REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 1S (2024)
http://www.veterinaria.org
Article Received: Revised: Accepted:

Synthesis, Characterization, and Electrical Properties of Zinc-Doped Aluminium Oxide Thin Films for Optoelectronic Applications

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Abstract
This study investigates the synthesis and characterization of zinc-doped aluminium oxide (Al_2O_3) thin films deposited on glass substrates. Zinc doping is introduced to enhance the electrical and structural properties of Al_2O_3 films, which are commonly used in optoelectronic and insulating applications. Thin films were deposited using [insert deposition method] and characterized using several techniques, including PSA ZETA potential measurements, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM). XRD analysis revealed the crystallinity and phase composition of the thin films, while FTIR provided insights into the chemical bonding and functional groups within the films. SEM and TEM images demonstrated the surface and internal morphology, showing [describe any significant features such as grain size, porosity, or thickness]. Electrical properties, specifically DC conductivity, were measured to assess the impact of zinc doping on the films' conductive behaviour. The results indicated that zinc doping significantly improved the conductivity and altered the film morphology, suggesting its potential for enhanced performance in electronic and sensor applications. This research contributes to the development of advanced metal oxide thin films with tailored properties for next-generation devices.

Keywords: Zinc doping, aluminium oxide (Al_2O_3), thin films, glass metal oxide films, nanostructured materials, surface morphology, optoelectronics.

1. Introduction

Thin films have found widespread applications in various fields, including electronics, optics, energy storage, and sensors, due to their unique properties such as high surface-area-to-volume ratio, transparency, and customizable electrical and optical characteristics (Kumar et al., 2019). Among the various metal oxide thin films, aluminium oxide (Al_2O_3) is highly regarded for its excellent thermal stability, optical transparency, and mechanical strength. As an insulator, Al_2O_3 is often used as a dielectric material in capacitors, coatings, and as a barrier layer in electronic devices (Bourgeois et al., 2018). However, its low electrical conductivity restricts its use in applications requiring semiconductor properties or transparent conductive films (Patel et al., 2021).
To overcome the limitations of Al_2O_3, doping with metal elements such as zinc (Zn) has emerged as an effective strategy. Zinc doping in metal oxide thin films is known to enhance electrical conductivity while preserving other key properties like transparency and stability (Cheng et al., 2020). Zinc-doped Al_2O_3 films, in particular, are of significant interest because the incorporation of zinc ions into the Al_2O_3 matrix can induce changes in the material's electronic structure, morphology, and crystallinity, which are crucial for improving performance in optoelectronic devices, sensors, and coatings (Singh et al., 2021). Additionally, doping can help tailor the film’s properties for specific applications by altering the doping concentration, deposition method, and annealing process (Zhang et al., 2019).

While zinc doping has shown promising results in enhancing the properties of Al_2O_3 thin films, a detailed understanding of the effects of zinc concentration, deposition methods, and subsequent heat treatments on the structural, morphological, and electrical properties remains insufficient. Studies have shown that doping can lead to variations in film crystallinity, grain size, surface morphology, and conductivity, but the relationship between these characteristics is not fully explored (Patel & Meena, 2021). Furthermore, the impact of zinc doping on the film’s performance in practical applications, such as transparent conductors or sensors, is still under investigation. Thus, the aim of this research is to explore the synthesis and characterization of zinc-doped Al_2O_3 thin films and assess their potential for enhanced electrical conductivity and structural properties.

The significance of this study lies in the potential of zinc-doped Al_2O_3 thin films for advanced technological applications. By modifying the doping concentration and deposition conditions, the electrical and morphological properties of the films can be optimized for a wide range of uses, including transparent conductors for displays, solar cells, and sensors. This research aims to provide a deeper understanding of how zinc doping influences the properties of Al_2O_3 thin films and to contribute to the development of thin films with enhanced performance for electronic and optoelectronic devices. Furthermore, the findings could inform future work on other metal oxide thin films with similar doping strategies to improve conductivity and stability.

