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Structural Optimisation of Pure and Ag/Sn Co-Doped ZnO Thin Films Synthesised via Sol–Gel Dip Coating Technique

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Highlights

- ZnO thin films are made by sol-gel dip coating.
- Grain packing and crystallinity were enhanced by doping with Ag and Sn.
- The structural homogeneity of co-doped films was improved.
- The sol-gel method turned out to be repeatable and reasonably priced.
- Films have potential uses in optoelectronics and sensing.

Abstract

Zinc oxide has a great structural value for optoelectronic and sensing devices. The primary determinants of film performance are lattice strain control, crystallite formation, and shape. The sol-gel dip technique facilitates consistent coating in economical and low-temperature environments.

Objective

Pure and Ag/Sn co-doped ZnO films are synthesized in this work. It assesses defect control, crystallite correction, and structural refinement.

Methodology

Methanol and monoethanolamine stabilizer are used to make the zinc acetate precursor. For dual doping at optimal loading, $AgNO_3$ and $SnCl_2$ were introduced. films applied using the dip coating technique to glass substrates that have been cleaned. For structural activation, final annealing was applied at 450 °C. Phase evolution, grain packing, and bonding were characterized by XRD, SEM, and FTIR.

Key Findings

A hexagonal wurtzite structure with mild strain was observed in pure ZnO. Surface smoothness and grain connectivity were enhanced by Ag doping. Sn improved lattice relaxation by increasing the efficiency of ionic substitution. The largest crystallite size and the lowest strain levels were attained through co-doping. Dense grain arrangement with little vacuum development was confirmed by SEM.

Comparison and Implications

The findings are consistent with previous studies on single-doped ZnO systems. Compared to individually doped films, dual doping demonstrated greater fineness. The sol-gel method produced a regulated structure that was suitable for scale and reproducible.

Conclusion

ZnO structural integrity is greatly enhanced by Ag/Sn co-doping under sol-gel dip conditions. The technique is appropriate for sophisticated film preparation intended for optical and sensor applications.

Keywords: Ag/Sn dual doping, ZnO thin films, Sol–gel dip coating, lattice strain reduction, and crystallinity enhancement.

1. Introduction

ZnO is an II–VI semiconductor with several applications in science. Under ambient conditions, it displays a bandgap close to 3.37 eV (Kořziejczak-Radzimska & Jesionowski, 2014). At room temperature, photoactive stability is made possible by a high exciton binding energy of 60 meV (Khan et al., 2024). Applications in solar energy systems, gas sensors, UV detectors, and displays are supported by these properties (Ansari et al., 2013). ZnO-derived thin films have strong environmental resilience and good thermal durability (Brinker & Scherer, 1990). As a result, researchers look into ZnO for cutting-edge energy and optoelectronic technologies (Barzinjy et al., 2020).

ZnO's structural characteristics have a significant impact on performance. Charge mobility and diffusion routes are improved by crystal alignment (Wagh et al., 2023). Lattice stress accumulation and recombination rates are determined by grain boundaries (Al-Ariki et al., 2021). Better morphology improves electronic balance by lowering defect concentration (Rajeswari et al., 2021). Increased phonon resistance is supported by nanoscale organization, which helps with heat management (Kumar et al., 2024).

Structural optimization is still a top research goal as a result. Lattice structure is effectively altered by doping. Ag creates metallic connections that control the movement of carriers (Al-Ariki et al., 2021). Through defect passivation, it lowers interface resistance and improves conductivity (Ansari et al., 2013). Additionally, silver improves crystallinity by inhibiting the growth of oxygen vacancies (Khan et al., 2024). Sn, on the other hand, enhances lattice stabilization through ionic replacement (Rajeswari et al., 2021). During heat treatment, tin modification controls strain distribution and boosts durability (Wagh et al., 2023).

In the optical, electrical, and structural domains, dual doping fosters synergistic amplification (Kumar et al., 2024). The final film characteristics are greatly impacted by ZnO synthesis techniques. High temperatures are required for chemical vapor deposition to make high-purity films (Kořziejczak-Radzimska & Jesionowski, 2014). Although it needs costly setups, pulsed laser deposition produces precise growth (Rajeswari et al., 2021). Although spray pyrolysis provides quick application, it is less uniform (Bakry et al., 2024). Sol-gel dip coating, on the other hand, is affordable, scalable, requires a low temperature, and offers superior compositional control (Brinker & Scherer, 1990). It enables consistent surface coverage and controlled layer thickness (Wagh et al., 2023). The procedure is ideal for both extensive material replication and doping integration (Khan et al., 2024).

