

Zn-doped SnO₂ nanoparticles: structural, optical, and electrical properties for optoelectronic applications

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Zn-doped SnO₂ nanoparticles were synthesized using the sol-gel method, employing tin chloride pentahydrate (SnCl₄·5H₂O) and zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O) as precursors, with a 5% Zn-to-Sn molar ratio. Acetic acid was used as a stabilizing agent, and the obtained gel was thermally treated at 400 °C to yield Zn-doped SnO₂ nanoparticles. X-ray diffraction (XRD) analysis confirmed the tetragonal rutile phase of SnO₂, with slight lattice distortion attributed to Zn incorporation and the associated formation of oxygen vacancies. Fourier transform infrared (FTIR) spectroscopy verified the presence of Zn-O and Sn-O bonding. UV-Vis spectroscopy revealed a red-shift in the absorption edge and a bandgap of 3.50 eV, indicating slight bandgap narrowing due to defect-induced states. Photoluminescence (PL) studies showed both near band-edge and defect-related emissions, confirming the presence of oxygen vacancy related states. The I-V characteristics exhibited linear (Ohmic) behavior at low bias and nonlinear behavior at higher bias, consistent with space-charge-limited conduction (SCLC). The combined structural, optical, and electrical results indicate that Zn doping effectively modifies the electronic structure and defect landscape of SnO₂ nanoparticles, suggesting potential for optoelectronic and photocatalytic applications.

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1. Introduction

Zn-doped SnO₂ nanoparticles are promising materials that have garnered significant attention due to its ability to enhance the properties of Tin oxide (SnO₂) in various applications [1-2]. The fundamental challenge with SnO₂ is its wide bandgap, which limits its ability to absorb visible light and restricts its photocatalytic and optoelectronic applications. Zn doping serves as an effective method for narrowing the bandgap and promoting the generation of charge carriers. The incorporation of Zn²⁺ ions into the SnO₂ lattice leads to the formation of donor levels, improving the material's conductivity and electronic properties, which is crucial for applications like gas sensors and transparent conductive films.

Zn doping creates lattice defects facilitating electron-hole separation and enhancing photocatalysis. These induced surface defects also play a pivotal role in enhancing surface reactivity, a key factor in improving gas-sensing performance. Enhanced charge transfer enables Zn-doped SnO₂ nanoparticles to exhibit improved gas sensing response (NO₂, CO, NH₃) [3].

The synthesis of Zn-doped SnO₂ nanoparticles through the sol-gel method provides high control over the composition, morphology and crystallinity of the material. The sol-gel process ensures uniform Zn doping within the SnO₂ lattice, which optimizes the crystalline structure and optical properties. The improved crystallinity and surface area resulting from Zn doping significantly enhance the material's photocatalytic degradation efficiency and gas

sensing capabilities [4]. Furthermore, Zn doping induces a narrower bandgap, allowing Zn-doped SnO₂ nanoparticles to absorb more visible light and exhibit better photocatalytic performance than undoped SnO₂ [5].

In terms of gas-sensing, Zn-doped SnO₂ nanoparticles exhibit enhanced sensitivity, selectivity and stability compared to pure SnO₂. The increased active sites and adsorption capacity of Zn-doped SnO₂ allow it to detect gases at lower concentrations, enhancing its application in environmental monitoring and industrial safety. The surface reactivity of Zn-doped SnO₂ nanoparticles plays a crucial role in improving sensor response time and reliability [6].

Beyond photocatalysis and gas sensing, Zn-doped SnO₂ nanoparticles are also being explored for use in transparent conductive oxide applications, where its ability to reduce charge recombination and improve charge transport makes it a potential candidate for transparent conductive electrodes. The improved conductivity and optical properties of Zn-doped SnO₂ can lead to support suitability for transparent conductive oxide [7].

Researchers have studied Zn-doped SnO₂ nanoparticles extensively, but few have fully examined how specific synthesis choices especially a 5% zinc doping level affect the link between structure and electronic properties, along with optical performance. Most existing work focuses on general synthesis methods and overlooks how lattice distortions, defects, and carrier behavior interact, which matters for specialized optoelectronic uses. This study fills that gap by detailing the structural, optical, and electrical properties of Zn-doped SnO₂ nanoparticles made via sol-gel

synthesis and calcined at 400°C. Using XRD structural analysis, UV-Vis bandgap measurement, and I-V characterization, we explain the physical reasons behind the performance gains and compare our results with recent studies to highlight the material's promise for gas sensing and optoelectronic devices.

