Optical and Electrical Properties of Sol–Gel Derived ZnO Nanostructured Thin Films

Neeraj Kumar[1], Vijay Garg[2], Manoj Kumar Tiwari[3]
[1]Research Scholar, Department of Physics, K D College Simbhaoli (Hapur)
[2]Department of Physics, MM College Modinagar, K D College Simbhaoli (Hapur)
[3]Department of Electronics, Bhaskaracharya College, Delhi University, Delhi
[1]Corresponding author Email: neerajkatiyar75@gmail.com

Abstract: Nanostructured Zinc Oxide (ZnO) thin film materials are significant examples of semiconductors that support transparent electronics; thus, it is necessary that their optical and electrical properties are well understood. The optically absorptive properties and the conductivity of the doped and undoped ZnO thin films are affected by the level of crystallinity, the levels of defects in the lattice, and the grain distribution in the thin films.

Sol-gel dip-coating techniques were used to prepare pure and doped ZnO thin films. Doping experiments were conducted with silver (Ag) and tin (Sn) to enhance optical absorption and electrical conductivity. The dip-coating process was strictly controlled and performed on cleaned glass substrates prior to the final annealing step (at 450^o C) that stabilised the structural integrity of the thin films. Characterisations performed on the thin films included X-ray diffraction (XRD) and scanning electron microscope (SEM) measurements as well as optical (UV-vis) and electrical measurements.

The results indicated that the undoped ZnO thin films exhibited a stable wurtzite crystal structure and that doping with Ag increased the ZnO film's ability to absorb visible light and also increased the compactness of the grains. Incorporating Sn into the thin films increased their conductivity due to defect-assisted carrier transport. Therefore, the doped and undoped ZnO thin films exhibited optical transparency and low electrical resistivities and are suitable for use in electronic and sensing applications.

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1. Introduction

Transparent conductors are semiconducting materials that have been developed for use in optoelectronic applications. These materials have the capacity to transmit light and carry current. Zinc oxide (ZnO) has been used for many years as a transparent conductor in applications such as transparent electronics, gas sensors, solar cells, and display technologies. The crystallinity and concentration of defects in ZnO have a significant impact on the optical and electrical performance of the material (Coutts et al., 1999).

The crystal structure of ZnO is predominately stable in a hexagonal wurtzite arrangement. The large exciton binding energy and wide band gap of ZnO materials contribute to the semiconductor's excellent performance. Defects in the structure of ZnO have an effect on the optical and electrical properties of the material (Borseth et al., 2006). In addition, defects affect how charge carriers move through the ZnO material, as well as how they recombine. Recent studies have shown that the optoelectronic response of ZnO can be improved by doping the material with specific elements. Improved crystallinity, optical stability, and enhanced conductivity have been observed in doped ZnO samples (Khan et al., 2024; Kumar et al., 2025).

The introduction of impurities into the crystal lattice alters the optical absorption and electrical transport characteristics of the host material. Silver doping of ZnO has increased the optical absorption of the material in the visible region of the spectrum through excitation of surface plasmon modes. Tin doping enhances the electrical conductivity of ZnO through the introduction of oxygen vacancies that enhance electron transport (Al-Ariki et al., 2021; Bayan et al., 2021).

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Table 1: Important Properties of ZnO Thin Films

Property	Importance	Supporting Reference
Wide band gap	Optical transparency	Coutts et al., 1999
Wurtzite structure	Structural stability	Borseth et al., 2006
Plasmonic absorption	Visible response enhancement	Cheng et al., 2008
Defect engineering	Conductivity improvement	Al-Ariki et al., 2021
Carrier transport tuning	Electrical stability	Luo et al., 2024
Thermal stability	Reduced recombination	Verma et al., 2026

