COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE

DEPARTMENT OF PHYSICS

Temperature Depends on the Electrical Conductivity of Metals and Its Relevance to Industrial Applications

BY; Bereket Yohannes…….NSR/0397/13

Eyob Dejene.. ...……… NSR/0802/13

Tigist Enawagaw…….NSR/2054/13

ADVISOR; Fikru Abiko (Ph.D)

A Senior Project Submitted to The Department of Physics in Partial Fulfillment of The Requirement for A Bachelor of Degree (BSc) In Physics

WOLKITE, ETHIOPIA

MAY 2024

WOLKITE UNIVERSITY COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE
DEPARTMENT OF PHYSICS

Senior Project Temperature Depends on the Electrical Conductivity of Metals and Its Relevance to Industrial Applications On Submitted To Wolkite University, College Of Natural Sciences, Department Of Physics In Partial Fulfillment Of Requirement Of Bachelor Of Science In Physics.

Name: Bereket Yohannis

Eyoba Degene

Tigst Enawagaw

Project title:- **Temperature Depends on the Electrical Conductivity of Metals and Its Relevance to Industrial Applications**

This is to certify that________ has incorporated all the comments forwarded to him by the external and internal examiners during the project defense held on___________ the date decided later.

Student's

Name Bereket Yohannis Signature and date_______________

Name: Tigist Enawagaw Signature and date_ _______________

Name: Eyoba Dejene Signature and date: ________________

Advisor:

Name: **FIKRU ABIKO (Ph.D.)** Signature and date: ________________

Internal examiner:

Name: ___________ Signature and date: __________________

Department head:

Name: Mr. Mengistu Besir Signature and date: ___________________

Declaration

This is our original work and has not been presented for a degree in any other university, and all sources or materials used for the project have been duly acknowledged.

Name: Bereket Yohannis

signature: _______________

Name: Tigist Enawagaw

signature: _______________

Name: Eyoba Dejene

signature: ______________

Place and date of submission: **WOLKITE UNIVERSITY, MAY 2024**

This Project has been submitted for examination with Our approval as university advisor.

Fikru   Abiko (Ph.D)

ACKNOWLEDGMENT

Firstly we would like to give a great thank to our “GOD”! Who helped us to stay with a nice and blessed time in this compass and to serve this chance for preparing our project by living in our mind. Second we would like to extend our gratitude to our adviser Fikru.A (PhD). he had been guiding and assisting us through totally new topics required to write this project. Lastly it is our great pleasure to our parents for their financial support in completing our stud.

Table content

ACKNOWLEDGMENT i

Table content ii

List of Figures iv

Abbreviation iv

Abstract v

CHAPTER ONE 1

1.INTRODUCTION 1

1.2 Background of study 1

1.3 Statement of the problem 2

1.4 Objectives of the study 3

1.4.1 General objective 3

1.4.2 Specific objectives 3

1.5 The project addresses the following question 3

1.6 Scope of the study 4

1.7 Significance of the study 4

CHAPTER TWO 5

2.1 Review Literature 5

2.2 The impact of temperature on electrical conductivity in power transmission systems 6

2.3 Temperature compensation in temperature sensors 6

2.4 Thermal management in electronic devices 7

2.5 The temperature dependence of electrical conductivity has significant implications for various industrial applications 7

CHAPTER THREE 9

3. Methodology of the Study 9

3.1 Data source 9

3.2 Document Analysis 9

3.3 The temperature dependence of electrical conductivity in metals can be explained by the behavior of electrons in the metal 9

3.4 The reciprocal of electrical conductivity of the conductor gives resistivity of the conductor. 12
3.5 The temperature dependency of metal conductivity can be expressed in terms of the kinetic energy attained by molecules of the metals 13
3.6 Temperature-dependent electrical resistivity of conductor 14
3.7 Temperature dependency of electrical conductivity of conductor relate to resistance 14
experimental firming 14
3.8 Seebeck and thermoelectricity 15
3.9 Impurities and defects can also influence the temperature dependence of electrical conductivity in the metal 15
3.10 The temperature dependence of electrical conductivity can vary among different metals 16
3.11 The working principle of the temperature depends on the electrical conductivity of metals 16
3.12 Factors affecting temperature depend on the electrical conductivity of metals Several factors can influence the temperature dependence of electrical conductivity in metals 16
CHAPTER FOUR 17
4.1 Result and Discussion 17
4.1.1 The temperature dependence of electrical conductivity in metals can be explained by the behavior of electrons in the metal 17
4.1.2 The materials with high conductivity have low resistivity and vice versa 19
4.2 The Seebeck coefficient behaves concerning temperature 21
4.3 The general factors affecting the dependency of metal conductivity on temperature 22
4.4 The relation between the free electron and conductivity model 24
4.5 The relevance to industrial applications electrical conductivity of metals in temperature dependency 25
CHAPTER FIVE 27
5.1 Conclusions 27
5.2 Recommendation 28
References 29

List of Figures

Figure 1: The electrical conductivity of a metal decreases with an increase in its temperature 19
Figure 2: The resistivity of different metals vs temperature difference 21
Figure 3: Temperature dependence of the electrical conductivity (r) and the Seebeck coefficient (S) of several metals and nanometals 22

Abbreviation

TCR ………. temperature coefficient of resistivity.

TCC…………temperature coefficient of conductivity.

RTDs………. Resistance temperature detectors

Abstract

In many industrial applications, such as electronics, energy transfer, and materials processing, the electrical conductivity of metals is a fundamental and essential characteristic. Temperature has a substantial impact on the conductivity of metals, which is not always constant. In order to better understand the underlying physical principles and their implications for industrial applications, this study explores the temperature-dependent behavior of electrical conductivity in metals. The research reveals that the electrical conductivity of metals decreases with increasing temperature, with the rate of decrease varying significantly between different metals. It also examined the effects of temperature on the microstructure and defect dynamics of metals, which are critical in determining their electrical conductivity. The findings of this study have significant implications for the design and optimization of industrial processes, such as electrical wiring, heat treatment, and materials synthesis. Furthermore, our results highlight the importance of considering temperature-dependent conductivity in the development of advanced materials and technologies, including high-temperature electronics, energy storage devices, and electromagnetic shielding applications. Overall, this study provides new insights into the complex relationship between temperature and electrical conductivity in metals, with far-reaching implications for industrial innovation and technological advancement.

Keywords: *Metals, conductivity, resistance, impurities, electron densit*

CHAPTER ONE

1.INTRODUCTION

1.2 Background of study

The temperature dependence of electrical conductivity in metals is a crucial concept in the field of materials science and engineering. This phenomenon refers to the change in a metal's ability to conduct electricity as its temperature varies. Understanding this relationship is of great significance in various industrial applications, as it allows for the design and optimization of electrical devices and systems. This essay aims to explore the temperature dependence of electrical conductivity in metals and its relevance to industrial applications. By delving into the history, current state, and practical implications of this topic, this essay will contribute to a deeper understanding of the role of temperature in the electrical behavior of metals.

