n, μ_p): carrier mobilities

This relationship shows that increasing the number of carriers or improving their mobility increases the conductivity of the material.

– Temperature Effect

In semiconductors, increasing temperature increases electrical conductivity because more electrons gain sufficient energy to become conduction carriers.

Therefore:

$$T \uparrow \Rightarrow \sigma \uparrow$$

This behavior is opposite to metals, where conductivity decreases with temperature due to increased atomic vibrations.

– Comparison with Other Materials :

- Conductors: high carrier concentration and high conductivity.
- Insulators: very low carrier concentration and negligible conductivity.
- Semiconductors: intermediate conductivity with controllable electrical behavior.

This controllability makes semiconductors suitable for electronic and power applications.

5.5 Applications of Semiconductors

The ability to control electrical conduction in semiconductors makes them essential materials in modern electrical and electronic systems. Their applications cover signal control, energy conversion, and optoelectronic technologies [4], [6].

A. Diodes

A diode is a semiconductor device based on a P–N junction. It allows current flow mainly in one direction and is widely used for:

- AC to DC rectification.
- Protection circuits.
- Signal processing.



B. Transistors

Transistors are semiconductor devices used for switching and amplification. A small input signal can control a larger electrical current, making them fundamental components in:

- Electronic circuits.
- Digital systems.
- Integrated circuits.



C. Power Electronics

Power semiconductor devices such as MOSFETs, IGBTs, and power diodes are designed to control high voltage and current.

They are used in:

- Motor drives.
- Electric vehicle systems.
- Renewable energy converters.
- Industrial power control.



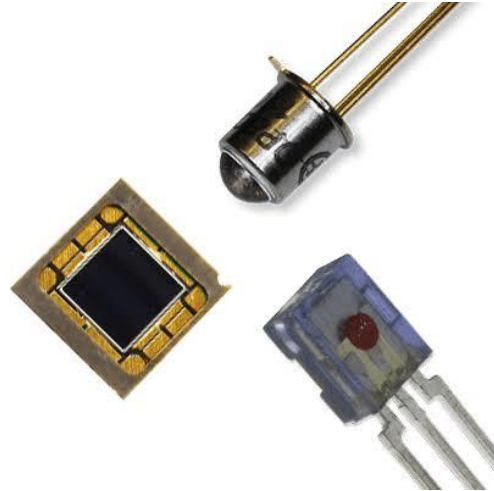
Advanced materials such as SiC improve efficiency by reducing losses and allowing higher temperature operation [6].

D. Photodetectors and Optoelectronics

Semiconductors can convert light energy into electrical signals through the generation of electron–hole pairs.

Applications include:

- Photodetectors.
- Optical communication systems.
- Solar cells.
- Light sensors.



The wide range of semiconductor applications results from their unique ability to control charge transport and interact with electrical and optical signals [4].

Chapter 6: Superconductors

Contents

6.1 Introduction	61
6.2 Fundamentals of Superconductivity	61
A. Zero Electrical Resistivity	61
B. Meissner Effect	62
C. Critical Parameters	62
6.3 Superconducting Materials	62
A. Low-Temperature Superconductors (NbTi)	62
B. High-Temperature Superconductors (YBCO)	63
6.4 Applications of Superconductors	64
.A HTS Power Cables	64
.B Superconducting Magnets	64
.C Magnetic Resonance Imaging (MRI)	65
.D Maglev Trains	65
6.5 Technological Challenges	66
A. Cooling Requirements	66
B. Mechanical Limitations	66

6.1 Introduction

Superconductors are advanced materials that exhibit exceptional electrical and magnetic properties when cooled below a critical temperature $((T_c))$. In this state, their electrical resistivity becomes zero, allowing current flow without Joule losses [18], [19].

Another fundamental property is the Meissner effect, where magnetic flux is expelled from the material, giving superconductors unique magnetic behavior [19].

Superconducting materials are classified into low-temperature superconductors (LTS) and high-temperature superconductors (HTS) depending on their operating temperature range. Their ability to carry very high currents and generate strong magnetic fields enables applications in energy systems, medical imaging, and advanced transportation technologies [20].

6.2 Fundamentals of Superconductivity

Superconductivity occurs when certain materials are cooled below their critical temperature, leading to a transition from a normal resistive state to a superconducting state [18].

A. Zero Electrical Resistivity

The main characteristic of superconductors is the complete disappearance of electrical resistance:

$$\rho = 0$$

Therefore, electrical current can flow without energy dissipation by the Joule effect, enabling highly efficient electrical systems [18].

B. Meissner Effect

The Meissner effect describes the expulsion of magnetic flux from the interior of a superconductor. This behavior makes superconductors perfect diamagnetic materials and enables applications such as magnetic levitation [19].