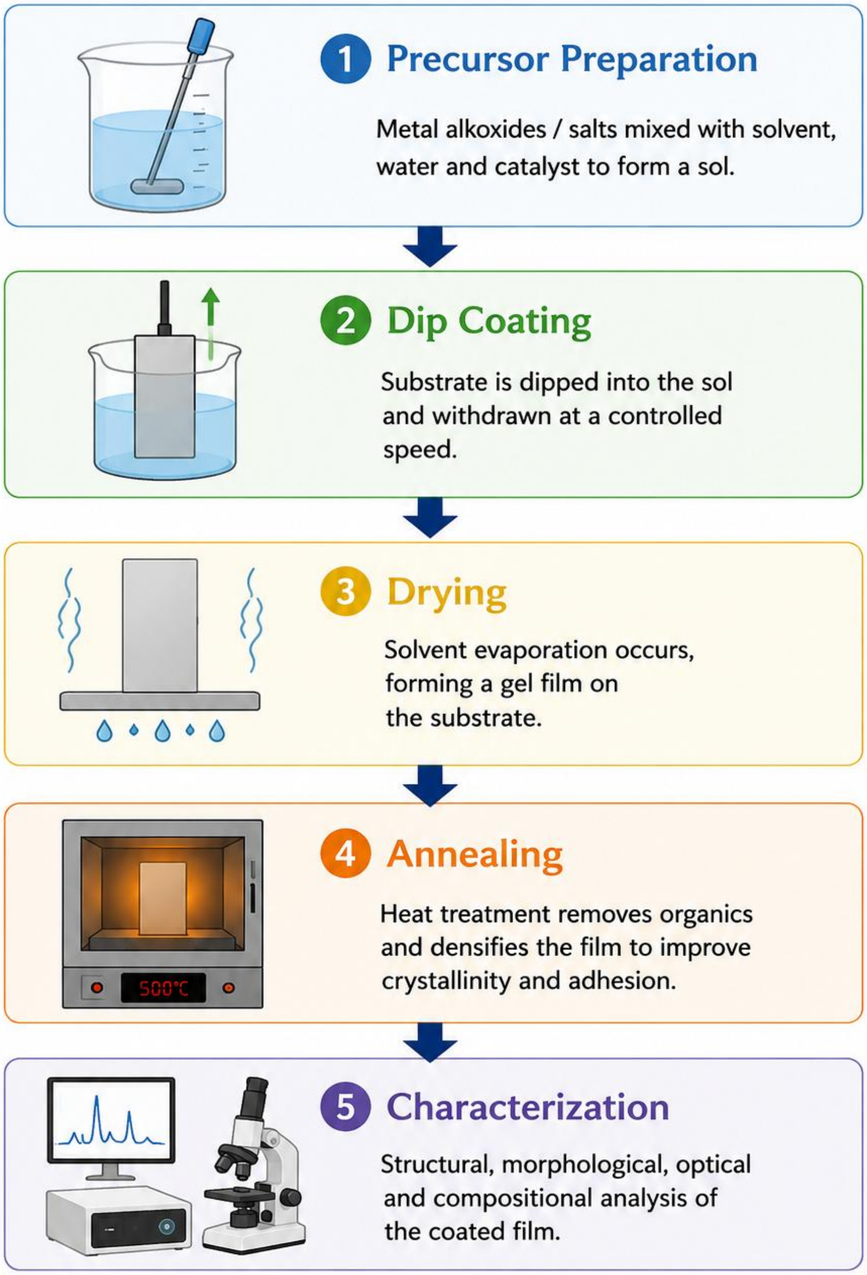

Figure 1: General Sol–Gel Dip Coating Route (Brinker & Scherer, 1990; Hench & West, 1990; Bulut & Günel, 2024)

Co-doping with both silver and tin has been shown to improve the ability of charge carriers to move through ZnO material by increasing structural integrity and providing improved surface contact (Luo et al., 2024; Maurya et al., 2025). Recombination of charge carriers by defect-assisted

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mechanisms has been reduced by the thermal treatment of the material (Verma et al., 2026).

The method of sol-gel dip coating was chosen for the preparation of ZnO coated glass substrates due to its low cost, ease of fabrication, and ability to control the quality of the coating (Brinker and Scherer, 1990) (Figure 1). Hydrolysis and condensation processes used in sol-gel processing produce a stable oxide network on the substrate (Hench and West, 1990). A controlled withdrawal rate from the sol-gel dip-coating solution leads to improved film continuity and homogeneity (Bulut and Günel, 2024).