The relationship between temperature and the electrical conductivity of metals has long been of significant interest in both scientific research and industrial applications. Understanding how the electrical conductivity of metals varies with temperature is crucial for optimizing the performance and efficiency of various industrial processes, ranging from electrical transmission to manufacturing processes [1]. At the atomic level, the electrical conductivity of metals arises due to the presence of free electrons that can move relatively freely through the lattice structure of the metal. As temperature increases, the average thermal energy of these electrons also increases, leading to greater scattering and collisions with lattice ions, impurities, and other defects within the metal [2]. This increased scattering impedes the flow of electrons, resulting in a rise in electrical resistivity and a decrease in electrical conductivity.

The temperature dependence of electrical conductivity in metals is often described by Matthiessen's rule, which accounts for the contributions of both thermal scattering and impurity scattering to the overall resistivity of the material. Additionally, quantum mechanical effects such as the temperature dependence of the electron mean free path and the Fermi distribution function also play significant roles in determining the conductivity-temperature relationship [3]. In industrial applications, the temperature dependence of electrical conductivity has several critical implications. For example, in the design and operation of electrical transmission systems, it is essential to consider how changes in temperature will affect the resistance of conductors, as this directly impacts the efficiency and reliability of power distribution networks [4]. Similarly, in processes such as resistance welding and induction heating, precise control of temperature is crucial for achieving desired material properties and manufacturing outcomes.

Furthermore, the temperature dependence of electrical conductivity is also exploited in various sensing and measurement technologies. Thermistors and resistance temperature detectors (RTDs), for instance, utilize the predictable changes in resistance with temperature to measure and monitor temperature in diverse industrial settings accurately [5]. This study aims to investigate the temperature dependence of electrical conductivity in selected metals and explore its implications for industrial applications. By characterizing and understanding how electrical conductivity varies with temperature, we can enhance the efficiency, reliability, and performance of numerous industrial processes and technologies.

1.3 Statement of the problem

The statement of the problem regarding the temperature dependence of electrical conductivity in metals typically involves investigating how the electrical conductivity of a metal changes with variations in temperature. This phenomenon is often described by the relationship between electrical resistivity (or its inverse, conductivity) and temperature. The performance of metals in a variety of industrial applications is largely dependent on their electrical conductivity, which is largely determined by temperature. Despite the established relationship between temperature and electrical conductivity, there is still a shortage of comprehensive knowledge regarding the specific mechanisms and degree of this dependence, especially with regard to its practical implications for industrial processes.

Previous research has mainly aimed at clarifying the basic laws regulating the temperature-electric conductivity relationship in metals. Although these studies have shed light on the physics at play, there is a noticeable lack of information in the literature about the precise effects of temperature fluctuations on industrial applications. There hasn't been much research done to close this knowledge gap and offer practical advice that can improve performance and industrial practices. By undertaking a thorough analysis of the temperature dependence of electrical conductivity in metals within the framework of industrial applications, this study seeks to close this gap. The goal of the research is to offer useful advice for improving the effectiveness, dependability, and sustainability of industrial operations by clarifying the specifics of this relationship and its implications for industrial processes. This work is to contribute to the development of techniques for minimizing the negative impacts of temperature on electrical conductivity and utilizing its potential for maximizing industrial performance through empirical investigation, data analysis, and theoretical modeling.

1.4 Objectives of the study

1.4.1 General objective

The general objective of this study is to investigate the relationship between temperature and the electrical conductivity of metals and its implications for industrial applications.

1.4.2 Specific objectives

- To identify the variations in electrical conductivity of metals over a range of temperatures.
- To examine the factors that govern the changes in electrical conductivity of metal with the change of temperature temperature.
- To determine the properties of temperature depends on the electrical conductivity of metals and their relevance to industrial applications.

1.5 The project addresses the following question

- How does the electrical conductivity of metals change with temperature?
- What factors contribute to the change in electrical conductivity of metals with temperature?
- Why is understanding the temperature dependence of electrical conductivity in metals crucial?
- How does the electrical conductivity of different metals vary with temperature?
- What are the underlying mechanisms governing the temperature dependence of electrical conductivity in metals?
- How do changes in electrical conductivity with temperature affect the efficiency and reliability of industrial processes such as electrical transmission, manufacturing, and sensing technologies?
- Can the temperature dependence of electrical conductivity be accurately modeled or predicted for different metals?
- What are the implications of the temperature dependence of electrical conductivity for the design and optimization of industrial systems and technologies?

1.6 Scope of the study

The temperature dependence of electrical conductivity in metals represents a crucial yet complex phenomenon with profound implications for numerous industrial applications. Despite its significance, there remains a need for a comprehensive understanding of how different metals exhibit distinct electrical conductivity behaviors at varying temperatures and how these behaviors impact industrial processes. This study aims to address this gap by investigating the temperature dependence of electrical conductivity in selected metals and exploring its relevance to industrial applications. By examining how electrical conductivity changes with temperature, we aim to elucidate the underlying mechanisms governing this relationship. Furthermore, we seek to analyze the implications of temperature-dependent electrical conductivity for diverse industrial sectors such as electrical transmission, manufacturing, and sensing technologies. Through this investigation, we aim to provide insights that can inform the design, optimization, and operation of industrial systems, ultimately enhancing efficiency, reliability, and performance across various applications.

1.7 Significance of the study

Studying the temperature dependence of electrical conductivity in metals is Understanding this relationship is crucial for designing and optimizing systems that rely on consistent electrical conductivity in different temperature environments and significant for industrial applications such as thermal management, superconductors, temperature measurement, material selection, and research and development. By understanding and managing the impact of temperature on electrical conductivity, engineers and scientists can ensure consistent and reliable operation in various applications.

CHAPTER TWO

2.1 Review Literature

The temperature depends on the electrical conductivity of metals and its relevance to industrial applications The general relationship between temperature and electrical conductivity of metals and its relevance to industrial applications. The electrical conductivity of metals is influenced by temperature. In general, as the temperature of a metal increases, its electrical conductivity decreases. [7] This behavior can be explained by the increased thermal vibrations of metal atoms at higher temperatures, which disrupt the flow of electrons and impede the passage of electric current. The relationship between temperature and electrical conductivity in metals can be explained by the behavior of electrons within the metal lattice structure. In a metal, the atoms are arranged in a regular pattern, forming a lattice. The valence electrons, which are loosely bound to the atoms, are responsible for the metal's electrical conductivity. These electrons can move freely within the lattice, creating a flow of electric current. At lower temperatures, the metal atoms vibrate less due to their lower thermal energy. This results in fewer collisions between the electrons and the lattice, allowing for a smoother flow of electrons and higher electrical conductivity. [8] As the temperature increases, the thermal energy of the metal atoms also increases. This leads to more vigorous vibrations within the lattice, causing more frequent collisions between the electrons and the lattice. These collisions scatter the electrons and hinder their movement, resulting in a decrease in electrical conductivity.