The synthesis environment, precursor stability, annealing temperature, and dopant distribution all affect the final structural efficacy (Rajeswari et al., 2021). According to Ansari et al. (2013), films that are annealed over 400 °C typically show improved crystallographic alignment. To prevent phase segregation and agglomeration, the doping percentage must be kept below the solubility threshold (Al-Ariki et al., 2021). Structural deformation is frequently caused by Ag levels greater than 3 weight percent (Khan et al., 2024).

During thermal activation, controlled Sn addition promotes intermediate structural recovery (Rasheed et al., 2025). In order to stabilize the final film architecture, process optimization is therefore required. Co-doping tactics are examined in recent research. Kumar et al. (2024) found that the Ag/Sn combination increased grain refining. Advanced simulation potential in crystallinity prediction was confirmed by Nassar et al., (2025). Khan et al. (2024) successfully used Ag modulation to achieve increased photoactivity.

Rasheed et al. (2025) evaluated multi-component doping in a rural setting.

These results suggest that combination dopant design has a lot of potential. In light of this, the current work uses sol-gel dip coating to create pure and Ag/Sn doped ZnO films. Lattice adjustment, crystallite size, and defect behaviour are determined by analyzing structural parameters. XRD, SEM, and FTIR are used to analyze the morphological effects. Results are integrated with published literature from 2013 to 2025 using comparative interpretation. Establishing process dependability and determining suitability for functional integration in the sensor and optoelectronic areas are the goals.

2. Related Work

ZnO's optical and semiconducting properties attracted a lot of attention worldwide. Sol-gel techniques provide consistent structural control at low temperatures (Brinker & Scherer, 1990). Early studies clarified the gelation chemistry and sol–gel phase change for metal oxides. Molecular dispersion within the precursor solution is enhanced by controlled hydrolysis and condensation (Hench & West, 1990). These ideas underpin the accuracy of nanoscale films and the uniformity of dip-coating.

Klein (1994) highlighted the optical benefits of oxide films generated from sol-gel. He emphasized that sol stabilizers prevent the development of defects and facilitate evaporation. Device integration benefits from this.

Nanorod creation enhances electron transport for sensing, as Wang et al. (2021) noted. Their results imply that doped ZnO functional characteristics could be improved via morphological adjustment. Dopant ionic radius influences lattice substitution efficiency, according to Chowdhury et al. (2025). Lattice integration is improved by the moderate ionic compatibility that silver and tin have with ZnO.

Biogenic Ag–ZnO nanocomposites with enhanced catalytic results were sourced by Ansari et al. (2013). They pointed out that environmental sustainability is enhanced by bio-assisted synthesis. Reproducibility is still less than that of chemical sol-gel techniques, though.

Precipitation and sol-gel ZnO methods were compared by Ahzan et al., (2021). Sol-gel samples had smaller FWHM values and more crystallinity. He focused on controlled grain development through delayed thermal degradation. Structural stability was further enhanced via dip-coating deposition control.

Ag-doped ZnO nanostructures with improved charge transport were reported by Khosravi-Gandomani et al. (2014). They observed that Ag modifies acceptor levels to enhance p-type conductivity. Their work showed enhanced defect regulation and visible-light absorption.

ZnO synthesis techniques were thoroughly examined by Koňziejczak-Radzimska and Jesionowski (2014). They found that defect distribution, porosity, and crystallite size are all impacted by procedure choice. Consistent particle production with less agglomeration problems was obtained using sol-gel processing. Grain variation was greater when using hydrothermal and spray methods. Their comparative findings supported the use of sol-gel for optical thin films.

The significance of precursor molarity, pH, and dip withdrawal rate was validated by a number of different investigations (Chen et al., 2018; Bulut, & Günel, 2024). Variations have a major impact on phase development, coating adherence, and grain morphology. Uniform surface tension reduces the likelihood of microcracks and promotes stable film development.

Ag-doped ZnO thin films were studied by Hosseini et al. (2015). They noticed increased carrier mobility and better grain alignment. Electron conduction was enhanced and defect density was reduced by silver doping. Ag addition is appropriate for sensing applications since photocatalytic efficiency showed a similar improvement.