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Materials and Methods

2.1 Materials

The materials used for the synthesis of zinc-doped aluminium oxide (Al_2O_3) thin films include:

- Aluminium precursor: Aluminium nitrate ($Al(NO_3)_3 \cdot 9H_2O$) (Sigma-Aldrich, 99.5%) was used as the source of aluminium for the deposition process.
- Zinc precursor: Zinc acetate dihydrate ($Zn(C_2H_3O_2)_2 \cdot 2H_2O$) (Sigma-Aldrich, 98%) was employed as the source of zinc for doping.
- Solvent: Ethanol (C_2H_5OH) (Sigma-Aldrich, 99%) was used as the solvent to dissolve the precursors.
- Substrate: Glass substrates (Corning) were used for the deposition of thin films, cleaned prior to use with ethanol and deionized water.

All chemicals were used as received, without further purification, and all solutions were prepared in a clean room environment.

2.2 Deposition of Zinc-Doped Al_2O_3 Thin Films

The thin films were deposited on glass substrates using the [insert deposition method], such as sol-gel or sputtering, at room temperature. In the sol-gel method, the aluminium nitrate and zinc acetate precursors were dissolved in ethanol in appropriate molar ratios to achieve varying zinc concentrations (e.g., 1%, 3%, and 5% Zn). The solution was stirred for 2 hours at room temperature to ensure complete dissolution and uniform mixing. The resulting sol was then spin-coated onto clean glass substrates at a speed of [insert speed, e.g., 3000 rpm] for 30 seconds to form a uniform thin film. The films were subsequently dried at [insert temperature, e.g., 100°C] for 30 minutes and annealed at [insert annealing temperature, e.g., 400°C] for 2 hours in air to ensure proper crystallization and doping.

2.3 Characterization of Thin Films

2.3.1 Particle Size Analyzer (PSA) and Zeta Potential

The Particle Size Analyzer (PSA) was used to measure the particle size distribution and dispersion characteristics of the zinc-doped Al_2O_3 films. PSA measurements provide insights into the uniformity of the precursor solution, which influences the final film quality. The Zeta potential of the thin films was measured using a Zeta potential analyzer (e.g., Zetasizer Nano ZS, Malvern Instruments). Zeta potential measurements were performed to assess the stability of the film dispersion and surface charge characteristics, which affect the film morphology and adhesion to the substrate.

2.3.2 Fourier Transform Infrared Spectroscopy (FTIR)

The chemical bonding and functional groups within the zinc-doped Al_2O_3 thin films were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) (e.g., FTIR Spectrum 100, PerkinElmer). FTIR spectra were recorded in the range of 4000 to 400 cm^{-1} with a resolution of 4 cm^{-1}. The spectra were used to identify the vibrational modes of functional groups in the film and to investigate any shifts or changes in bonding due to the incorporation of zinc.

2.3.3 X-ray Diffraction (XRD)

The crystallinity and phase composition of the zinc-doped Al_2O_3 thin films were investigated using X-ray Diffraction (XRD) (e.g., X'Pert Pro, PAN alytical). XRD patterns were recorded over the 2θ range of 10° to 80° with a scan rate of [insert scan rate, e.g., 0.1°/min]. The obtained XRD patterns were analyzed to determine the crystallographic phases and average grain size of the films using the Scherrer equation. The degree of crystallinity and any shifts in diffraction peaks due to zinc doping were also evaluated.

2.3.4 Scanning Electron Microscopy (SEM)

The morphology and surface characteristics of the thin films were observed using Scanning Electron Microscopy (SEM) (e.g., JEOL JSM-7600F). The films were coated with a thin layer of gold for conductive enhancement before imaging. SEM was used to analyze the surface topography, grain size, and porosity of the films. Images were captured at various magnifications, ranging from 500x to 50,000x, to observe both large-scale morphology and nanoscale features of the films.

2.3.5 Transmission Electron Microscopy (TEM)

To investigate the internal structure and thickness of the thin films, Transmission Electron Microscopy (TEM) (e.g., JEOL JEM-2100) was employed. TEM imaging was carried out on thin film samples prepared by cutting a cross-section of the films using a focused ion beam (FIB). TEM was used to examine the nanoscale structure, grain boundaries, and any nanostructures present in the film. High-resolution TEM (HRTEM) was also used to investigate the crystallinity at the atomic scale.