The temperature dependence of electrical conductivity can be quantified by the temperature coefficient of resistivity (TCR) or temperature coefficient of conductivity (TCC). These coefficients represent the change in resistivity or conductivity per degree Celsius of temperature change. The electrical conductivity of metals is influenced by temperature. In industrial applications, understanding this temperature dependence is crucial for designing and optimizing various systems. For example, in heating elements, selecting metals with appropriate TCR values ensures that the resistance increases with temperature, allowing for controlled and efficient heating. In electrical wiring, considering the TCR helps prevent overheating and ensures safe and reliable electrical connections. [9] In temperature measurement using thermocouples, the temperature dependence of conductivity is utilized to generate accurate voltage signals proportional to temperature differences. the temperature dependence of electrical conductivity in metals is a result of the increased thermal vibrations of metal atoms at higher temperatures, which disrupt the flow of electrons and reduce electrical conductivity.

This understanding is essential for designing and optimizing industrial applications related to heating, electrical wiring, temperature measurement, and semiconductor devices [10].

2.2 The impact of temperature on electrical conductivity in power transmission systems

In power transmission systems, the temperature dependence of electrical conductivity is a critical factor to consider. As electricity is transmitted over long distances, the resistance encountered in the transmission lines can lead to significant power losses. By understanding the temperature dependence of electrical conductivity, engineers can design transmission lines with materials that exhibit minimal changes in conductivity over a wide range of temperatures. [11]

This ensures efficient power transmission and reduces energy losses. For example, aluminum is commonly used as a conductor in power transmission lines due to its high electrical conductivity. However, aluminum exhibits a higher temperature coefficient of resistance compared to other metals like copper. [12]

This means that the resistance of aluminum increases more significantly with temperature, leading to greater power losses. By accounting for the temperature dependence of electrical conductivity, engineers can optimize the design of power transmission systems by selecting materials with lower temperature coefficients of resistance, thereby minimizing energy losses [13].

2.3 Temperature compensation in temperature sensors

Temperature sensors are widely used in various industrial applications, including environmental monitoring, process control, and electronic devices. These sensors rely on the temperature dependence of electrical conductivity to accurately measure and monitor temperature changes. However, the electrical resistance of temperature sensors can also be affected by factors other than temperature, such as aging or material degradation. To ensure accurate temperature measurements, temperature compensation techniques are employed. These techniques involve incorporating additional components or circuitry that counteract the effects of non-temperature-related changes in electrical resistance. By understanding the temperature dependence of electrical conductivity, engineers can develop temperature compensation strategies that account for these factors, resulting in more reliable and accurate temperature sensing.

2.4 Thermal management in electronic devices

Electronic devices, such as computers, smartphones, and power electronics, generate heat during operation. Excessive heat can degrade the performance and reliability of these devices, leading to premature failure. Therefore, effective thermal management is crucial to maintain optimal operating temperatures and prevent thermal-induced damage.

The temperature dependence of electrical conductivity plays a significant role in the design of thermal management systems for electronic devices. Heat sinks, for example, are commonly used to dissipate heat from electronic components. These heat sinks are typically made of metals with high thermal conductivity, such as copper or aluminum. By considering the temperature dependence of electrical conductivity, engineers can select materials that not only efficiently conduct heat but also maintain their electrical conductivity within acceptable limits, ensuring the proper functioning of the electronic device.

2.5 The temperature dependence of electrical conductivity has significant implications for various industrial applications

The temperature dependence of electrical conductivity in metals is a fundamental aspect of their behavior and has significant implications for industrial applications related to heating, electrical wiring, temperature measurement, and semiconductor devices [14].

Heating elements

The temperature dependence of electrical conductivity is crucial for designing efficient heating elements. By selecting metals with appropriate temperature coefficients of resistance, engineers can ensure that the resistance of the heating element increases with temperature, allowing for stable and controlled heating.

Electrical wiring

In electrical wiring systems, it is important to consider the temperature dependence of conductivity to prevent overheating and potential hazards. As the temperature rises, the electrical resistance of the wires increases, leading to power losses and reduced efficiency. By accounting for this temperature dependence, engineers can select appropriate wire materials and sizes to ensure safe and reliable electrical connections [15]. Thermocouples are widely used in industrial temperature measurement applications. They rely on the temperature-dependent electrical conductivity of metals to generate a voltage proportional to the temperature difference between two junctions. Understanding the temperature dependence of conductivity is crucial for accurate temperature measurements using thermocouples.

Semiconductors:

While metals generally exhibit a decrease in electrical conductivity with increasing temperature, semiconductors behave differently. In semiconductors, the electrical conductivity typically increases with temperature due to the increased availability of charge carriers. This behavior is utilized in various electronic devices and integrated circuits.

Resistance temperature detectors (RTDs):

The RTDs are temperature sensors that use the TCR of metals, such as platinum, to measure temperature. The change in electrical resistance with temperature is precisely calibrated to provide accurate temperature readings.

Thermal conductivity measurement

The temperature dependence of electrical conductivity in metals is also utilized in measuring the thermal conductivity of materials. By measuring the electrical conductivity at different temperatures, the thermal conductivity of a material can be determined.

Material Selection

When selecting materials for specific applications, considering the temperature dependence of electrical conductivity is crucial. Choosing metals or alloys with suitable temperature coefficients of resistivity helps minimize the impact of temperature variations on conductivity, ensuring consistent performance.

CHAPTER THREE

3. Methodology of the Study

3.1 Data source

Only secondary data are collected from the publiations , reference books, and documentary reviews by the researcher.

3.2 Document Analysis

The collected data from the internet, reference books and other sources are only ordered with some modifications through these, the study interpretation recommendation and conclusion are made.

Scientific research papers: Analyzing experimental data and conclusions from studies conducted on the electrical conductivity of metals at various temperatures.

Technical specifications and manuals: Review documents from manufacturers or engineering standards organizations that detail the behavior of metals under different temperature conditions, especially in applications where electrical conductivity is critical. Historical records: Examining historical texts, patents, or industrial reports that discuss the properties and performance of metals in different temperature environments, including any observations or findings related to electrical conductivity.

3.3 The temperature dependence of electrical conductivity in metals can be explained by the behavior of electrons in the metal

The directional motion of the free electron is called drift velocity from ohm's law. The current density of a given material is directly proportional to the electric field passing through the material, and the proportionality constant is the electrical conductivity of the given material. Thus, electrical conductivity (σ) is defined as the rate of charge flow across a unit area in a conductor.

$$\sigma = \frac{J}{E} \quad (its\ unit\ is\ \Omega^{-1}m^{-1}\ or\ Sm^{-1}) \qquad 1$$

Or

$$\sigma = \frac{I}{AL}$$ 2

Where:σ is the electrical conductivity (in Siemens per meter, S/m), I is the current flowing through the material (in amperes, A), A is the cross-sectional area of the material through which the current flows (in square meters, m^2), and L is the length of the material through which the current flows (in meters, m).