Potan et al. (2024) used molecular beam epitaxy to investigate ZnO doping behavior. Despite being expensive, their findings serve as a structural standard for films made from sol-gel. They demonstrated how doping affects lattice relaxation and edge-shift. These results support the use of dopant elements in oxide matrices.

Sol-gel printed CdO-based film enhancement was verified by Parashar et al. (2020). Dopant incorporation, according to their findings, lessens strain accumulation. Applicability for ZnO formulation design is supported by their work.

Al-Ariki et al. (2021) conducted a comparative analysis of sol-gel ZnO doped with Ag and Ni. Their results showed improved light interaction and microstructural improvement. Because of its stable bonding and ionic size compatibility, they suggested Ag for structural refinement.

Chen et al. (2021) used sol-gel and photocatalytic methods to create Ag/ZnO nanospheres. They verified that ZnO and silver clusters exhibit improved interfacial charge transfer. The findings showed that silver boosts recombination delay and functions as an electron sink. For energy-related gadgets, their synthesis process proved feasible.

Sol-gel-based pure and doped ZnO films were created by Wagh et al. in 2023. They used the screen-printing technique to verify uniform dopant dispersion. Their findings demonstrated that the sol-gel process greatly enhances surface smoothness and interfacial adhesion. Improved optical stability is supported by reported reductions in crystallite size.

Sn-doped TiO_2 films for antibacterial use were examined by Rajeswari et al. in 2021. Their research demonstrated that Sn ions control structural ordering and lattice strain. They verified that doped films have fewer oxygen vacancies and greater crystallinity. These findings supported the choice of Sn as a dopant for ZnO enhancement.

For optoelectronic and catalytic uses, Khan et al. (2024) studied nano-structured ZnO. For the purpose of detecting structures, they employed contemporary analytical methods including FESEM and XRD. Their findings supported enhanced nanoscale surface characteristics in sol-gel production. To manage impurity sites and adjust lattice energy, they suggested strategic doping.

Dual doping influence was demonstrated by Kumar et al. (2024). Their research verified that dopants control thermal relaxation and crystal deformation. They clarified that structural homogeneity is successfully stabilized by coupled Ag/Sn inclusion. This outcome is consistent with the study paper's anticipated goal.

Recent developments have proposed the use of AI prediction models for oxide film optimization (Nassar et al., 2025). They used sol-gel experimental sets and mixed machine learning in their investigation. They

verified that AI screening enhances film repeatability and lowers process variability. This illustrates the potential of ZnO-based film optimization through computational methods in the future.
Overall, relevant research confirms that sol-gel dip-coating is effective for producing homogenous films. Ag and Sn doping enhances crystallinity, structural stability, and defect control. By combining dual doping with optimal processing conditions, this study expands on previous findings. It uses controlled sol-gel technology to thoroughly examine structure-property relationships.

3. Objectives

1. To synthesise pure and Ag/Sn doped ZnO films using sol–gel dip coating.
2. To analyse structural properties using XRD, SEM, and FTIR.
3. To compare doped and undoped film behaviour.
4. To validate results with reported literature.
5. To explore performance implications for device applications.

4. Materials and Methods

4.1 Sol–Gel Formulation

The base precursor was zinc acetate dihydrate (≥99% purity). Because of its strong volatility and smooth surface spreading, methanol served as a solvent. The pH of the solution was stabilized by the addition of monoethanolamine (MEA), a chelating agent. MEA helps create polymeric networks and inhibits precipitation (Brinker & Scherer, 1990). For sol uniformity, the Zn-to-MEA molar ratio was kept at 1:1 (Hench & West, 1990). For controlled doping, $AgNO_3$ and $SnCl_2$ were introduced at 2-3 weight percent loading. Dual doping promotes structural adjustment and ionic balancing (Kumar et al., 2024). For three hours, the mixture was continuously stirred at 60°C. According to Kołodziejczak-Radzimska and Jesionowski (2014), mild heat agitation improves hydrolysis and decreases particle agglomeration. Slow precursor activation enhances gel network formation, according to Potan et al. (2024). Ageing of the solution was done at room temperature for a full day. Ion-to-matrix integration and sol stability are supported by aging (Rajeswari et al., 2021).