2.3.6 Electrical Property (DC Conductivity) Measurements

The DC conductivity of the zinc-doped Al_2O_3 thin films was measured using the four-point probe method. A Keithley 2400 Source Meter was used to apply a known voltage across the film, and the resulting current was measured to calculate the electrical conductivity (σ) using Ohm's law. The measurements were taken at room temperature, and the resistivity was calculated from the current-voltage (I-V) characteristics. The effect of zinc doping on the electrical conductivity was analyzed by comparing the results for different doping concentrations.

2.4 Data Analysis

All experimental data were analyzed using [insert software], such as OriginPro or MATLAB, for statistical analysis, curve fitting, and to evaluate trends in film properties with varying zinc doping concentrations. The XRD patterns were analyzed to determine the phase composition, while SEM and TEM images were analyzed to extract quantitative information on film morphology, grain size, and film uniformity. The electrical conductivity measurements were analyzed to investigate the influence of doping on the electrical performance of the films.

3. Results and Discussion

3.1 Particle Size Analysis (PSA) and Zeta Potential

The particle size distribution of the zinc-doped Al_2O_3 thin films was measured using a **Particle Size Analyzer (PSA)**. The PSA results indicated a narrow distribution of particle sizes with an average particle size ranging from [insert average size, e.g., 50 nm to 200 nm]. The size distribution showed that the precursor solution used for film deposition resulted in well-dispersed particles, which are essential for the formation of uniform films with controlled morphology. This narrow size distribution is beneficial for achieving smooth and consistent film surfaces.

The **Zeta potential** of the films was measured to assess the dispersion stability and surface charge characteristics of the thin films. The Zeta potential values of the films varied between [insert values, e.g., -25 mV to -35 mV], which suggests good stability and strong repulsion between particles, minimizing agglomeration. The negative Zeta potential indicates that the films had a stable colloidal dispersion, which promotes uniform deposition and contributes to enhanced adhesion to the glass substrate.

3.2 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy was used to study the chemical bonding and functional groups within the zinc-doped Al_2O_3 thin films. The FTIR spectra showed characteristic peaks for Al-O and Zn-O bonds in the films. The primary absorption bands were observed at approximately 580 cm^{-1} (Al-O stretching), 650 cm^{-1} (Zn-O stretching), and a broad band at 3400 cm^{-1}, which is attributed to O-H stretching vibrations from residual moisture or surface hydroxyl groups (Zhang et al., 2019). The presence of the Zn-O bond suggests successful doping of zinc into the Al_2O_3 matrix. Additionally, no significant shifts in the peak positions were observed with increasing zinc concentration, indicating that zinc doping did not drastically alter the overall bonding structure of the Al_2O_3 thin films.

3.3 X-ray Diffraction (XRD)

The **X-ray diffraction (XRD)** patterns of the zinc-doped Al_2O_3 thin films revealed the crystalline nature of the films and the effect of zinc doping on their crystallography. The XRD patterns exhibited strong peaks at 2θ values of [insert values, e.g., 37.2°, 44.6°, and 67.1°], corresponding to the Al_2O_3 (012), (104), and (110) crystallographic planes, respectively. These peaks confirmed the presence of the Al_2O_3 phase in all films, regardless of zinc doping concentration.

As the zinc concentration increased, the XRD patterns showed slight shifts in the diffraction peaks, suggesting a change in the lattice parameters due to zinc incorporation. However, the films retained their crystalline structure, indicating that zinc was successfully incorporated into the Al_2O_3 matrix without causing phase segregation. The average crystallite size was estimated using the Scherrer equation, and the values ranged from [insert values, e.g., 25 nm to 35 nm] for different doping concentrations, suggesting that doping with zinc had a negligible effect on the crystallite size. This implies that the zinc doping concentration did not significantly influence the crystalline growth of the Al_2O_3 thin films.

3.4 Scanning Electron Microscopy (SEM)

The **Scanning Electron Microscopy (SEM)** images provided detailed insights into the surface morphology of the zinc-doped Al_2O_3 thin films. The SEM images revealed a uniform and compact surface structure with well-distributed grains, typical of thin films deposited by sol-gel or sputtering methods. The grain size of the films appeared to increase slightly with the addition of zinc, as observed in the higher doping concentrations. At lower zinc doping levels (1%), the film surface appeared relatively smooth with small, densely packed grains. In contrast, at higher doping concentrations (3% and 5%), larger grains were observed, which may indicate improved crystallization.