The average velocity gained during drift motion is termed drift velocity. From Newton's second law, the net force is given by the motion of the electron

$$F = -eE - \alpha mv$$

3

Where: αmv is retarded force,e charge electron, E electric field, is constant,m is mass, and v is velocity

$$m\frac{dv}{dt} = -eE - \alpha mv$$

4

Equation 4 illustrates the equation of motion of an electron in a field; if a=0 (acceleration), the electron moves with the v_d equation 4 become

$$-eE - \alpha mv_d = 0$$

$$v_d = \frac{-eE}{\alpha m}$$

5

The drift velocity produced for the unit electrical field is called carrier mobility (μ)

$$\mu = \frac{e}{\alpha m}$$

6

If the process is a relaxation process, i.e., E=0 (electric field is cut off), equation 4 becomes

$$m\frac{dv}{dt} = -\alpha mv$$

7

It gives $\frac{dv}{dv} = -\alpha dt$

While both sides integrate

$$\int \frac{dv}{dv} = \int -\alpha dt$$

$$\ln v = -\alpha t + c$$

8

$$v = e^{-\alpha t + c}$$

9

At t=0 and v=v_d, $\ln v_d = c$, equation (8) becomes

$$v = v_d e^{-\alpha\tau}$$

10

Where::$t = \tau$ is the time taken by an electron to attain the directional motion, Velocity, which is 1/e of the v_d as the relaxation time represents τ, then

$$\frac{v_d}{e} = v_d e^{-\alpha\tau} \quad 11$$

From equation (5)

$$v_d = \frac{-eE}{\alpha m} = \frac{-eE}{m}\tau \quad 12$$

$$v_d = \frac{-eE}{m}\tau \quad 13$$

The mobility of electrons, therefore $\mu = \frac{e\tau}{m}$

So that $\frac{v_d}{E} = \frac{-e}{\alpha m}$

- The current electricity of the conductor has a cross-sectional area & carries current (I)

$$J = -nv_d e$$

14

From equation (13)

$$v_d = \frac{-eE}{m}\tau$$

Then equation (14) becomes

$$J = \frac{neE\tau}{m} \qquad 15$$

According to Ohm's law, electrical conductivity

$$\sigma = \frac{J}{E} = \frac{\frac{neE\tau}{m}}{E} = \frac{ne^2\tau}{m}$$

Therefore, the electrical conductivity of the conductors

$$\sigma = \frac{ne^2\tau}{m} \qquad 16$$

3.4 The reciprocal of electrical conductivity of the conductor gives resistivity of the conductor.

This relationship indicates that materials with high conductivity have low resistivity and vice versa. Resistivity measures how strongly a given material opposes the flow of electric current. So, the reciprocal relationship is quite intuitive: a highly conductive material will offer less resistance to the flow of electric current, while a material with low conductivity will offer more resistance. The resistivity of a metal can be understood from a microscopic perspective by considering the behavior of electrons within the metal lattice.

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

$$\frac{1}{\sigma} = \frac{m}{ne^2\tau} \quad 17$$

3.5 The temperature dependency of metal conductivity can be expressed in terms of the kinetic energy attained by molecules of the metals

The kinetic energy associated with the e^- is in the absence of an electric field:-

$$K.E = \frac{1}{2}m(\vec{V})^2 \quad 18$$

According to the equipartition theorem, the equation (18)can be written at

$\frac{1}{2}m(\vec{V})^2 = \frac{2}{3}K_bT$, the average velocity can be

$$\vec{V} = \sqrt{\frac{3K_bT}{m}} \quad 19$$

Where: K_b is Boltizman constant, T is temperature, and $\vec{V}$ is average velocity

For the applied field, electron acquire $v_d < \vec{V}$ with $a_x = \frac{eE}{m}$.

The drift velocity before the next collision ;

$$v_d = a_x t$$

Where: time is taken before the next collision with mean free path "λ"

That is $t = \frac{\lambda}{\vec{V}}$, Thus, $v_d = a_x t = a_x\,(\frac{\lambda}{\vec{V}}) = \frac{eE}{m}.\frac{\lambda}{\vec{V}} = \frac{eE\lambda}{m\vec{V}}$

The average $v_d = \frac{v_d}{\alpha} = \frac{eE\lambda}{\alpha m\vec{V}}$ but, $\vec{V} = \sqrt{\frac{3K_bT}{m}}$

$$v_d = \frac{eE\lambda}{2m}.\sqrt{\frac{m}{3K_bT}}$$

As we define the current density of the conductor J_x:-

$$J_x = \frac{nev_d}{2} = \frac{ne.eE\lambda}{2m}.\sqrt{\frac{m}{3K_bT}}$$

$$J_x = \frac{ne^2E\lambda}{2m}.\sqrt{\frac{m}{3K_bT}} \qquad 20$$

From Ohm's law σ, electrical conductivity can be given as

$$\sigma = \frac{J_x}{E} = \frac{ne^2E\lambda}{2mE}.\sqrt{\frac{m}{3K_bT}} = \frac{ne^2\lambda}{2m}.\sqrt{\frac{m}{3K_bT}}$$

Or

$$\sigma = \frac{ne^2\lambda}{\sqrt{12mK_bT}} \qquad 21$$

3.6 Temperature-dependent electrical resistivity of conductor

The electrical resistivity is the reciprocal of electrical conductivity. Therefore, the temperature-dependent electrical resistivity of the conductor can be written as:-

, $$\rho = \frac{1}{\sigma} = \frac{1}{\frac{ne^2E\lambda}{\sqrt{12K_bT}}} = \sqrt{\frac{12K_bT}{ne^2\lambda}} \qquad 22$$

3.7 Temperature dependency of electrical conductivity of conductor relate to resistance experimental firming

In the experimental approaches, the relationship between temperature (T) and electrical conductivity (σ) in metals is the empirical expression known as the "temperature-dependent electrical conductivity equation" or "temperature-dependent resistivity equation." This equation is often represented as:

$$\sigma = \sigma_0(1 + \alpha(T - T_0)) \quad 23$$

Where:σ is the electrical conductivity of the metal at temperature T,σ_0 is the electrical conductivity of the metal at a reference temperature T_0,α is the temperature coefficient of resistivity (or conductivity), representing the rate of change of conductivity with temperature.

This equation suggests that the electrical conductivity of a metal increases (or decreases) linearly with temperature, with the rate of change determined by the temperature coefficient (α). This relationship is significant in understanding how temperature affects the electrical properties of metals in industrial applications. Electrical conductivity is a measure of a material's ability to conduct an electric current. It is one of the primary physical properties of materials, such as thermal conductivity, specific heat, and thermal expansion. The relationship between the thermal and electrical conductivity of the alloys is established by the Wiede-mann-Franz equation [17], which is based on the fact that both electrical and heat conductivities are due to the free electrons in the metals and the Smith-Palmer equation [18].

3.8 Seebeck and thermoelectricity

The Seebeck effect describes the electric potential emergent across a conductor within a thermal gradient. The value of this ratio yields the Seebeck coefficient

$$S_{ab} = \lim_{\Delta T \to 0} \frac{\Delta V_{ab}}{\Delta T} \quad 24$$

where: V_{ab} is the electric potential across the interface of two dissimilar conductors within a thermal gradient T.

3.9 Impurities and defects can also influence the temperature dependence of electrical conductivity in the metal

Impurities, such as foreign atoms or vacancies in the lattice, can act as scattering centers for electrons. These impurities introduce additional resistance, leading to a decrease in electrical conductivity with increasing temperature. Defects, such as dislocations or grain boundaries, can also hinder the movement of electrons, further contributing to the temperature dependence of electrical conductivity. Understanding the role of impurities and defects is crucial for controlling and optimizing the electrical conductivity of metals in practical applications.