2. Synthesis of the Zn-doped SnO₂ nanoparticles

Zn-doped SnO₂ nanoparticles were synthesized using the sol-gel method [8-10], a versatile and effective approach that offers precise control over doping concentration, particle size, and morphology. The sol-gel synthesis method employed in this study ensures good reproducibility due to controlled precursor chemistry and processing conditions. Key parameters such as precursor concentration, pH, temperature, and aging time were carefully maintained constant across all synthesis batches to ensure uniform Zn incorporation and consistent structural properties.

The synthesis begins by dissolving tin chloride pentahydrate (SnCl₄·5H₂O) in ethanol to prepare the precursor solution. Zinc nitrate (Zn(NO₃)₂·6H₂O) is added as the dopant source, with a molar ratio of 5% Zn relative to Sn to achieve the desired doping level. A stabilizing agent, such as acetic acid or citric acid, is introduced to control hydrolysis and maintain solution stability.

The mixture is continuously stirred for several hours and heated to 70-80 °C to promote hydrolysis and polycondensation reactions, leading to the formation of a homogeneous gel. The obtained gel is then dried at 100-120 °C to remove residual solvent and moisture, resulting in a solid xerogel.

The xerogel is subsequently calcined at 400°C for 4 hours to induce crystallization and obtain Zn-doped SnO₂ nanoparticles. This calcination step plays a crucial role in enhancing crystallinity and removing organic residues while preserving the doped SnO₂ phase. After calcination, the product is cooled to room temperature and stored in a desiccator to prevent moisture absorption and maintain material stability for further characterization.

3. Characterization methods

The synthesized Zn-doped SnO₂ nanoparticles were characterized using various analytical techniques. The structural properties were determined by XRD using a Rigaku Mini Flex 600 desktop diffractometer, operating with CuK α radiation ($\lambda = 1.5406 \text{ \AA}$). FTIR spectroscopy was employed to identify functional groups in the wavenumber range of 400-4000 cm⁻¹, performed on a

Perkin Elmer Spectrum II with a spectral resolution of 0.5 cm⁻¹ and a wavelength accuracy of 0.1 cm⁻¹ at 3000 cm⁻¹. Optical properties and the energy band gap were evaluated using UV-Vis spectroscopy with a Perkin Elmer Lambda 950 spectrophotometer, offering a wavelength accuracy of $\pm 0.08 \text{ nm}$ across the 200-800 nm range. PL studies were conducted using a Horiba Jobin Yvon spectrometer, with a 325 nm He-Cd laser serving as the excitation source.

4. Results and discussions

4.1. Structural analysis

The XRD pattern of Zn-doped SnO₂ nanoparticles, shown in Fig. 1, provides detailed insight into the structural characteristics of the synthesized material. The major diffraction peaks are indexed to the (110), (101), (200), and (211) planes, corresponding to the tetragonal rutile phase of SnO₂ (JCPDS card No. 41-1445), confirming that the original crystal structure is retained after Zn doping. The absence of any distinct diffraction peaks corresponding to ZnO (JCPDS card No. 36-1451) or other secondary phases indicates that Zn is predominantly incorporated into the SnO₂ lattice without forming a separate crystalline phase within the detection limit of XRD. The high intensity and sharpness of the diffraction peaks further confirm the good crystallinity of the nanoparticles, even at the relatively low calcination temperature of 400 °C.

A slight shift in the diffraction peaks toward lower 2θ values is observed compared to pristine SnO₂, which can be attributed to lattice expansion caused by the substitution of Sn⁴⁺ ions (0.69 Å) with slightly larger Zn²⁺ ions (0.74 Å). This substitution induces local lattice distortion and strain within the crystal structure. Furthermore, the replacement of higher-valence Sn⁴⁺ ions with lower-valence Zn²⁺ ions introduces charge imbalance, which is typically compensated by the formation of oxygen vacancies or interstitial defects. These observations collectively provide strong evidence for substitutional doping of Zn into the SnO₂ lattice rather than phase segregation [11].