C. Critical Parameters

The superconducting state depends on three limits:

- **Critical temperature ((T_c)):** maximum temperature for superconducting operation.
- **Critical magnetic field ((H_c)):** maximum magnetic field before losing superconductivity.
- **Critical current density ((J_c)):** maximum current density the material can carry [18], [20].

Exceeding any of these limits causes a transition back to the normal resistive state.

6.3 Superconducting Materials

Superconductors are mainly divided into two categories according to their critical temperature [18], [20].

A. Low-Temperature Superconductors (NbTi)

Niobium-Titanium (NbTi) is a widely used low-temperature superconductor:

$$T_c \approx 9.2K$$

It requires cooling using liquid helium ($\approx 4.2K$).

Main characteristics[18]:

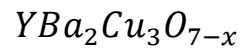
High current capacity.

Good mechanical flexibility.

Suitable for superconducting coils.

B. High-Temperature Superconductors (YBCO)

Yttrium Barium Copper Oxide (YBCO):



has:

$$T_c \approx 92K$$

It can operate using liquid nitrogen cooling ($\approx 77K$).

Advantages:

- Higher operating temperature.
- Reduced cooling cost.
- High current capability.

Limitation:

Ceramic structure with mechanical brittleness [19], [20].

6.4 Applications of Superconductors

The unique properties of superconductors, especially zero electrical resistivity and the ability to generate strong magnetic fields, make them suitable for advanced electrical, medical, and transportation applications [18], [20].

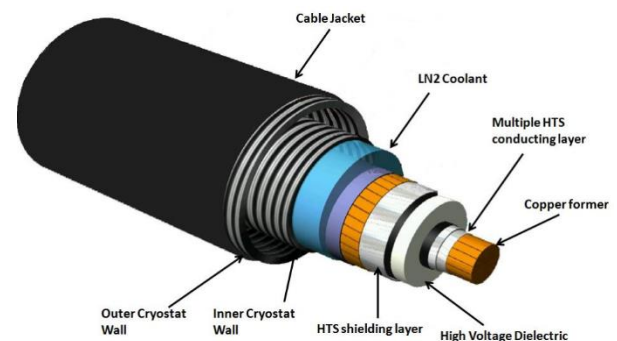
A. HTS Power Cables

High-Temperature Superconducting (HTS) cables are designed to transmit large amounts of electrical power with very low losses.

Their main advantages include:

- Very high current-carrying capacity.
- Reduced Joule losses.
- Smaller dimensions compared with conventional copper or aluminum cables.

These properties make HTS cables attractive for high-density urban power networks [20].



B. Superconducting Magnets



Superconducting materials can carry large currents without resistive heating, allowing the production of very strong magnetic fields.

Applications include:

- Scientific research equipment.
- Particle accelerators.
- High-field magnetic systems.

The main advantage is the generation of intense and stable magnetic fields with high efficiency [18].

C. Magnetic Resonance Imaging (MRI)

MRI systems use superconducting coils, commonly made from NbTi, to produce stable and powerful magnetic fields for medical imaging.

- The use of superconductors provides:
- High magnetic field stability.
- Improved image quality.

Continuous operation with reduced energy losses [19].

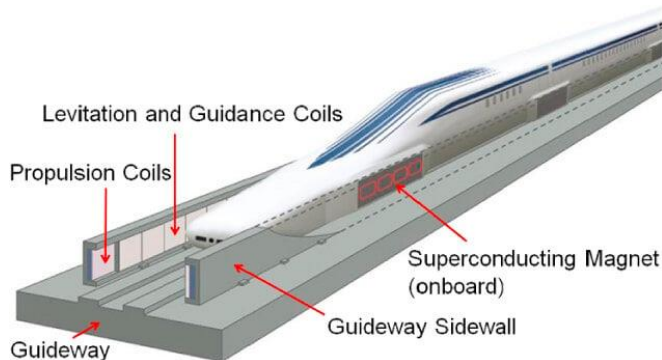


D. Maglev Trains

Magnetic levitation (Maglev) trains use superconducting magnets to generate lifting and propulsion forces.

Advantages include:

- Elimination of mechanical contact between train and track.
- Very high operating speeds.
- Reduced friction and maintenance requirements.



Maglev systems represent one of the most advanced transportation applications of superconducting materials [20].

6.5 Technological Challenges

Despite their advantages, superconductors face several practical limitations [18], [20].

A. Cooling Requirements

Superconductivity requires operation below (T_c).

- NbTi → liquid helium cooling.
- YBCO → liquid nitrogen cooling.

Cooling systems increase complexity and operating cost.