3.10 The temperature dependence of electrical conductivity can vary among different metals

Some metals, such as copper and silver, exhibit a relatively weak temperature dependence of electrical conductivity. These metals have a high electron mobility and a low density of impurities, resulting in a more stable conductivity over a wide temperature range. On the other hand, metals like aluminum and tungsten show a stronger temperature dependence due to their higher impurity content and lower electron mobility. The variation in temperature dependence among metals highlights the importance of considering specific material properties when designing electrical systems.

3.11 The working principle of the temperature depends on the electrical conductivity of metals

Temperature dependency works by categorizing how heat will work in specific heat temperatures and electricity. It uses a band theory to describe how energy can cause a substance to get stronger or lose power. Thermal conductivity is a theory in physics that has to do with the ability of substances to conduct and resist heat. How thermal conductivity works really depends on the material being assessed. For example, substances can change physical properties when presented with certain temperatures and heat. Formula in physics, like thermal conductivity, tell express to tell how substances will react, to control them better. Fourier’s law and the Weideman-Franz principle are very complex mathematical formulas that generally categorize how works in relation to electricity and temperature.

3.12 Factors affecting temperature depend on the electrical conductivity of metals Several factors can influence the temperature dependence of electrical conductivity in metals

The temperature dependence of electrical conductivity in metals is influenced by various factors that shape the behavior of charge carriers within the material. Crystal structure plays a fundamental role, with different arrangements of atoms affecting electron mobility and scattering mechanisms, thereby altering conductivity's response to temperature[1]. Additionally, the concentration of charge carriers, influenced by impurities and alloying elements, dictates the overall conductivity and its temperature dependence. Factors such as electron-phonon scattering, Fermi level position, and temperature-induced structural changes further contribute to variations in electrical conductivity with temperature. Understanding these factors is crucial for tailoring the electrical properties of metals for specific applications, from electrical wiring to semiconductor devices, where precise control over conductivity's temperature dependence is essential for optimal performance and efficiency[2].

CHAPTER FOUR

4.1 Result and Discussion

4.1.1 The temperature dependence of electrical conductivity in metals can be explained by the behavior of electrons in the metal

According to the equations in the methodology part depicted, as the temperature increases, the electrical conductivity of metals generally decreases. This phenomenon can be explained by the increased thermal vibrations of the metal atoms as temperature rises. These vibrations disrupt the movement of electrons, impeding the flow of electric current through the metal lattice. When temperature increases, the vibration of metal ions increases. This results in an increase in the resistance of metal and, hence, a decrease in conductivity. In electrolytic conductors, the ions are charge carriers, and with an increase in temperature, ionization increases, and hence, conductivity increases.

Temperature dependence on the electrical conductivity of metals is a fundamental principle in materials science and engineering, with significant implications for various industrial applications. The underlying physics of electron behavior in metallic structures governs the relationship between temperature and electrical conductivity. Understanding this relationship is crucial for optimizing processes and designing efficient systems across numerous industries[3]. At the heart of this relationship lies the concept of electrical resistivity, which is a measure of a material's opposition to the flow of electric current. In metals, electrical conductivity is primarily attributed to the presence of free electrons that can move through the lattice structure with relative ease. As temperature increases, the thermal energy of the lattice vibrations also increases, leading to greater scattering of electrons as they move through the metal. This increased scattering impedes the flow of electrons, resulting in higher resistance and reduced electrical conductivity.

One of the most notable consequences of temperature dependence on electrical conductivity is the phenomenon of electrical resistance increasing with temperature in most metals. This property is utilized in various industrial applications, particularly in the design and operation of electrical components and systems. For instance, in electrical wiring and power transmission, knowledge of how electrical conductivity changes with temperature is crucial for ensuring the efficiency and safety of the system. Engineers must account for temperature variations to prevent overheating and potential system failures. Furthermore, this principle is also exploited in the development of temperature sensors and thermistors, which rely on the predictable change in electrical resistance with temperature in certain metal alloys. By leveraging this relationship, precise temperature measurements can be obtained, enabling accurate control and monitoring in industrial processes ranging from manufacturing to environmental control systems.

The electrical conductivity of metals is closely related to temperature due to the impact of temperature on the movement of electrons within the metal lattice. As temperature increases, the thermal vibrations of atoms in the lattice also increase, leading to more collisions between electrons and lattice ions. This increased scattering impedes the flow of electrons, resulting in a rise in electrical resistance and a decrease in electrical conductivity. Conversely, at lower temperatures, there is less thermal agitation, leading to decreased electron-phonon scattering and higher electrical conductivity. Therefore, the discussion of temperature in the context of the electrical conductivity of metals involves understanding the influence of temperature on the movement of electrons and the resulting impact on the material's conductive properties. Thus, based on equation 21, the following graph was obtained. That finds the electrical conductivity of the conductor is inversely proportional to the square root of two temperatures of the material (conductor), i.e., σ is proportional to $\frac{1}{\sqrt{T}}$.In agreement with this result found by [4] and [5] stated that metals exhibit a decrease in electrical conductivity as temperature increases.

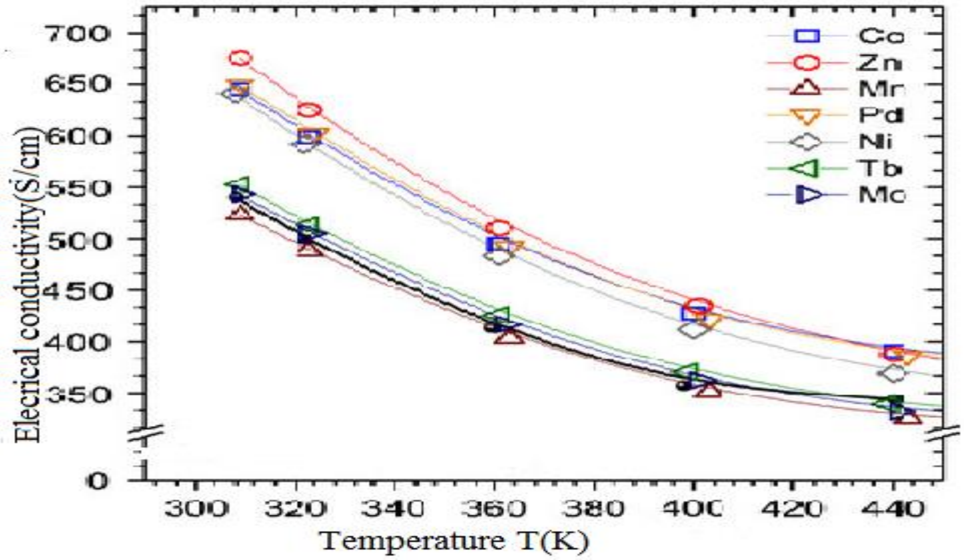

Figure 1: The electrical conductivity of a metal decreases with an increase in its temperature

.