Very weak additional features observed in the diffraction pattern may be attributed to minor surface segregation or trace residual species arising from the sol-gel synthesis and the relatively low calcination temperature. However, their negligible intensity confirms that the bulk structure remains phase-pure and is dominated by the SnO₂ lattice. Such minor surface effects are not expected to significantly influence the bulk structural properties but may contribute to enhanced surface reactivity, which is beneficial for catalytic and sensing applications.

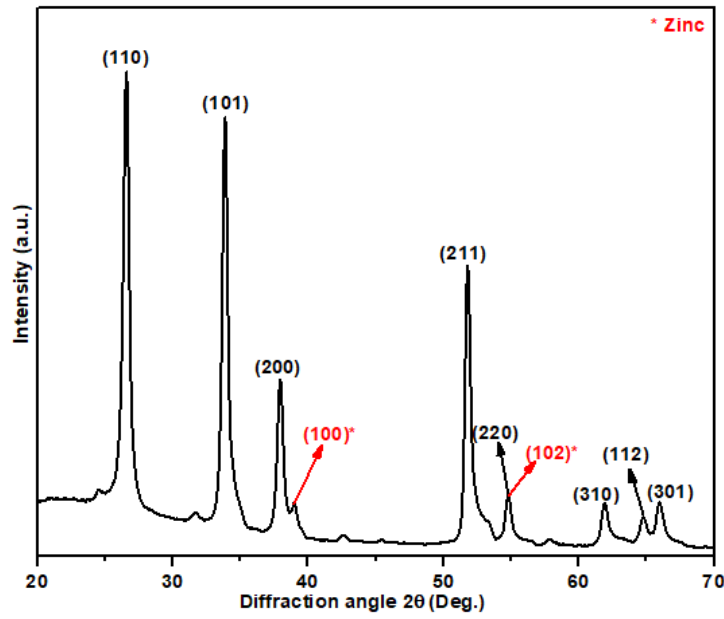


Fig. 1. XRD pattern Zn-doped SnO₂ nanoparticles confirms rutile SnO₂ phase with Zn-induced peak shifts (colour online)

The crystallite size has been determined from the XRD data using Scherer's formula,

$$D = \frac{k\lambda}{\beta \cos\theta} \text{ (nm)}$$

The dislocation density (δ) is calculated using the following equation.

$$\delta = \frac{15\beta \cos\theta}{4\alpha D} \text{ lines / m}^2$$

Micro strain (ϵ) is calculated using,

$$\epsilon = \frac{\beta}{4\cos\theta}$$

The relationship between the stacking fault probability (α) and the peak shifts (β) is described by the following expression.

$$\alpha = \left[\frac{2\pi^2}{45(3\tan\theta)^2} \right] \beta (\text{\AA})$$

Table 1. Structural parameters of Zn-doped SnO₂ nanoparticles

Planes	Crystalline Size (nm)	Dislocation Density (10^{15} lines/m ²)	Stacking Fault Probability ($\text{\AA}$)	Elastic Strain
110	14.03	8.4968	0.0055	0.0112
101	17.19	5.6599	0.0040	0.0072
200	19.06	4.6030	0.0035	0.0058
211	20.42	4.0092	0.0029	0.0041

The structural parameters of Zn-doped SnO₂ nanoparticles, presented in Table 1, provide an in-depth understanding of the crystallographic and microstructural effects induced by zinc incorporation. The analysis spans key parameters such as crystalline size, dislocation density, stacking fault probability and elastic strain, offering insights into the structural and mechanical behaviour of the material.

The crystallite size of Zn-doped SnO₂ nanoparticles varies from 14.03 nm for the (110) plane to 20.42 nm for the (211) plane, indicating anisotropic crystal growth influenced by Zn doping. The smaller crystallite size along the (110) plane suggests a higher degree of lattice distortion and defect incorporation, whereas larger crystallites in higher-index planes indicate relatively reduced strain and more stable crystal growth.

The dislocation density decreases from 8.4968×10^{15} lines/m² for the (110) plane to 4.0092×10^{15} lines/m² for the (211) plane, confirming that smaller crystallites possess a higher density of lattice imperfections. These defects introduce localized energy states within the bandgap and play a significant role in modifying the electronic and optical properties of the material.

Similarly, the microstrain decreases from 0.0112 for the (110) plane to 0.0041 for the (211) plane, indicating relaxation of lattice distortion along different crystallographic directions. The induced strain and defect states contribute to band structure modification through defect-induced energy levels and band tailing effects.