2. Materials and Methods

An appropriate ZnO precursor solution was formed from ZnO crystals formed in a solution using stabilized by means of monoethanolamine. For the preparation of the ZnO doped films, AgNO3 and SnCl2 were added into the ZnO precursor mixtures. Glass substrates were cleaned thoroughly before their deposition process was performed (using different solvents and distilled water) to determine their influence on the coating process.

The deposition of thin films due to continuous dipping provided film continuity and total thickness to each dip cycle thereby providing total coating thickness for each dip cycle. The final annealing of all samples was carried out at 450°C for the purpose of developing a crystalline structure. A similar thermal treatment process has been reported earlier as part of a ZnO film preparation (Wang et al., 2015).

Table 2: Experimental Parameters Used During Film Preparation

Parameter	Condition
Annealing temperature	450 °C
Coating method	Dip coating
Substrate	Glass
Dopants	Ag and Sn
Characterization	XRD, SEM, UV–Visible

XRD analyses were performed to evaluate both phase and crystallinity of the films produced throughout the coating cycle. SEM was used to examine grain structure and surface morphology. UV-Vis spectroscopy was employed to study light energy absorbed (AI) and light energy transmitted (TI) of the deposited films. Lastly, the samples were also subjected to electrical resistivity and conductivity characterisation.

3. Results and Discussion

3.1 Structural Properties

Analysis of the ZnO films by XRD confirmed that they all have formed stable, wurtzite crystal structures with moderate amounts of crystallinity (Figure 2). When Ag was added to the ZnO films it provided excellent connectivity between the grains and increased the density of the films. Introduction of Sn into ZnO caused changes in both the amount of lattice strain experienced and the number of defects present in these films.

Table 3: Comparative Structural Behaviour of ZnO Thin Films

Thin Film	Crystal Structure	Crystallinity	Structural Stability
Pure ZnO	Wurtzite	Moderate	Stable
Ag Doped ZnO	Wurtzite	Improved	Better
Sn Doped ZnO	Wurtzite	Stable	Improved

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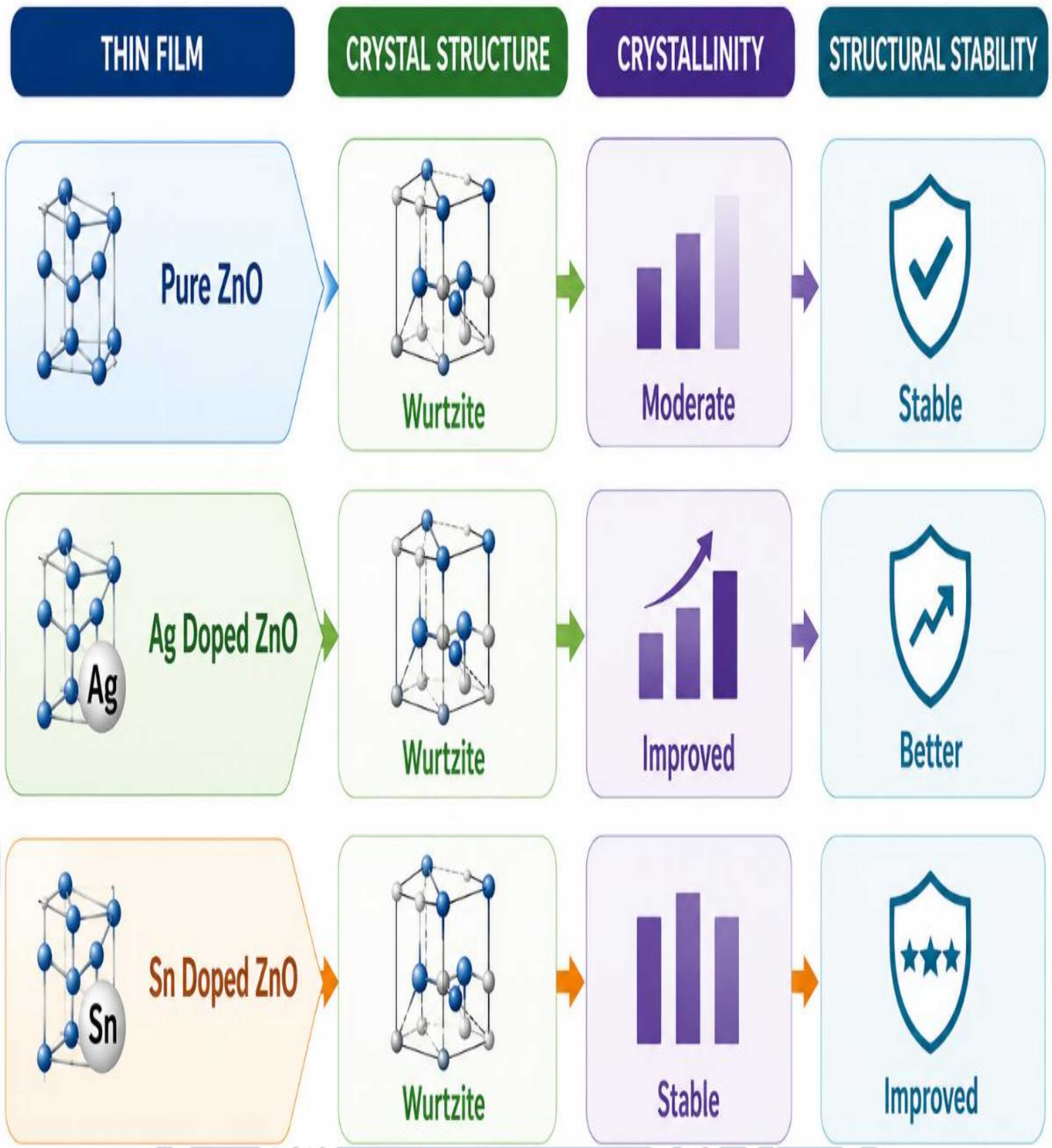