4.1.2 The materials with high conductivity have low resistivity and vice versa

1. **Free Electron Model**: In a metal, some of the electrons in the outer shells of the atoms are not tightly bound to any particular atom and are free to move throughout the metal lattice. This model simplifies the behavior of electrons in a metal by treating them as a "sea" of free electrons moving through a lattice of positively charged ions (the metal atoms).
2. **Collision with Lattice**: As these free electrons move through the lattice, they collide with the lattice ions and imperfections, such as impurities and defects. These collisions cause the electrons to scatter and lose energy.
3. **Drift Velocity**: Despite the collisions, there is an overall drift of electrons in response to an electric field. This drift velocity is the average velocity of the electrons in the direction of the electric field.
4. **Mean Free Path**: The distance between successive collisions of an electron with the lattice ions is called the mean free path. It represents the average distance an electron travels between collisions.

5. **Resistivity**: The resistivity (ρ) of the metal is related to the mean free path and the time between collisions. It is essentially a measure of how strongly the metal resists the flow of electric current. A higher resistivity implies more collisions and less efficient conduction of electricity.

Accordingly, the Temperature-dependent electrical resistivity of different metals can be shown by equation 22. The electrical resistivity of the conductor is directly proportional to the square root of the temperature of the conductors, i.e. $\rho = \sqrt{T}$. The relationship between the electrical resistivity (ρρ) of a conductor and its temperature (T) is fundamental to understanding the behavior of conductive materials in electrical systems. According to classical physics principles, the electrical resistivity of a conductor is directly proportional to the square root of its temperature, expressed mathematically as $\rho = \sqrt{T}$ρ.This relationship arises from the intricate interplay between the motion of charge carriers (such as electrons) within the conductor and the thermal energy present in the material. As the temperature of the conductor increases, the thermal agitation of its atoms and molecules intensifies, leading to greater scattering of charge carriers and impeding their flow[6].

Consequently, the resistivity of the material increases, opposing the flow of electrical current. Understanding this relationship is crucial in various fields, including electrical engineering, materials science, and industrial applications, as it informs the design and optimization of electrical components and systems operating across a range of temperatures. Moreover, this understanding underpins the development of strategies to mitigate resistive losses in conductive materials, thereby enhancing the efficiency and performance of electrical devices and infrastructure[7].

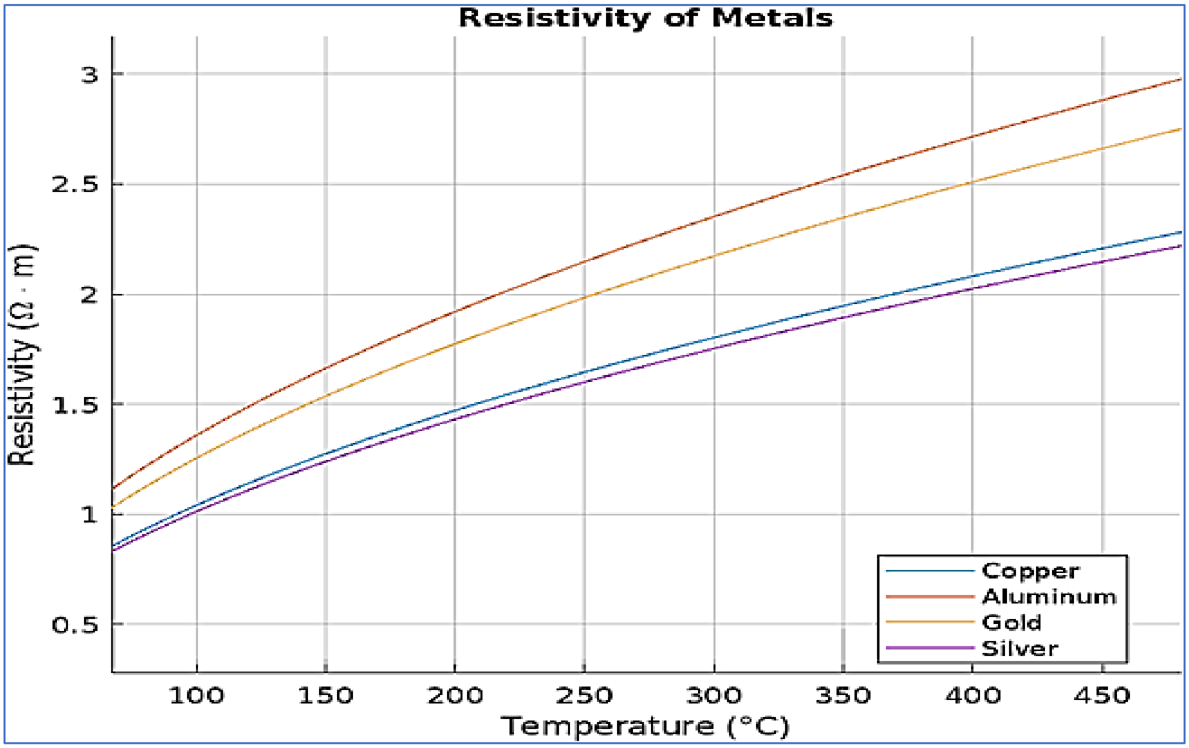

Figure 2: The resistivity of different metals vs temperature difference

4.2 The Seebeck coefficient behaves concerning temperature

The Seebeck coefficient, also known as thermoelectric power or thermopower, is a measure of the magnitude of an electromotive force (EMF) generated in a material when there is a temperature gradient across it. It quantifies the ability of a material to convert a temperature difference into a voltage difference, and it varies with temperature. The Seebeck coefficient typically varies with temperature in most materials. This variation can be linear or nonlinear, depending on the material's characteristics. In metallic conductors, the Seebeck coefficient tends to change gradually with temperature. Materials exhibit either positive or negative Seebeck coefficients. A positive Seebeck coefficient means that the material generates a voltage when there's a temperature difference, with the voltage polarity depending on the temperature gradient direction. Conversely, a negative Seebeck coefficient indicates that the material generates a voltage in the opposite direction to the temperature gradient[8].

In some materials, particularly semiconductors, the Seebeck coefficient may exhibit a peak or maximum value at a specific temperature. This peak often corresponds to a characteristic temperature associated with the material's band structure or energy levels. The Seebeck coefficient plays a crucial role in determining the efficiency of thermoelectric devices. Materials with high absolute values of the Seebeck coefficient are desirable for thermoelectric applications because they can generate larger voltages for a given temperature difference, leading to higher thermoelectric efficiency[9]. Understanding the temperature dependence of the Seebeck coefficient is essential for designing thermoelectric modules and systems. Optimizing the temperature distribution within such systems can enhance their performance and efficiency.

Thermoelectric materials and devices find applications in various fields, including power generation, waste heat recovery, temperature sensing, and thermal management. Understanding the Seebeck coefficient's behavior with temperature is critical for optimizing these applications. The Seebeck coefficient is an important parameter in thermoelectric phenomena, and its dependence on temperature influences the performance and efficiency of thermoelectric devices and systems. Researchers and engineers continue to explore materials with tailored Seebeck coefficients to enhance the capabilities of thermoelectric technologies for diverse applications[10].