The observed variation in crystallite size across different crystallographic planes indicates anisotropic crystal growth influenced by Zn doping. This anisotropy can affect charge transport by creating direction-dependent pathways for carrier mobility. Smaller crystallites with higher defect density enhance surface reactivity, which is beneficial for catalytic and sensing applications, whereas larger crystallites with reduced defects facilitate improved

charge transport. Thus, the balance between crystallite size and defect density plays a crucial role in determining the overall functional performance of Zn-doped SnO₂ nanoparticles.

Overall, the combined influence of crystallite size, defect density, and lattice strain governs the functional properties of Zn-doped SnO₂ nanoparticles. The increased defect density and reduced crystallite size enhance the surface-to-volume ratio, providing more active sites for catalytic and sensing applications, while controlled defect states facilitate improved charge separation. These results confirm that Zn doping effectively tailors the structural properties of SnO₂ while maintaining phase purity, making Zn-doped SnO₂ nanoparticles promising for optoelectronic and photocatalytic applications.

4.2. Fourier Transform Infrared Spectroscopy

The FTIR spectrum of Zn-doped SnO₂ nanoparticles (Fig. 2) provides insight into both the intrinsic lattice vibrations and surface chemical features of the material. The spectrum can be broadly divided into two regions: (i) low wavenumber region (<1000 cm⁻¹), corresponding to intrinsic metal-oxygen vibrations, and (ii) high wavenumber region (>1000 cm⁻¹), mainly associated with surface-adsorbed species and residual functional groups.

In the low wavenumber region, the strong absorption band observed at 659 cm⁻¹ is attributed to the characteristic stretching vibrations of Sn-O and Zn-O bonds, confirming the formation of the Zn-doped SnO₂ lattice. These intrinsic vibrational modes validate the structural integrity of the oxide framework and support the successful incorporation of Zn into the SnO₂ matrix [12].

In contrast, the higher wavenumber region is dominated by features related to surface adsorbates and residual species. The broad band at 3536 cm⁻¹ corresponds to O-H stretching vibrations, indicating the presence of surface hydroxyl groups and adsorbed moisture, which are commonly observed in nanostructured metal oxides due to their high surface area. The peak at 2925 cm⁻¹ is assigned to C-H stretching vibrations, likely arising from trace organic residues from the sol-gel synthesis process.

Additional peaks observed at 2289 cm⁻¹ and 2163 cm⁻¹ can be attributed to adsorbed CO₂ or carbonate-related species and weakly bound carbonyl groups, respectively. These features originate from the interaction of the nanoparticle surface with atmospheric species rather than intrinsic lattice vibrations. Similarly, weaker bands around 2539 cm⁻¹ and 1825 cm⁻¹ may be associated with minor surface-bound impurities or carbonyl species.

The peaks at 1525 cm⁻¹ and 1285 cm⁻¹ are assigned to bending and stretching modes of surface-associated species, which may include contributions from metal-oxygen interactions as well as residual functional groups. However, these features are secondary compared to the dominant lattice vibration observed in the lower wavenumber region.

Overall, the FTIR results confirm the successful formation of Zn-doped SnO₂ nanoparticles, with the intrinsic Sn-O and Zn-O vibrations clearly distinguished from surface-related adsorbates. The presence of hydroxyl and carbonate species reflects the active surface chemistry of the nanoparticles, which can be advantageous for applications such as gas sensing and photocatalysis.