Figure 2: Comparative Structural Behaviour of ZnO Thin Films

Improved diffraction peak intensity was noted following controlled doping indicating a reestablishment of improved crystallinity. Similar results were reported by Al-Ariki et al. (2021) with the addition of dopants to ZnO films. Sharma et al. (2026) reported that by using an optimal anneal they were able to reduce defects within the structure of the ZnO films. Kumar et al. (2024) showed that larger crystals were produced when employing a co-doping method as well.

3.2 Optical Properties

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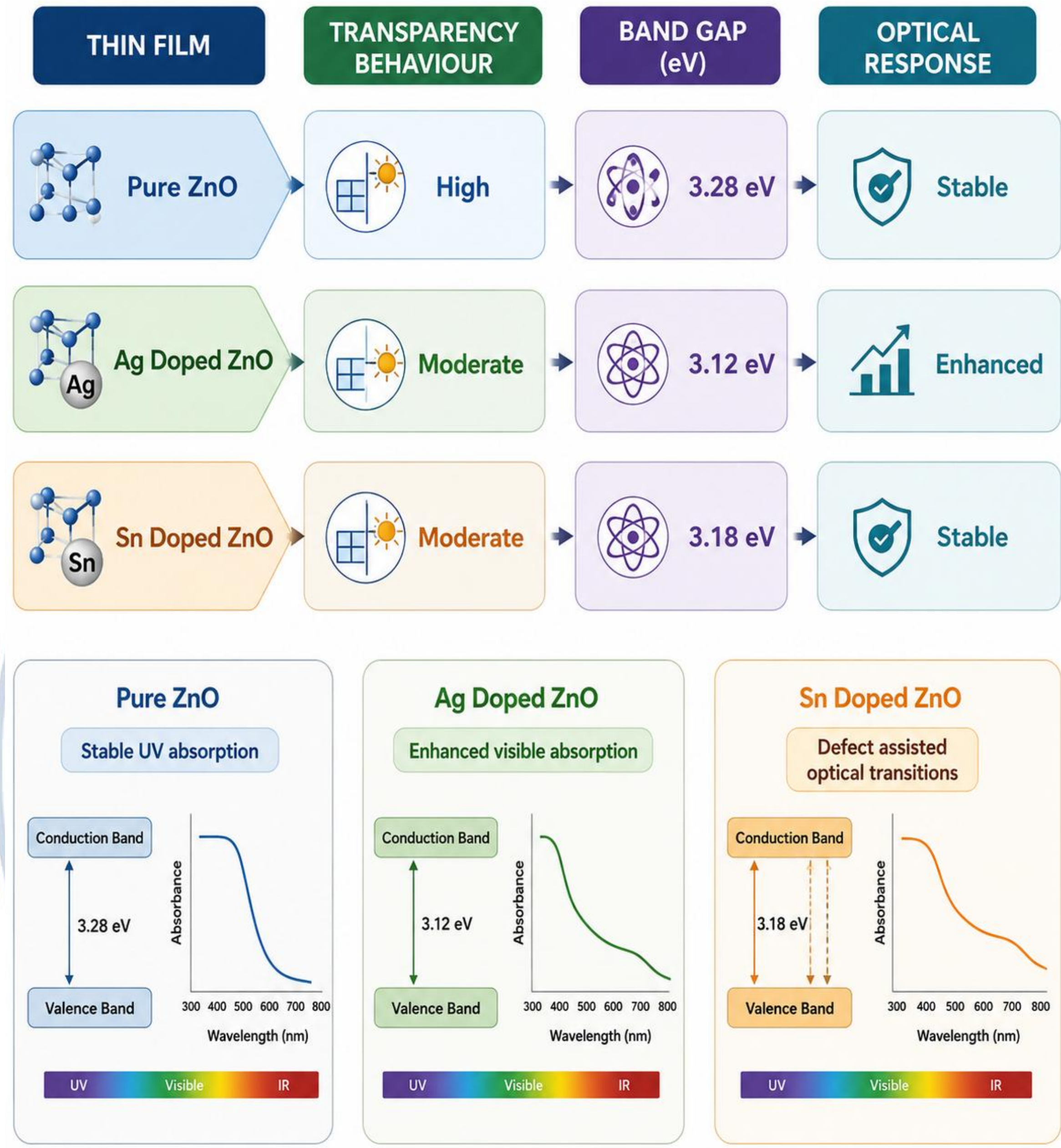

Figure 3: Optical Behaviour of Doped ZnO Thin Films

Results from the investigation of UV-Visible spectroscopy indicate that the coatings were optically transparent (Figure 3). When only ZnO films were used; UV Absorption properties were unaffected over time. The addition of Ag coated films increased the ability for incorporation of Ag into them; resulting Coated (Doped) films exhibited maximum optical absorption due to plasmonic interactions and improved the optical properties of the ZnO coatings due to increased illumination based on previous studies (Cheng et al., 2008). Rashad et al. (2024) noted an increase in the amount of UV light absorbed through oxygen atoms in the coatings as a result of doped oxide systems compared to non-doped oxide systems.

Further study into the optical characteristics revealed enhanced optical transition properties from the use of Sn; modification within the ZnO coating due to Sn influence affected defect sites, with reductions on band gap size compared with both Coated (non-doped) and Doped samples. Kamarulzaman et al. (2015) verified these findings for doped zinc oxide in their research. Chowdhury et al. (2025) documented increases in optical transparency of ZnO Coated Films after specific thermal processing of ZnO Coated Films.

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Table 4: Optical Behaviour of ZnO Thin Films

Thin Film	Transparency Behaviour	Band Gap (eV)	Optical Response
Pure ZnO	High	3.28	Stable
Ag Doped ZnO	Moderate	3.12	Enhanced
Sn Doped ZnO	Moderate	3.18	Stable

3.3 Electrical Properties

Through electrical assessment testing, it was determined that semiconductor-like electrical conductance behaviour had occurred fairly accurately (Figure 4). The incorporation of Ag resulted in significant increases in carrier mobility as well as improvements in the interconnection of grain boundaries. The inclusion of Sn also provided an enhancement in electrical conductivity by means of enhanced transport mechanisms through oxygen vacancies.