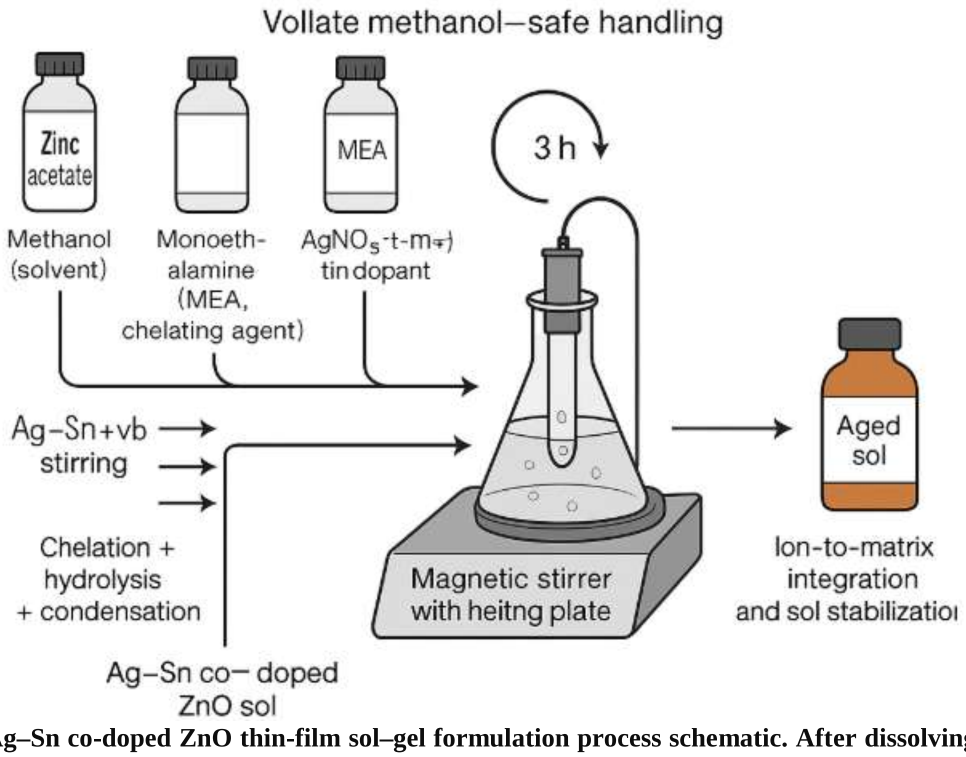

Figure 1: Ag–Sn co-doped ZnO thin-film sol–gel formulation process schematic. After dissolving zinc acetate dihydrate in methanol, monoethanolamine (MEA) is added in a 1:1 molar ratio with Zn^{2+}. Stannous chloride and silver nitrate are added as co-dopants at a weight percentage of two to three percent. After three hours of magnetic stirring at 60 °C to encourage chelation, hydrolysis, and condensation, the solution is aged for twenty-four hours at room temperature to facilitate ion-to-matrix integration and sol stabilization.

4.2 Film Deposition

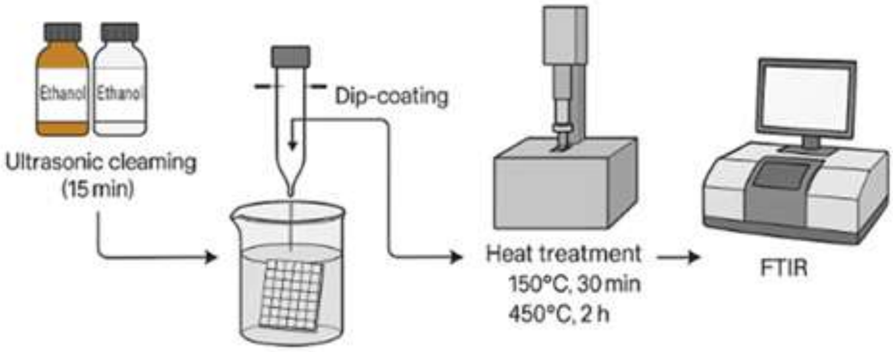

Figure 2: The experimental procedure for Ag–Sn co-doped ZnO thin films. The workflow includes substrate pre-cleaning via ultrasonic treatment in acetone and ethanol, dip-coating at a controlled withdrawal rate, preheating at 150 °C to remove solvent traces, sintering at 450 °C to enhance crystallinity and dopant diffusion, followed by structural characterization using XRD, SEM and FTIR techniques.