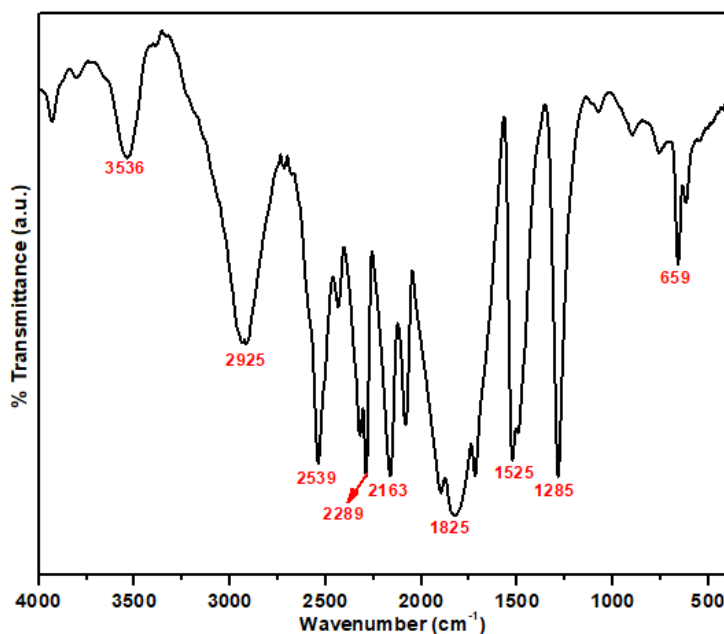


Fig. 2. FTIR spectrum of Zn-doped SnO₂ nanoparticles showing characteristic Zn-O/Sn-O vibrations (colour online)

4.3. Optical properties

The UV-Vis absorption spectrum of Zn-doped SnO₂ nanoparticles (Fig. 3) reveals the influence of Zn incorporation on the optical properties of the material. A prominent absorption peak is observed at 336 nm, corresponding to high-energy electronic transitions from the valence band to the conduction band. The optical bandgap of Zn-doped SnO₂ nanoparticles was determined using the Tauc relation for a direct allowed transition:

$$(\alpha h\nu)^2 = A(h\nu - E_g)$$

where α is the absorption coefficient, $h\nu$ is the photon energy, A is a constant, and E_g represents the optical bandgap energy. The bandgap value was obtained by extrapolating the linear portion of the plot of $(\alpha h\nu)^2$ versus $h\nu$ to the energy axis, as shown in Fig. 4. The absorption edge is identified at 362 nm, corresponding to a photon energy of 3.50 eV, which represents the direct optical bandgap of the synthesized nanoparticles.

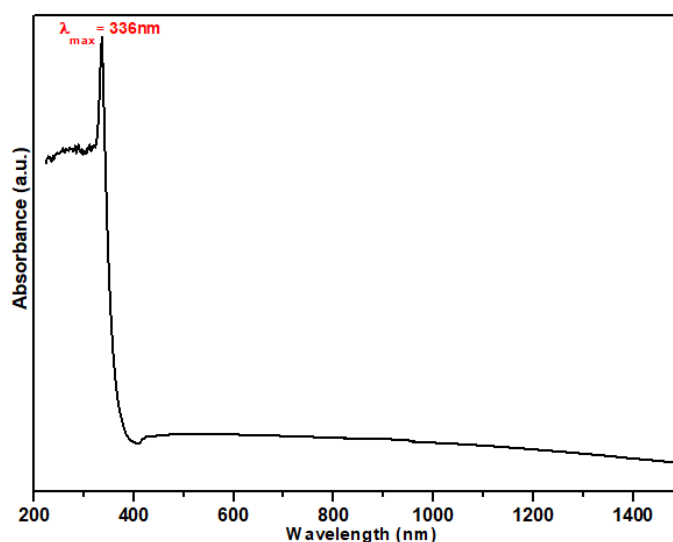


Fig. 3. UV-Vis absorption spectrum of Zn-doped SnO₂ nanoparticles exhibiting bandgap narrowing (colour online)

Table 2 compares the bandgap values of Zn-doped SnO₂ nanoparticles with previously reported studies, showing good agreement with the trend of gradual bandgap reduction with increasing Zn concentration.

Table 2. Comparison of bandgap values of Zn-doped SnO₂ nanoparticles

Sample	Synthesis Method	Zn Doping (%)	Bandgap (eV)	Reference
Pure SnO ₂	Sol-gel	0	3.6	[13]
Zn:SnO ₂	Hydrothermal	3	3.55	[14]
Zn:SnO ₂	Sol-gel	5	3.50	This work
Zn:SnO ₂	Co-precipitation	7	3.45	[15]

The obtained bandgap value (3.50 eV) shows a slight reduction compared to pristine SnO₂ (3.60 eV), indicating bandgap narrowing upon Zn doping. This shift in the absorption edge from 344 nm to 362 nm suggests an extension of absorption toward longer wavelengths within the near-UV region. Although the reduction is modest (~0.10 eV), such tuning is significant in wide bandgap semiconductors, as it enhances photon absorption and improves photo-response.