B. Mechanical Limitations

Many superconducting materials, especially ceramic HTS materials, are brittle and sensitive to mechanical stress.

Challenges include:

- Difficult manufacturing.
- Risk of cracking.

Need for protective structures [19], [20].

Chapter 7: Material Selection Criteria

Contents

7.1 Introduction	68
7.2 Material Selection Criteria	69
A. Functional Requirements	69
B. Environmental Constraints	69
C. Economic Considerations	70
7.4 Durability and Sustainability	70
A. Service Life and Reliability	70
B. Recycling and Environmental Impact	71
7.5 Case Studies	71
A. Transformer Material Selection	71
B. Electric Motor Material Selection	72
C. High-Voltage Insulator Material Selection	72

7.1 Introduction

The selection of materials is a critical step in the design of electrical and electronic systems. The performance, reliability, safety, and cost of any device depend strongly on the properties of the materials used in its construction [1], [21].

In practical engineering, no material can provide all required properties simultaneously. Therefore, engineers must select materials by balancing several factors, including electrical, magnetic, thermal, mechanical, environmental, and economic requirements [2].

A suitable material must not only perform its main function but also maintain its properties under operating conditions throughout the expected service life of the system. Factors such as temperature, humidity, electromagnetic fields, ageing, and maintenance requirements must be considered during the selection process [21], [22].

This chapter presents the main criteria used for selecting materials in electrical engineering and demonstrates their application through practical examples involving transformers, electric motors, and high-voltage insulation systems.

7.2 Material Selection Criteria

The selection of a material for an electrical engineering application requires evaluating several criteria to ensure the required performance, reliability, and economic efficiency of the system. The main criteria include functional requirements, environmental conditions, and economic factors [1], [21].

A. Functional Requirements

The selected material must satisfy the specific function required in the electrical system. properties include:

- Electrical properties: conductivity for conductors and dielectric strength for insulating materials.
- Magnetic properties: permeability and magnetic losses for cores and magnetic components.
- Thermal properties: heat resistance and thermal conductivity.
- Mechanical properties: strength, flexibility, and resistance to mechanical stresses.

The choice depends on the role of the material within the device and the operating conditions [2].

B. Environmental Constraints

Electrical materials are exposed to different environmental conditions that may affect their performance and lifetime. factors include:

- Operating temperature.
- Humidity and moisture.
- Corrosion and chemical exposure.
- Mechanical vibrations and external stresses.

The material must maintain its electrical and mechanical properties under these conditions to ensure reliable operation [10], [21].

C. Economic Considerations

Material selection must also consider the total cost of the system, not only the initial price of the material. Its aspects include:

- Raw material cost.
- Manufacturing and processing requirements.
- Maintenance needs.
- Expected service life.

The optimal choice is usually a compromise between technical performance, durability, and overall cost [21], [23].

7.4 Durability and Sustainability

The selection of electrical materials must consider not only their initial performance but also their ability to operate reliably over a long period while minimizing environmental impact. Durability and sustainability have become important criteria in modern engineering design [21], [22].

A. Service Life and Reliability

The service life of a material depends on its ability to maintain its required properties under operating conditions.

Main factors affecting reliability include:

- Thermal ageing caused by continuous temperature exposure.
- Electrical stress, especially in insulation systems.
- Mechanical fatigue and vibration.

- Corrosion and environmental degradation.

Materials with high durability reduce maintenance requirements, improve system reliability, and increase the lifetime of electrical equipment [1], [10].

B. Recycling and Environmental Impact

Modern material selection also considers the environmental impact throughout the product life cycle.

Important aspects include:

- Recyclability of materials such as copper and aluminum.
- Reduction of hazardous substances.
- Lower energy consumption during manufacturing.
- Sustainable management at the end of equipment life.

Selecting recyclable and environmentally friendly materials contributes to more sustainable electrical technologies while maintaining required technical performance [22], [23].

7.5 Case Studies

This section illustrates how material selection criteria are applied in real electrical engineering systems. The objective is to show how functional, environmental, and economic constraints guide the choice of materials in practical devices [1], [21].

A. Transformer Material Selection

A power transformer requires materials with high magnetic performance and excellent electrical insulation.

- **Core material:** Silicon steel (Fe-Si) is used due to its high permeability and reduced hysteresis and eddy current losses. Laminated structures are applied to further reduce losses [2].
- **Winding material:** Copper or aluminum is selected depending on cost and weight constraints, due to their high electrical conductivity [2].
- **Insulation system:** Mineral oil or solid polymer insulation is used to ensure dielectric strength and thermal stability [10].

The selection aims to minimize energy losses while ensuring thermal and electrical reliability.