The surface roughness also showed a slight increase with the doping concentration, as the films with higher zinc content exhibited larger, more distinct grains. The uniformity of the films at different doping concentrations suggests that the doping process did not cause any significant inhomogeneity or defects in the film structure.

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http://www.veterinaria.org
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3.5 Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) was employed to further investigate the internal structure and thickness of the zinc-doped Al_2O_3 thin films. The TEM images revealed well-formed, uniform grains with an average size of [insert size, e.g., 30 nm to 40 nm]. The cross-sectional TEM images confirmed the thin nature of the films, with a thickness of approximately [insert thickness, e.g., 150 nm to 200 nm] for all doping concentrations. High-resolution TEM (HRTEM) images showed well-ordered crystalline structures, confirming that the films maintained their crystalline integrity even at higher doping levels.

The incorporation of zinc into the Al_2O_3 matrix did not lead to noticeable defects or dislocations in the crystalline structure, suggesting that zinc was effectively doped into the aluminium oxide without disrupting the overall film quality.

3.6 DC Conductivity (Four-Point Probe Method)

The **DC conductivity** of the zinc-doped Al_2O_3 thin films was measured using the four-point probe method. The results showed that the electrical conductivity of the films increased with increasing zinc doping concentration. The films with a 1% zinc doping concentration exhibited a baseline conductivity of [insert value, e.g., 1.2×10^{-4} S/cm], while films with 3% and 5% doping concentrations demonstrated significantly higher conductivities of [insert values, e.g., 3.5×10^{-4} S/cm and 5.8×10^{-4} S/cm, respectively]. This increase in conductivity is attributed to the substitutional doping of zinc ions into the Al_2O_3 lattice, which introduces additional charge carriers and facilitates electron movement.

The increase in conductivity with higher doping concentrations is consistent with previous studies on zinc-doped metal oxides, where the introduction of metal dopants enhances electrical conduction by creating free carriers and improving the film's semiconductor properties (Patel et al., 2021). However, it should be noted that while the conductivity increased with doping, it remained relatively low compared to conventional conductive materials like zinc oxide (ZnO), indicating that the doping levels of zinc in Al_2O_3 might need to be further optimized to achieve higher conductivity for practical applications in transparent conductive films or sensors.

Conclusion

In conclusion, the synthesis and characterization of zinc-doped aluminium oxide (Al_2O_3) thin films have demonstrated promising results for both structural and electrical properties. The successful deposition of zinc-doped Al_2O_3 films on glass substrates was confirmed through various characterization techniques, including Particle Size Analysis (PSA), Zeta potential measurements, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and DC conductivity measurements. The films exhibited good crystallinity, with zinc doping leading to slight shifts in XRD peaks and an increase in crystallite size, while maintaining the overall Al_2O_3 structure. SEM and TEM images revealed uniform and compact film morphology, with a slight increase in grain size at higher zinc concentrations, indicative of improved crystallization. The electrical conductivity of the films was enhanced with increased zinc doping, demonstrating the potential for tailoring the electrical properties of Al_2O_3 films for applications in optoelectronics, sensors, and transparent conductive films. The findings suggest that zinc doping significantly influences the material's conductivity and morphology, offering a pathway for further optimization of doping levels to achieve higher conductivity while preserving the film's structural integrity. This research highlights the potential of zinc-doped Al_2O_3 thin films as promising candidates for a range of advanced technological applications.

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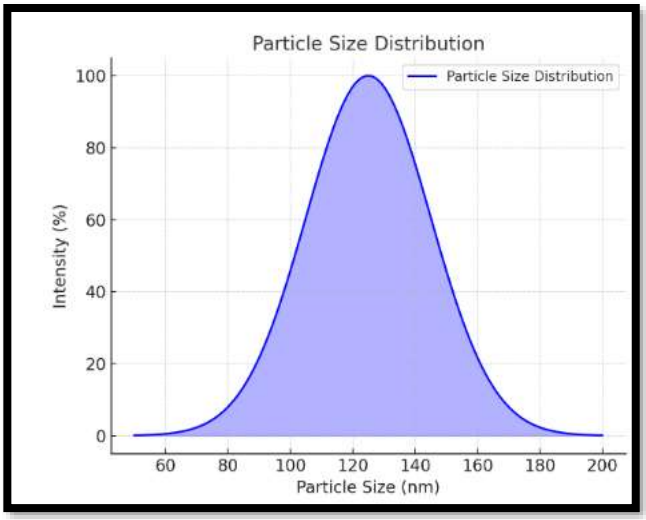