The observed bandgap narrowing can be attributed to structural and electronic modifications induced by Zn²⁺ substitution. As confirmed by XRD analysis, Zn²⁺ ions (0.74 Å), having a slightly larger ionic radius than Sn⁴⁺ ions (0.69 Å), introduce lattice expansion, strain, and defect states such as oxygen vacancies. These defect states create localized energy levels within the bandgap, effectively reducing the energy required for electronic transitions. This mechanism is consistent with defect-induced bandgap narrowing rather than Moss-Burstein-type band filling, which typically results in bandgap widening.

The combined structural and optical results indicate that Zn doping effectively modifies the electronic structure of SnO₂ while preserving its tetragonal rutile phase. The moderate bandgap reduction and extended absorption in the near-UV region suggest that Zn-doped SnO₂ nanoparticles are promising for applications such as transparent conductive oxides (TCOs) and photocatalysis, where controlled optical absorption and high transparency are essential.

These results establish a clear structure-property relationship between doping-induced defects and optical behaviour. However, further studies, including Hall effect measurements and X-ray photoelectron spectroscopy (XPS), are required to quantitatively evaluate carrier concentration and band structure modifications.

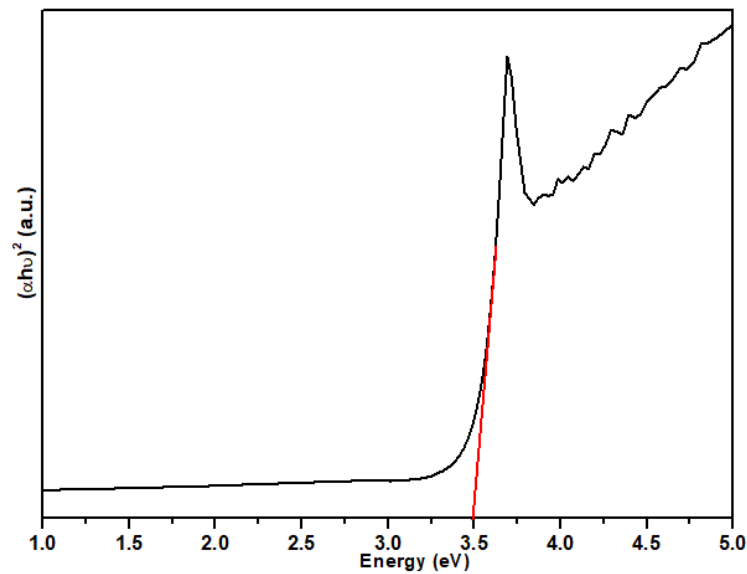


Fig. 4. Tauc plot of Zn-doped SnO₂ nanoparticles confirming direct bandgap nature (colour online)

4.4. Photoluminescence studies

The PL spectrum of Zn-doped SnO₂ nanoparticles (Fig. 5) provides valuable insight into the electronic structure and defect states of the material. The spectrum exhibits multiple emission peaks at 329 nm, 352 nm, 367 nm, 378 nm, 413 nm, 428 nm, 463 nm, and 469 nm, corresponding to different radiative recombination processes within the material.

The emission peaks in the UV region (329–378 nm) are attributed to near band-edge (NBE) emissions, arising from the recombination of electrons in the conduction band with

holes in the valence band. These transitions reflect the intrinsic electronic structure of Zn-doped SnO₂ and confirm the presence of allowed optical transitions.

The visible emission peaks at 413 nm, 428 nm, 463 nm, and 469 nm are associated with defect-related transitions, primarily originating from oxygen vacancies and Zn-induced defect states within the bandgap. These defects introduce localized energy levels that act as trapping centers for charge carriers. The recombination of electrons and holes via these defect states gives rise to the observed visible emissions.