B. Electric Motor Material Selection

Electric motors require materials that combine magnetic efficiency, electrical conductivity, and mechanical strength.

- **Stator and rotor core:** Laminated Fe-Si sheets to reduce magnetic losses.
- **Windings:** Copper is preferred for its high conductivity and compact design.
- **Permanent magnets (if applicable):** NdFeB or ferrite magnets depending on performance and cost requirements [20].

The main objective is high efficiency, reduced losses, and long operational life.

C. High-Voltage Insulator Material Selection

High-voltage insulators must withstand strong electric fields and harsh environmental conditions.

- **Solid insulators:** Porcelain or polymer-based materials (e.g., XLPE) for high dielectric strength and mechanical support.
- **Surface design:** Special profiles are used to increase creepage distance and reduce flashover risk.

- **Environmental resistance:** Materials are selected to resist humidity, pollution, and temperature variations [10], [21].

The key requirement is maintaining insulation integrity under long-term electrical and environmental stress.

These case studies demonstrate that material selection is always a compromise between electrical performance, mechanical requirements, environmental resistance, and cost optimization.

References

- [1] M. F. Ashby, *Materials Selection in Mechanical Design*, 4th ed., Burlington, MA, USA: Butterworth-Heinemann, 2011.
- [2] W. D. Callister Jr. and D. G. Rethwisch, *Materials Science and Engineering: An Introduction*, 10th ed., Hoboken, NJ, USA: John Wiley & Sons, 2018.
- [3] D. R. Askeland and W. J. Wright, *The Science and Engineering of Materials*, 7th ed., Boston, MA, USA: Cengage Learning, 2016.
- [4] S. O. Kasap, *Principles of Electronic Materials and Devices*, 5th ed., New York, NY, USA: McGraw-Hill, 2022.
- [5] A. J. Moulson and J. M. Herbert, *Electroceramics: Materials, Properties, Applications*, 2nd ed., Chichester, UK: Wiley, 2003.
- [6] D. A. Neamen, *Semiconductor Physics and Devices: Basic Principles*, 4th ed., New York, NY, USA: McGraw-Hill, 2012.
- [7] W. F. Smith and J. Hashemi, *Materials Science and Engineering*, 10th ed., New York, NY, USA: McGraw-Hill Education, 2022.
- [8] M. F. Ashby and D. R. H. Jones, *Engineering Materials 1: An Introduction to Properties, Applications and Design*, 5th ed., Oxford, UK: Butterworth-Heinemann, 2018.
- [9] L. Solymar, D. Walsh, and R. R. A. Syms, *Electrical Properties of Materials*, 10th ed., Oxford, UK: Oxford University Press, 2018.
- [10] P. Hipault, *Materials for Electrical Engineering*, Paris, France: Ellipses, 2019.
- [11] S. O. Kasap, *Principles of Electronic Materials and Devices*, 4th ed., New York, NY, USA: McGraw-Hill Education, 2017.
- [12] R. E. Hummel, *Electronic Properties of Materials*, 5th ed., New York, NY, USA: Springer, 2011.
- [13] G. K. Mithal, *Electrical Engineering Materials*, 2nd ed., New Delhi, India: Khanna Publishers, 1991.
- [14] L. Solymar, D. Walsh, and R. R. A. Syms, *Electrical Properties of Materials*, 10th ed., Oxford, UK: Oxford University Press, 2018.

- [15] A. K. Bain and P. Chand, *Fundamentals of Dielectrics*, in *Pyroelectric Materials: Physics and Applications*, Wiley-VCH, 2023.
- [16] G. Bertotti, *Hysteresis in Magnetism: For Physicists, Materials Scientists, and Engineers*, San Diego, CA, USA: Academic Press, 1998.
- [17] J. M. D. Coey, *Magnetism and Magnetic Materials*, Cambridge, UK: Cambridge University Press, 2010.
- [18] M. Tinkham, *Introduction to Superconductivity*, 2nd ed., New York, NY, USA: McGraw-Hill, 1996.
- [19] C. P. Poole Jr., H. A. Farach, and R. J. Creswick, *Superconductivity*, 3rd ed., Amsterdam, Netherlands: Academic Press, 2014.
- [20] R. G. Sharma, *Superconductivity: Basics and Applications to Magnets*, Berlin, Germany: Springer, 2015.
- [21] M. F. Ashby, *Materials Selection in Mechanical Design*, 5th ed., Oxford, UK: Butterworth-Heinemann, 2016.
- [22] M. F. Ashby, *Materials and Sustainable Development*, 2nd ed., Oxford, UK: Butterworth-Heinemann, 2015.
- [23] G. Dieter and L. Schmidt, *Engineering Design*, 5th ed., New York, NY, USA: McGraw