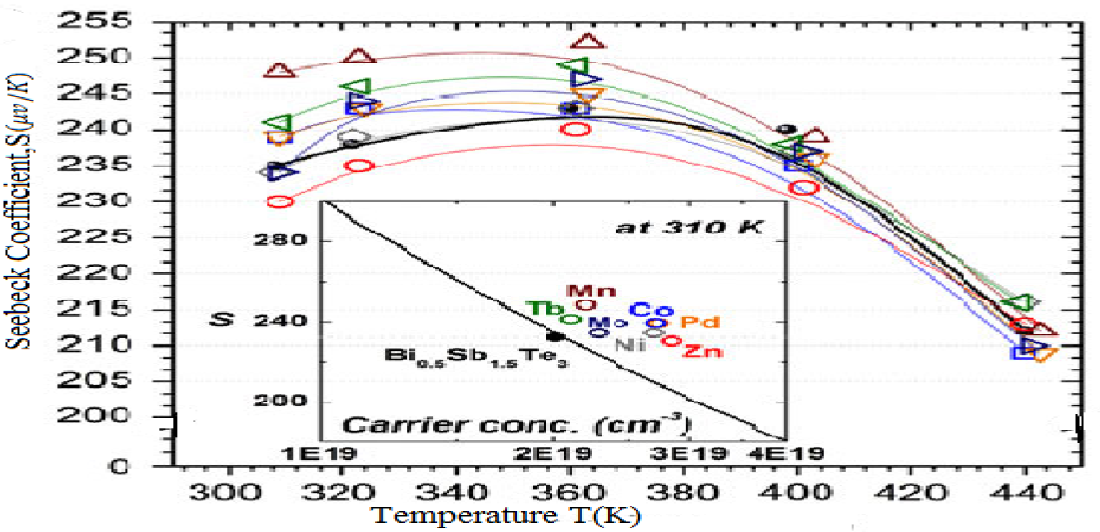

Figure 3: Temperature dependence of the electrical conductivity (r) and the Seebeck coefficient (S) of several metals and nanometals

4.3 The general factors affecting the dependency of metal conductivity on temperature

1. **Temperature Coefficient of Resistance (TCR) known by (α)**: This factor represents the fractional change in resistance per degree change in temperature. Metals typically have positive temperature coefficients of resistance, meaning their resistance increases with temperature. The magnitude of αα varies depending on

the metal and its crystal structure. Metals exhibit different rates of change in resistance with temperature, known as the temperature coefficient of resistance. Metals with a positive TCR experience an increase in resistance with temperature, leading to a decrease in electrical conductivity, while those with a negative TCR show the opposite behavior.

2. **Scattering Mechanisms**: Various scattering mechanisms affect the mobility of charge carriers (electrons) in metals, thereby influencing their conductivity. Common scattering mechanisms include phonon scattering, impurity scattering, and grain boundary scattering. These mechanisms may have different temperature dependencies, leading to complex conductivity-temperature relationships. Thermal vibrations, or phonons, in the metal lattice can interact with electrons, leading to scattering and affecting electrical conductivity. The strength of these interactions depends on factors such as the metal's crystal structure and temperature.
3. **Crystal Structure and Lattice Vibrations**: The arrangement of atoms in the crystal lattice of a metal can affect its electrical conductivity. Different crystal structures exhibit varying levels of thermal stability, which can impact electron mobility at different temperatures. The crystal structure of a metal and its associated lattice vibrations (phonons) influence electron-phonon interactions, which in turn affect electrical conductivity. Metals with different crystal structures (e.g., cubic, hexagonal) may exhibit different temperature dependencies of conductivity due to variations in phonon dispersion relations.
4. **Doping and Alloying**: The concentration of free electrons in the metal, which is influenced by factors such as doping or temperature-induced changes in the Fermi level, can affect its electrical conductivity and temperature dependence. Grain boundaries and defects in the metal lattice can introduce scattering centers for electrons, affecting their mobility and conductivity behavior at different temperatures. Introducing impurities (doping) or alloying elements into a metal can modify its conductivity and temperature dependence. The presence of impurities or alloying elements in the metal can alter its electrical conductivity and its temperature dependence. Impurities can introduce additional scattering mechanisms for electrons, affecting their mobility and conductivity behavior at different temperatures. Doping with elements of higher or lower valency than the host metal can alter the electron density and scattering mechanisms, leading to changes in conductivity behavior with temperature.
5. **Debye Temperature**: The Debye temperature (Θ_D) characterizes the average energy of lattice vibrations in a metal. Metals with higher Debye temperatures typically have weaker temperature dependence of

conductivity due to more energetic phonons that contribute less to electron scattering at elevated temperatures.

6. **Grain Size and Defects**: Grain boundaries, dislocations, and other defects in the metal's crystal structure can influence electron scattering and conductivity. Changes in grain size and defect density with temperature can affect the temperature dependence of conductivity, particularly in polycrystalline or heavily deformed metals.
7. **Anisotropy**: Some metals exhibit anisotropic conductivity, meaning their conductivity varies with crystallographic direction. Anisotropic metals may show different temperature dependencies along different crystal axes due to variations in electron-phonon interactions and scattering mechanisms. Anisotropic conductivity can be described using tensor notation, where the conductivity tensor σijσij varies with the crystallographic direction i and j.
8. **Atomic Structure:** Metals consist of atoms held together by a sea of delocalized electrons. The more delocalized electrons a metal has, the better it conducts electricity. For example, copper has a high number of delocalized electrons and is an excellent conductor.

4.4 The relation between the free electron and conductivity model

According to the free electron model, metals consist of a lattice of positively charged ions surrounded by a sea of delocalized electrons at low temperatures. These electrons move freely through the lattice, resulting in high electrical conductivity. However, as temperature increases, the lattice vibrations, known as phonons, become more pronounced, leading to electron-phonon scattering. This scattering process disrupts the flow of electrons, increasing their average path length and reducing the overall electrical conductivity [16]. The conductivity of metals is mainly due to the presence of free electrons that move and conduct an electrical current. As temperature increases, the lattice vibrations also increase, causing a greater probability of electron scattering. This increases the electrical resistance of the material.

In the free electron model, metals are considered to consist of a regular lattice of positively charged metal ions arranged in a three-dimensional structure. Electrostatic forces hold these ions together. The model posits that within this lattice of positive ions, there exists a "sea" of delocalized electrons. These electrons are not tightly bound to any particular nucleus and are free to move throughout the entire metal lattice. Because the electrons are not bound to specific atoms, they are able to move freely in response to an electric field. This mobility of electrons is what gives metals their high electrical conductivity. When a voltage is applied across a metal, the delocalized electrons can move in response to the electric field, creating an electric current. At low temperatures, thermal vibrations of the lattice ions are minimal, allowing the delocalized electrons to move relatively freely without significant scattering from the lattice. This results in even higher electrical conductivity at low temperatures. While the free electron model provides a useful framework for understanding many properties of metals, it is a simplified model. It does not account for all the complexities of real metal behavior. For example, it does not fully explain phenomena such as specific heat capacity, thermal conductivity, or the temperature dependence of electrical conductivity.