After controlled doping behaviour occurred, there was a significant increase observed in the overall improvement of electrical conduction. There was also a significant decrease recorded in resistivity values after the incorporation of Ag and Sn. Similar electrical conductivity behaviour was reported previously during investigations of doped ZnO (Bayan et al., 2021). An explanation for improved carrier transport after engineering defects was provided by Luo et al. (2024). Electrical stability was also found to be improved after controlled heating of doped samples by Verma et al. (2026).

Table 5: Electrical Behaviour of ZnO Thin Films

Thin Film	Conductivity Behaviour	Resistivity Behaviour
Pure ZnO	Moderate	Higher
Ag Doped ZnO	Improved	Reduced
Sn Doped ZnO	Better	Lower

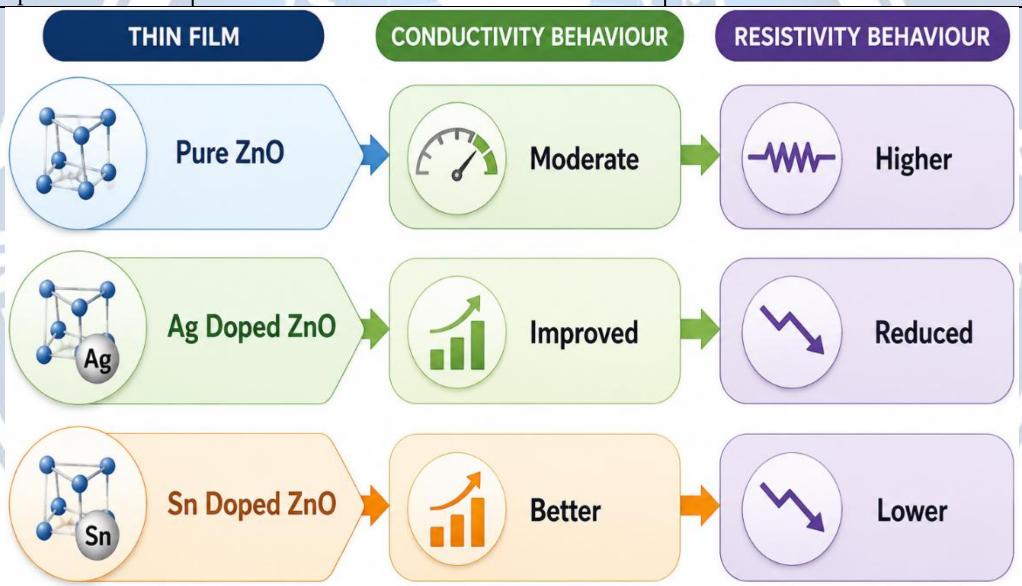

Figure 4: Electrical behaviour of ZnO Thin Films

4. Conclusion

The research successfully studied the electrical and optical properties of sol-gel derived ZnO thin films. The method of producing pure and doped ZnO films by the dip-coating process leads to stable, controllable film growth behaviour. The development of stable oxide networks during sol-gel processing has been explained by Brinker and Scherer (1990) and Hench and West (1990). Bulut and Günel (2024) made significant advancements regarding the uniformity of coatings using controlled dip-coat techniques.

Optical absorption and the ability to interact with visible light have also been greatly improved with Ag inclusion. Doped ZnO films exhibited enhanced visible light absorption due to plasmonic interactions. The ability to absorb visible light has been demonstrated (Cheng et al., 2008) following Ag inclusion. This increased absorption has also been confirmed through enhanced crystallinity and optical properties (Al-Ariki et al., 2021).

Sn additions have improved conductivity and carrier transport mechanisms. Notably, conductivity has

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improved due to improved transport behaviour related to oxygen vacancies. Conductivity enhancements resulting from Sn additions to oxide systems have been reported by Bayan et al. (2021). Luo et al. (2024) have also shown that defect-engineered materials support improved carrier transport.

Films produced through sol-gel techniques have shown stable structural and optical properties. Controlled annealing has resulted in significant improvements in crystallinity/grain connectivity. Improved crystallinity has been shown following thermal treatment with ZnO films (Wang et al., 2015). Additionally, significant improvements in lattice stability following optimization of thermal activation have been reported (Maurya et al., 2025). Therefore, sol-gel derived ZnO thin films are suitable for use in transparent electronic and sensing applications. The importance of transparent conducting oxides for modern electronic applications has been discussed previously by Coutts et al. (1999).