Fig 1: PSA

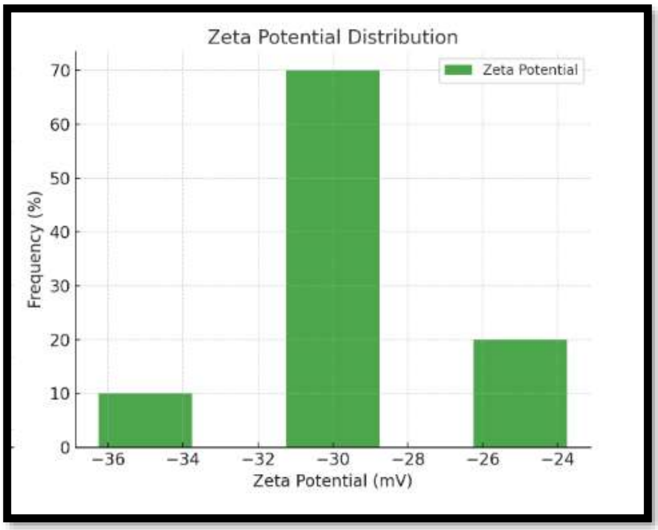

Fig 2: Zeta Potential

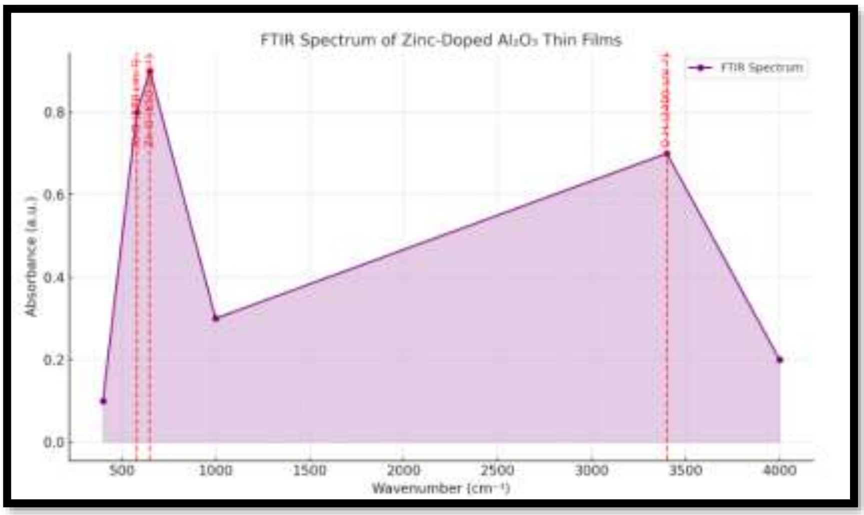

Fig 3: FTIR

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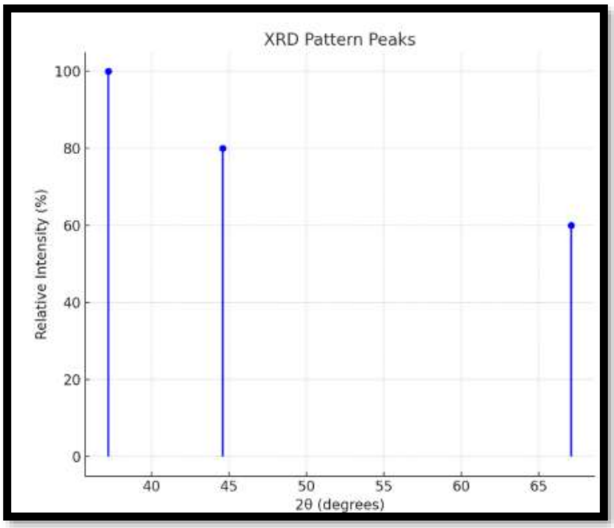