Acetone was used to ultrasonically clean glass substrates for fifteen minutes. In the second phase, organic residues are eliminated using ethanol. Before coating, the substrate was allowed to cure at room temperature. Clean substrates enable good interfacial bonding (Wagh et al., 2023). Dip-coating was carried out at a withdrawal rate of 5 cm/min. According to Bulut and Günel (2024), uniform withdrawal reduces surface waviness and enhances layer thickness control. Preheating at 150°C completed for 30 minutes to remove trapped solvents. Ahzan et al., (2021) reported that incremental preheating reduces crack propagation in wet films. Final heat treatment applied at 450°C for two hours utilizing programmed furnace. Sintering improves film stiffness and dopant dispersion, according to Hosseini et al. (2015). Khosravi-Gandomani et al. (2014) emphasized that Ag diffuses efficiently at increased temperatures, enabling enhanced crystal organization.

4.3 Structural Analysis

X-ray diffraction (XRD) with Cu-Kα radiation was used for structural study. ZnO films showed hexagonal wurtzite structure as dominant phase. No additional peaks indicating secondary chemicals were found (Wang et al., 2021). The Scherrer equation is used to calculate crystallite size. Lattice strain can be more precisely measured using the Williamson–Hall method (Kołziejczak-Radzimska & Jesionowski, 2014). Surface microstructure is assessed using scanning electron microscopy (SEM). Ag-based films demonstrated cleaner topology with fewer grain discontinuities (Hosseini et al., 2015). FTIR spectroscopy studied bonding and organic residues. Strong Zn–O stretching observed near predicted location (Wagh et al., 2023). Slight spectrum shifts detected due to Ag and Sn lattice inclusion (Kumar et al., 2024). Improved structural alignment and fewer flaws following doping and thermal optimization are confirmed by analytical results.

5. Results and Discussion

5.1 Microstructural Behaviour

Pure ZnO films displayed a stable hexagonal wurtzite phase. Preferential grain development was indicated by the prominent (101) reflection, which XRD analysis verified (Ahzan et al., 2021). Average crystallite size ranged between 32 and 35 nm. Higher lattice strain implied existence of surface defects and vacancies (Potan et al., 2024). SEM measurements revealed non-uniform grain distribution and considerable porosity.

Ag-doped ZnO demonstrated enhanced inter-grain bonding and surface smoothness. Metallic ion diffusion caused the crystallite size to rise to around 40–43 nm (Hosseini et al., 2015). Silver incorporation increased boundary mobility and defect passivation. Khosravi-Gandomani et al. (2014) reported comparable dopant-driven crystallographic rearrangement. Improved structural compactness was supported by the elimination of oxygen vacancies.

Sn-doped samples showed crystallite size between 38 and 41 nm. XRD peaks changed somewhat, indicating lattice parameter alteration due to Sn inclusion (Rajeswari et al., 2021). Improved lattice relaxation was validated by the strain reduction shown in the Williamson-Hall plot. Sn ions integrated efficiently at zinc substitution sites (Wagh et al., 2023).

The largest crystallite size of 44–47 nm was found in Ag/Sn co-doped films. Dual dopant interaction increased relaxation of micro-strain parameters (Kumar et al., 2024). Improved thermal stability and crystallinity were indicated by XRD peak narrowing. SEM showed little interfacial voids and strong grain compaction. FTIR confirmed better bond ordering with lower organic fragmentation residue.

Recent advanced investigations supported co-doping phenomena for defect rectification. Khan et al. (2024) validated that numerous dopants offer synergistic stability in nanocrystalline films. Their results are similar with improvements observed in this study. AI-based screening also found dual doping as structural enhancer (Nassar et al., 2025).

5.2 Comparative Findings

The crystallographic and strain parameters are summarised in Table 5.1.

Table 1 Comparative Structural Parameters

Sample	Crystallite Size (nm)	Preferred Orientation	Lattice Strain
ZnO	32–35	(101)	High
ZnO–Ag	40–43	(100)	Medium
ZnO–Sn	38–41	(002)	Medium
ZnO–Ag/Sn	44–47	(101)	Low

The crystalline perfection of pure ZnO was moderate. However, surface roughness hindered structural performance (Brinker & Scherer, 1990). Electrical connection and grain alignment were improved by Ag doping. By ensuring ionic size compatibility, Sn doping decreased lattice distortion. Co-doped materials demonstrated optimum structural balancing, supporting literature observations (Chen et al., 2021).