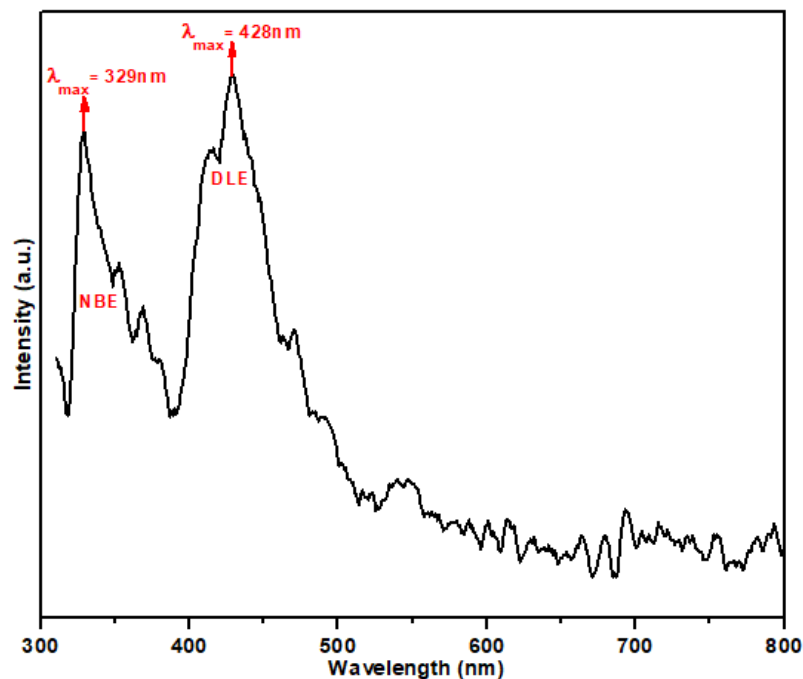


Fig. 5. PL spectrum of Zn-doped SnO₂ nanoparticles showing defect-related emissions (colour online)

The presence of these defect states indicates that Zn doping modifies the lattice structure by introducing strain and oxygen vacancies, consistent with XRD analysis. While oxygen vacancies play a significant role in enhancing conductivity and photocatalytic activity by facilitating charge separation, an excessive concentration of such defects can act as recombination centres, leading to increased carrier losses and reduced material stability. Therefore, maintaining an optimal defect concentration is essential to balance performance and stability in Zn-doped SnO₂ nanoparticles.

The appearance of emissions at longer wavelengths (>470 nm) suggests the presence of deep-level trap states, which are typically associated with more complex defect structures. These deep traps can prolong carrier lifetime but may also increase non-radiative recombination pathways if present in excess.

Overall, the PL results indicate that Zn doping introduces a controlled level of defects in SnO₂, which plays a crucial role in tuning the charge carrier dynamics. Such

controlled defect engineering is particularly beneficial for photocatalytic applications, while careful optimization is required to maintain efficient performance in optoelectronic devices [16].

4.5. I-V characteristics

Fig. 6 shows the current-voltage (I-V) characteristics of Zn-doped SnO₂ nanoparticle deposits. The measured current density increases with applied voltage, reaching a maximum value of 2.68×10^{-4} mA/cm² at an applied voltage of 0.449 V.

At low applied bias (below ~0.2 V), the I-V curve exhibits a linear relationship, indicating Ohmic conduction behaviour. In this region, the current is proportional to voltage, suggesting that charge transport is governed by thermally generated carriers and interparticle contacts within the nanoparticle network. [17].

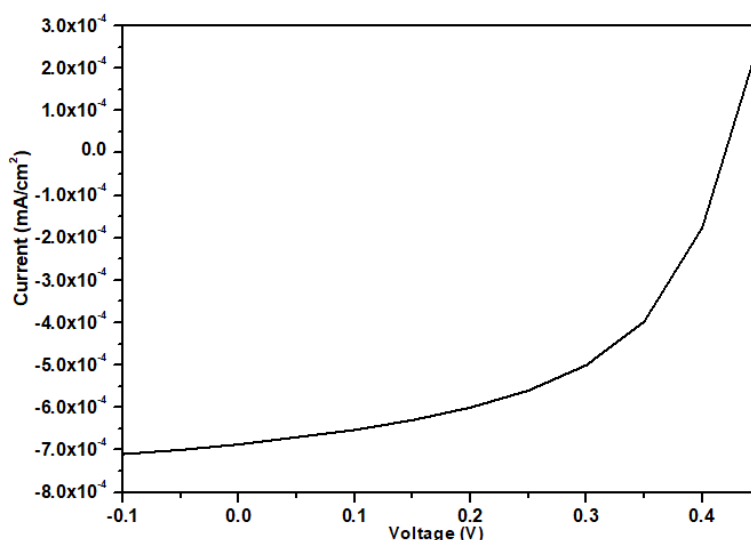


Fig. 6. I-V characteristics of Zn-doped SnO₂ nanoparticle deposits showing Ohmic→SCLC transition

As the applied voltage increases beyond ~0.2 V, the I-V characteristics deviate from linearity and exhibit a nonlinear trend, which is attributed to space-charge-limited conduction (SCLC). In this regime, the injected charge carriers dominate over thermally generated carriers, leading to the formation of space charge within the material. The presence of trap states, introduced by Zn doping and associated defects such as oxygen vacancies, influences the carrier transport and contributes to the observed SCLC behaviour.