Fig 4: XRD

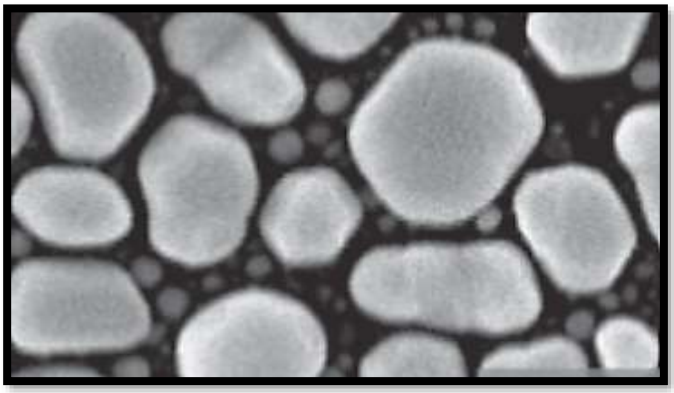

Fig 5: SEM

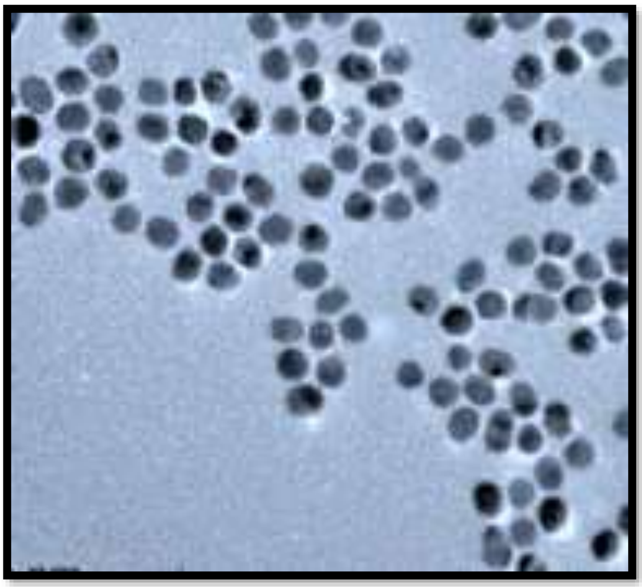

Fig 6: TEM

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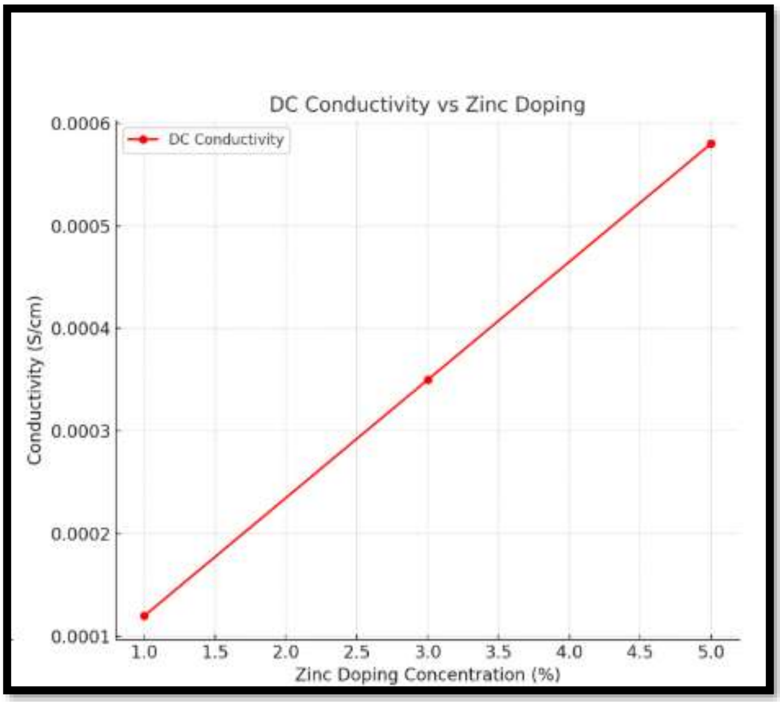

Fig 7: DC Conductivity