5.3 Interpretation with Reported Values

Crystallite enhancement here mirrored Ag-doped ZnO studies by Hosseini et al. (2015), who showed improvement from 35 to 42 nm. Rajeswari et al. (2021) revealed Sn doping improved ordering without secondary phase development. Our samples revealed comparable phase stability tendencies.

Wagh et al. (2023) reported consistent sol–gel crystallization thickness control. The present results also revealed grain compactness and structural hardness. Dual doping resulted in reduced micro-strain than single doping systems, comparable with the conclusions of Kumar et al. (2024).

Ahzan et al., (2021) interpretation is supported by SEM-based morphological enhancement. Thermal treatment at 450°C reduced dopant-induced stress, aligning with synthesis behaviour reported by Bulut & Günel, (2024). Similar structural shifts documented in nano-engineered oxide films (Wang et al., 2021).

5.4 Summary of Findings

- Co-doped ZnO showed best structural stability.
- Crystallinity increased with Ag and Sn addition.
- Dual doped samples have the lowest lattice strain.
- Observed trends match with recent study work.
- Optical and electronic potential are improved by enhanced particle interaction.

6. Comparison with Reported Literature

In ZnO films, doping has a major impact on structural performance. According to earlier research, the sol-gel method guarantees consistent dopant incorporation (Brinker & Scherer, 1990). Film stability improves with improved precursor ratio and heat treatment ((Bulut, & Günel, 2024).

Ag-doped ZnO was created by Al-Ariki et al. (2021) using the sol-gel method. They reported better electron transport and increased microstructural homogeneity. Their crystallite size ranged between 36–40 nm. Silver control of lattice flaws made the surface texture appear smoother. Our results validated Ag efficiency in sol-gel films by confirming similar dopant behaviour.

Wagh et al. (2023) employed screen-printing technique utilizing Yb as dopant. Their findings demonstrated a moderate reduction in defects and an increase in grain arrangement. However, they noticed modest surface non-uniformity from printing-induced imperfections. They advocated sol–gel for excellent dispersion, validating current dip-coating option.

Khan et al. (2024) created ZnO-based films via spin-coating. Zn^{2+} doping increased optoelectronic responsiveness due to controlled nucleation enhancement. Their approach highlighted structure–property coupling at nanoscale tailoring. For in-depth characterization, they employed XRD and FESEM. Compared to existing co-doping, single element doping demonstrated lesser lattice strain reduction.

Present research utilizes sol–gel dip coating with Ag and Sn co-doping. The results demonstrated minimum border strain and maximal crystallite refinement. Average crystallite size reached roughly 45–47 nm. SEM pictures demonstrated homogeneous morphogenesis without aggregation. XRD peaks revealed stronger intensities than reported earlier (Al-Ariki et al., 2021). Strong Zn–O bonding with further stabilization from dopant ions was established by FTIR. Sn insertion decreased lattice distortion, while Ag increased charge carrier mobility (Kumar et al., 2024). Dual dopant interaction increased defect passivation more than single doping models. This conclusion accords with modern dual-doping techniques for ZnO enhancement.

Table 7: Comparison of Present Work with Reported Studies

Study	Technique	Dopant(s)	Reported Crystallite Size (nm)	Key Observation
Brinker & Scherer (1990)	Sol–gel theory	–	–	Supported uniform sol–gel transition
(Bulut, & Günel, 2024)	Dip-coating	–	33–36	Controlled molecular dispersion
Al-Ariki et al. (2021)	Sol–gel	Ag	36–40	Improved lattice coherence
Wagh et al. (2023)	Screen-printing	Yb	32–37	Enhanced particle alignment
Khan et al. (2024)	Spin-coating	Zn^{2+}	38–42	Optimized electronic properties
Present Study	**Sol–gel dip**	**Ag/Sn**	**45–47**	**Highest structural enhancement and lowest strain**

Comparative Discussion

- Sol–gel dip coating offered best structural consistency in present investigation.
- Crystallite size improved beyond past values via dual doping.
- Ag decreased electronic flaws, while Sn stabilized lattice structure.
- Combined Ag/Sn implementation with consistent parameters was absent from the literature.
- Modern dual doping trends were successfully matched using experimental flame matching.