Although the transition to SCLC behaviour is evident from the nonlinear I-V response, quantitative estimation of trap density was not performed in this study due to the

absence of precise parameters such as film thickness and dielectric constant required for such calculations. This will be considered in future work.

The observed conduction behaviour indicates that Zn doping modifies the charge transport mechanism by introducing defect states that influence carrier injection and trapping. These results suggest that Zn-doped SnO₂ nanoparticles possess tunable electrical properties, which are relevant for applications in optoelectronic and sensing devices.

Table 3. Key properties of Zn-doped SnO₂ nanoparticles vs literature

Parameter	This Work (5% Zn)	Unit	Technique	Literature Value	Notes	Reference
Bandgap	3.5	eV	UV-Vis	3.55 eV (3% Sn:ZnO) ; 3.6 eV (pure SnO ₂)	0.10 eV narrowing vs pure SnO ₂	[18,19]
Absorption edge	362	nm	UV-Vis	344 nm (pure SnO ₂)	Redshift vs undoped	[19]
Crystallite size (110)	14	nm	XRD	9-34 nm (Zn:SnO ₂ co-precipitation)	Strain-induced	[19]
Crystallite size (211)	20.4	nm	XRD	-	Largest plane	
Dislocation density	$4.0\text{--}8.5 \times 10^{15}$	lines/m ²	XRD	Higher defects with Zn doping	Defect engineering	[19]
I-V current density	2.68×10^{-4}	mA/cm ²	I-V	Improved conductivity	Max at 0.449 V (nanoparticle deposits)	[20]
I-V voltage	0.45	V	I-V	Ohmic→SCLC transition similar	Ohmic→SCLC transition	[20]
PL band-to-band peaks	329, 352, 367, 378	nm	PL	437, 465 nm (defect peaks)	Oxygen vacancies	[19]
Zn-O/Sn-O vibration	659	cm ⁻¹	FTIR	Similar lattice modes	Lattice confirmation	[20]

Note: Carrier concentration wasn't measured (no Hall effect data available). I-V characterization was done on nanoparticle Deposits

5. Conclusion

Zn-doped SnO₂ nanoparticles were successfully synthesized via the sol-gel method with calcination at 400 °C, yielding a tetragonal rutile phase with crystallite sizes ranging from 14.0 to 20.4 nm, as confirmed by XRD (Fig. 1, JCPDS 41-1445). FTIR analysis verified the presence of Zn-O and Sn-O bonds at 659 cm⁻¹ (Fig. 2). UV-Vis spectroscopy revealed a bandgap of 3.50 eV with an absorption edge at 362 nm, indicating a slight narrowing (~0.10 eV) compared to pure SnO₂ (Table 2, Fig. 3-4). Photoluminescence studies confirmed the presence of defect states, with near band-edge emissions at 329-378 nm and defect-related emissions associated with oxygen vacancies in the range of 413-469 nm (Fig. 5). The I-V characteristics of nanoparticle deposits exhibited a maximum current density of 2.68×10^{-4} mA/cm² at 0.449 V, showing a transition from Ohmic to space-charge-limited conduction behaviour (Fig. 6). Structural analysis revealed dislocation densities in the range of 4.0 to 8.5×10^{15} lines/m², indicating the presence of controlled lattice defects. The observed lattice strain due to substitution of Zn²⁺ ions (0.74 Å) for Sn⁴⁺ ions (0.69 Å) plays a key role in defect formation and band structure modification. The present study primarily supports the potential of Zn-doped SnO₂ nanoparticles for optoelectronic and photocatalytic applications, based on the observed structural, optical, and electrical properties. The moderate bandgap tuning, controlled defect states, and charge transport behaviour are favourable for these applications. While gas sensing potential is suggested due to the presence of surface defects and active sites, further experimental validation is required.

Future work will focus on Hall effect measurements to determine carrier concentration, XPS to analyse defect states, and thin-film fabrication to evaluate performance in transparent conductive oxide (TCO) applications.

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