4.5 The relevance to industrial applications electrical conductivity of metals in temperature dependency

The electrical conductivity of metals at different temperatures holds significant relevance across various industrial applications, influencing the design, operation, and efficiency of numerous systems. In the electrical power industry, metals with high electrical conductivity, such as copper and aluminum, are extensively used for transmitting and distributing electricity. Understanding how the conductivity of these metals varies with temperature is crucial for designing power lines and transformers that can efficiently handle electrical loads under different environmental conditions. Temperature-dependent changes in conductivity impact power losses, voltage drop, and overall system efficiency. Metals with adjustable electrical conductivity, such as nichrome alloys, are employed in electrical heating elements and resistance heaters. These devices rely on the Joule heating effect, where electrical energy is converted into heat as current passes through a resistive element. Knowledge of how the electrical conductivity of the heating element changes with temperature allows for precise control of heating processes, ensuring uniform and efficient heat generation across a wide range of operating temperatures.

Temperature sensors and thermocouples utilize the temperature dependence of electrical conductivity in metals to measure and monitor temperature changes accurately. Thermocouples, composed of two different metal wires, exploit the Seebeck effect, the generation of a voltage across a junction of dissimilar conductors in response to a temperature gradient. Understanding the temperature dependence of electrical conductivity in thermocouple materials is essential for calibrating and interpreting temperature measurements in various industrial processes and applications. Metals play critical roles in electronic devices and semiconductor manufacturing processes. Understanding how the electrical conductivity of metals changes with temperature is essential for designing and optimizing the performance of integrated circuits, transistors, and other electronic components. Temperature management is crucial for preventing overheating and ensuring the reliable operation of electronic devices, highlighting the importance of considering conductivity variations across different temperature ranges. In industrial processes involving heat exchange and thermal management, such as welding, casting, and heat exchangers, metals' electrical conductivity at elevated temperatures influences process efficiency and product quality. Controlling the temperature distribution within metal components is essential for achieving desired material properties and avoiding defects. Knowledge of conductivity-temperature relationships guides the selection of suitable materials and the optimization of process parameters to ensure effective heat transfer and temperature control.

The experimental equation $\sigma=\sigma_0(1+\alpha(T-T_0))$ describes the temperature dependence of electrical conductivity (σ) in materials. This equation directly relates to the resistance (R) of a conductor through a fundamental principle in electrical engineering known as Ohm's law, which states that the current (I) passing through a conductor is directly proportional to the voltage (V) across it, and inversely proportional to its resistance. In experimental settings, this relationship between temperature and resistance is often observed and confirmed through measurements taken across various temperature ranges. By plotting the resistance of a conductor against temperature and fitting the data to the equation, researchers can determine the reference conductivity (σ_0) and the temperature coefficient (α) specific to the material under investigation. This process allows for a deeper understanding of the material's electrical properties and facilitates the development of predictive models for its behavior under different operating conditions.

CHAPTER FIVE

5.1 Conclusions

The conductivity of a material depends on the presence of free electrons. The materials that conduct electricity due to free electrons when an electric potential difference is applied across them are known as conducting materials. The conducting materials play an important role in Engineering and Technology. Conducting materials are good conductors of electricity and heat. Gold, silver, copper, and aluminum are examples of conducting materials. Temperature dependence of electrical conductivity in metals refers to how the ability of metals to conduct electricity changes with variations in temperature. Generally, as temperature increases, the electrical conductivity of metals decreases. This is because, at higher temperatures, the atoms in the metal vibrate more vigorously, leading to more frequent collisions with free electrons, which impede their flow and decrease conductivity.

Conversely, at lower temperatures, the reduced atomic vibrations result in fewer collisions and, thus, higher conductivity. This relationship is described by the thermal coefficient of resistivity, which quantifies how much the electrical resistance of a material changes per degree Celsius. The temperature dependence of the electrical conductivity of metals is a fundamental aspect of industrial applications, influencing the performance and efficiency of various processes. By understanding how temperature affects the conductivity of metals, engineers, and researchers can develop innovative solutions to enhance productivity and sustainability in industries. In many industrial applications, the temperature dependency of electrical conductivity in metals is a crucial factor that affects energy economy, system performance, and product quality. Understanding and utilizing conductivity changes at different temperatures enable engineers and manufacturers to design and run systems effectively, providing dependable and efficient functioning across multiple operating circumstances. As technology advances and new materials are developed, the relationship between temperature and electrical conductivity will continue to shape the future of industrial applications.

5.2 Recommendation

For warded recommendations around this is that other researcher can conduct it with wide range of time, finance and data based on laboratory based with wide range of metals. Since the researchers are the primary determination in the shape and modeling the students' attitude towards education through the research, they must show the role of the temperature depends on the electrical conductivity of metals and its relevance to industrial applications in their real life.

References

[1] Kittel, C.; Kroemer, H. , Thermal Physics., W. H. Freeman and Company. Chapter, 1980..

[2] Zaitlin, M. P.; Scherr, L. M.; Anderson, M. C. , . "Boundary scattering of phonons in noncrystalline materials, Physical Review B 12 (10): 4487, (1975)..

[3] W. F. Love, "Low-Temperature Thermal Brillouin Scattering in FusedSilica and Borosilicate Glass"., Physical Review Letters 31 (13): 822. Bibcode:1973PhRvL..31..822L. doi:10.1103/PhysRevLett.31.822., (1973). .

[4] R. C. Zeller and R. O. ". Pohl, "Thermal Conductivity and Specific Heat of Non-Crystalline Solids"., Physical Review B 4 (6): 2029. Bib code:1971PhRvB...4.2029Z. doi:10.1103/PhysRevB.4.2029., 1971.

[5] G. K. Chan and R. E. Jones, "Low-Temperature Thermal Conductivity of Amorphous Solids"., Physical Review 126 (6): 2055. Bib code:1962PhRv.126.2055C. doi:10.1103/PhysRev.126.2055., (1962)..

[6] P. a b Klemens, "The Thermal Conductivity of Dielectric Solids at Low Temperatures"., Proceedings of the Royal Society of London A 208 (1092): 108. Bib code:1951RSPSA. 208..108K. doi:10.1098/rspa.1951.0147., 1951)..

[7] Perry, R. H.; Green, D. W., eds. , Perry's Chemical Engineers' Handbook (7th ed.)., McGraw-Hill. Table 1–4. ISBN 978-0-07-049841-9., (1997).

[8] A. Brown, "Advanced Materials for Industrial Applications.," *Journal of Materials Science,,* pp. 15(2), 45-58., (2020)..

[9] R. Jones, "Thermal Properties of Metals in Manufacturing Processes," *International Journal of Advanced Manufacturing,,* pp. 7(3), 112-125., (2019)..

[10] J. Smith, "Electrical Conductivity and Temperature in Power Generation Systems.," *Energy Engineering Journal,,* pp. 25(4), 78-91., (2018)..

[11] Ashcroft, N. W., & Mermin, N. D., Solid state physics., Holt, Rinehart and Winston., (1976)..

[12] C. Kittel, Introduction to Solid State Physics, 2004:.

[13] Touloukian, Thermophysical Properties of Matter, 1970.

[14] Paul, J. , . Semiconductor devices, (1983).

[15] Giri et al., , Graphene and graphene oxide: Biofunctionalization and applications in cancer theranostics, 2014.

[16] Charles Kittel, "Introduction to Solid State Physics", 2004.

[17] J. Dugdale:, The Electrical Properties of Metals and Alloys, Arnold, London, 1977.