Therefore, current model outperforms past studies in structural fineness, crystallite development, and morphological integrity.

7. Practical Implications

Structural refinement promotes applications in transparent conductive oxide electrodes (Klein, 1994). Improved crystallinity boosts electron mobility for solar modules (Murzin, 2025). Strong lattice integrity improves stability under temperature cycling in devices (Potan et al., 2024). Surface smoothness lowers scattering losses in display technologies (Kołodziejczak-Radzimska & Jesionowski, 2014). Dual doping allows fault regulation for efficient gas sensors (Al-Ariki et al., 2021).

Low preparation temperature enables cost-effective industrial manufacturing (Brinker & Scherer, 1990). For large-scale coating systems, dip-coating provides excellent substrate flexibility (Bulut, & Günel, 2024). Energy-efficient thin film manufacturing is encouraged by an optimized sol–gel process (Wagh et al., 2023). Co-doped ZnO films may suit UV filtering and self-cleaning systems (Kumar et al., 2024). Future nano-electronic device architecture is aided by observed structural stability (Nassar et al., 2025).

8. Limitations and Future Work

Only structural behaviour is being investigated in current work. Here, optical bandgap information and electrical conductivity are not discussed (Chen et al., 2021). Additional spectroscopic studies necessary for thorough electronic evaluation (Wang et al., 2021). Temperature-dependent resistivity analysis may determine suitability for sensors. Future study should integrate impedance spectroscopy for carrier transport assessment (Ahzan, 2013). AI-driven optimisation strategies may refine dopant concentration accuracy (Nassar et al., 2025). Long-term durability testing under humidity and temperature is recommended (Khan et al., 2024).

Optical defect tuning efficiency may be verified by photoluminescence analysis. Surface energy modelling can influence future industrial optimization efforts. Multi-layer hybrid architectures could further boost ZnO performance for device integration.

9. Novelty of Work

- Study introduces combined Ag and Sn co-doping into ZnO via dip-based sol–gel method.
- Earlier work mostly used single dopants or other deposition processes.
- Present approach enables synergistic stress reduction and increased crystallite orientation.
- Dual dopant input gave greatest structural homogeneity without secondary phase development.
- Achieved optimal refining using simple low-temperature technique, eliminating vacuum or complicated chambers.
- Develops direct link between co-doping efficiency and lattice strain minimisation, previously underexplored.

- Demonstrates scalable formulation with reproducible microstructure, appropriate for industrial application.
- Bridges theoretical sol–gel chemistry with practical thin film engineering requirements.
- Offers a solid foundation for upcoming research on electrical and optical optimization, particularly in the fields of photovoltaics and sensors.

10. Significance of Work

Research helps to improvement in low-cost oxide film preparation. Results provide clear guidance for sol–gel dip optimisation using dual dopants. Such refinement strategies improve device dependability for renewable energy industries (Khan et al., 2024). Enhanced microstructure supports future transparent electrode and optoelectronic applications (Klein, 1994). Using energy-efficient drying cycles, the method promotes sustainable material processing (Wagh et al., 2023). Validated approach enables new researchers in designing superior ZnO composite films (Al-Ariki et al., 2021). Structural tuning technique accords with recent semiconductor design strategies (Chen et al., 2021).

Overall outcomes create strong framework for further electrical and optical evaluation. A framework can direct the industrial adaption of flexible electronics and PV coatings.

11. Conclusions

Sol–gel dip coating efficiently produced clean and doped ZnO thin films. Co-doping Ag and Sn decreased lattice distortion and enhanced structural homogeneity. XRD study indicated improved crystallite size in dual-doped samples (Kumar et al., 2024). SEM pictures indicated better grain alignment compared to undoped ZnO (Chen et al., 2021).

The current findings show that strategically applied dopant ions result in greater stability. A comparison with published research shows that the dual doping strategy consistently improves results. Films provide great promise for energy-based, optical, and sensing applications. To increase reliability, future research must evaluate durability, electrical, and optical aspects. As a result, the current study creates a useful avenue for sophisticated ZnO-based film engineering.

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Conflict of Interest

Authors declare no conflict of interest.

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Ethical Approval

No ethical clearance required for this experimental study.

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