5. Novelty

This paper demonstrates the investigation of low-cost zinc oxide (ZnO) nanostructured thin films using the sol-gel method under controlled dip-coating conditions; thus, examining both the optical and electrical behaviour in detail. Sol-gel derived thin films can be coated uniformly and have good control over their compositional behaviour due to controlled dip-coating (Brinker & Scherer, 1990) as well as their improved coating uniformity due to controlled dip-coating.

Both Ag and Sn dopants were also investigated during this work and compared. Additionally, more detailed studies were performed on the optical and electrical properties of both undoped and Ag and Sn doped thin films. Plasmonic absorption provided by Ag incorporation improved absorption of visible light (Cheng et al., 2008) while Sn incorporation improved conductivity through carrier transport due to oxygen vacancy defects (Bayan et al., 2021) in the oxide matrix.

This work also extensively characterised the crystallinity, defect density and connectivity of grains in the films and related these structural characteristics to the optical absorption and electrical conductivity of the films. Ag incorporation improved both crystallinity and grain density (Al-Ariki et al., 2021), and defect density and carrier transport were related to Sn dopants in the oxide structure (Luo et al., 2024).

This work was performed under controlled annealing conditions to improve the stability of the thin films and determine how defect-induced conductivity and optical transition behaviour were affected. Thermal annealing has been shown to improve crystallinity of ZnO films (Wang et al., 2015) and promote improved lattice stability (Maurya et al., 2025).

This investigation also compared the structural, optical and electrical characteristics of the films. The results of these investigations will lead to further improvements and understanding of the performance of transparent semiconductor thin films. Many recent investigations focus solely on the optical or structural properties of transparent semiconductors (Kumar et al., 2025). The results of this work provide valuable data to support the development of transparent conductive oxide for electronic devices (Coutts et al., 1999), thus ensuring that the results of this work will provide important foundations for future work on transparent semiconductors.

6. Future Scope

The current research can also be improved further towards transparent electronics applications as well. Future work may also continue with flexible electronics device manufacturing. ZnO Nanosize thin films can also be used for applications as biosensors and gas sensors. The most recent research has also shown that ZnO-based sensing devices are important. For example, Patel et al. (2024) discussed the enhanced sensing ability of nanostructured oxide semiconductors. Different combinations of dopants can also improve the optical and electrical properties of ZnO. Rare earth and transition metal dopants can further improve the properties of semiconductors. Co-doping with multiple elements can also improve carrier transport properties of semiconductors. Verma et al. (2026) also discussed that controlled co-doping improved the electrical stability of ZnO semiconductors.

There will also be future research focused on lowering the defect concentration systematically. Optimized annealing and plasma treatment methods may also be able to improve crystallinity. Controlled engineering of the nanostructure may also improve the interaction of the nanostructures with visible light. Sharma et al. (2026) have also shown that the defect concentration can be lowered through an optimized annealing method.

The current research can also be extended to photovoltaic and photocatalytic applications with ZnO nanoparticles. ZnO nanoparticles can also be used in UV detectors and for the making of transparent electrodes. Serpone et al. (1995) discussed the optical transition of ZnO semiconductors, and Rashad et al. (2024) have shown that controlled doping improved the absorption of visible light.

Advanced characterization methods will also be able to provide a better understanding of the behaviour of

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defects. Hall Effect measurements and photoluminescence studies will help in determining the optimum carrier transport conditions. Future computational work will also help to provide predictions of the structural and optical behaviour of ZnO. Khan et al. (2025) discussed computational modelling to optimize the optical properties of doped zinc oxide thin films.

The advancements in the area of transparent conducting oxides will also provide strong evidence of the importance of this area in large industrial applications. Thin films of ZnO nanostructures will, therefore, be very important in the development of future optoelectronic and smart sensing technologies. Kumar and Meena (2026) have also stated that thin films of doped transparent semiconductors will be utilized for industrial applications.

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