University: University of Mohamed Kheider - Biskra

Faculty: Faculty of Science and Technology

Department: Common Core in Science and Technology

Electrical Engineering Materials

Pedagogical Handout

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Academic Year: 2025/2026

Chapter 2: Conductive Materials

2nd Year Engineering students

Contents

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].

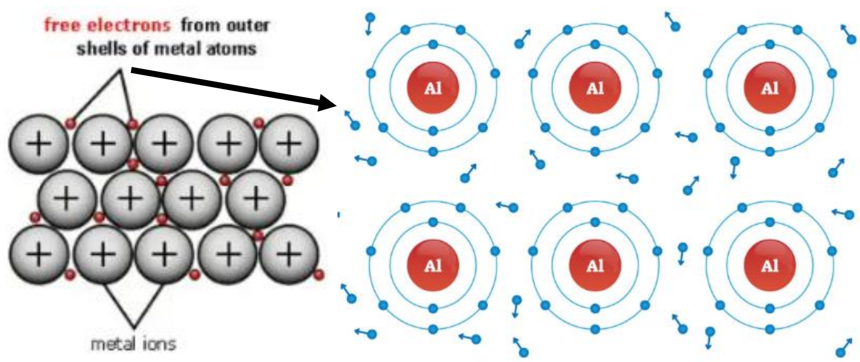


Figure 2.1 Free electron model

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].

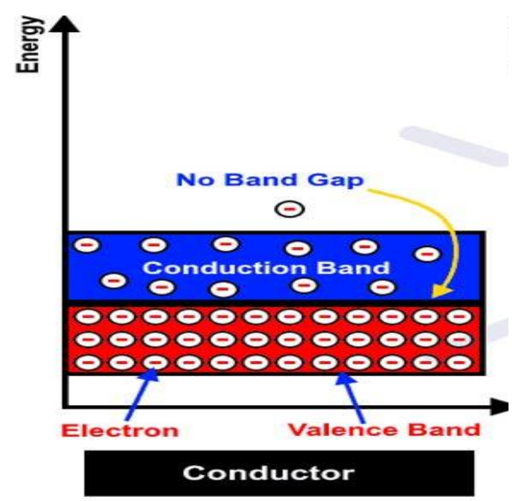


Figure.2 2 Energy band diagram for conductors

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].

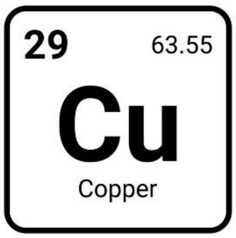
This microscopic description forms the physical basis for understanding why metals such as copper and aluminum are preferred in electrical engineering applications.

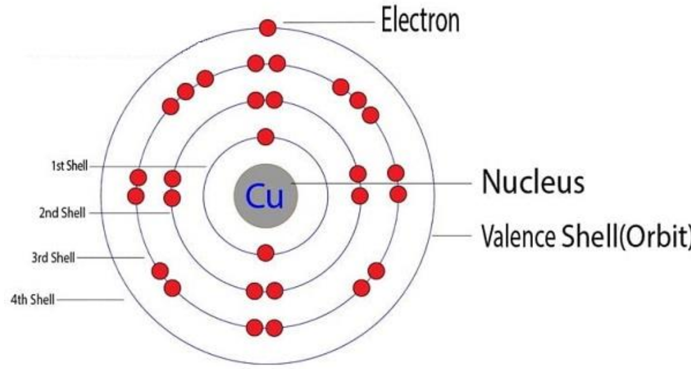
2.3 Conductive Metals (Copper, Aluminum, Alloys)

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:





$[\mathrm{Ar}], 3d^{10}, 4s^{1}$

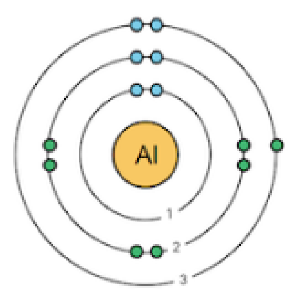
Copper contributes **one free conduction electron per atom** (from the $4s^1$ orbital). These electrons become delocalized within the metallic lattice, forming an electron gas responsible for its high conductivity.

- Free electrons per atom: **≈ 1 electron/atom**
- Electron distribution: valence electron ($4s^1$) → 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:



$[\mathrm{Ne}], 3s^{2}, 3p^{1}$

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

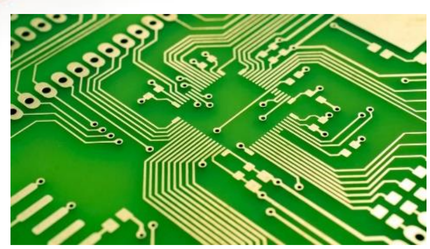
The choice of conductive materials depends on the electrical, mechanical, and economic requirements of the application. Copper and aluminum are the most widely used conductors in electrical engineering due to their high conductivity and availability [4], [10].

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.

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