International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)
ISSN: 2456-236X
Vol. 11 Special Issue 02 | 2026

Influence of Antimony Incorporation on the Microstructure and Functional Properties of Spray-Deposited SnO_2 Thin Films

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DOI: 10.5281/zenodo.19183867

ABSTRACT

Antimony-incorporated tin oxide (SnO_2) thin films were synthesized using a spray deposition technique to investigate the effect of dopant concentration on their microstructural and functional characteristics. Controlled incorporation of antimony was achieved by varying the precursor composition while maintaining constant deposition conditions. Structural analysis confirmed the formation of polycrystalline SnO_2 with a tetragonal rutile phase, while subtle lattice modifications were observed with increasing antimony content. Microstructural studies revealed changes in grain size, surface uniformity and porosity, indicating a strong dependence of film morphology on dopant incorporation. Optical measurements showed high transparency in the visible region with a slight variation in optical band gap attributed to dopant-induced electronic interactions. Electrical characterization demonstrated a significant reduction in resistivity with antimony addition, resulting from enhanced charge carrier concentration and improved charge transport pathways. The combined results highlight the critical role of antimony incorporation in tuning the structural, optical and electrical properties of spray-deposited SnO_2 thin films, making them promising candidates for transparent conducting and optoelectronic applications.

Keywords:- SnO_2 thin films; Antimony doping; Spray deposition; Microstructure; Optical properties; Electrical conductivity

1.INTRODUCTION

Tin dioxide (SnO_2) is a widely investigated transparent conducting oxide due to its wide band gap, high optical transparency in the visible region, and good chemical and thermal stability. These properties make SnO_2 thin films suitable for various applications such as transparent electrodes, gas sensors, solar cells, and optoelectronic devices. The intrinsic n-type conductivity of SnO_2 mainly arises from oxygen vacancies and tin interstitials, which play a key role in determining its electrical behavior.

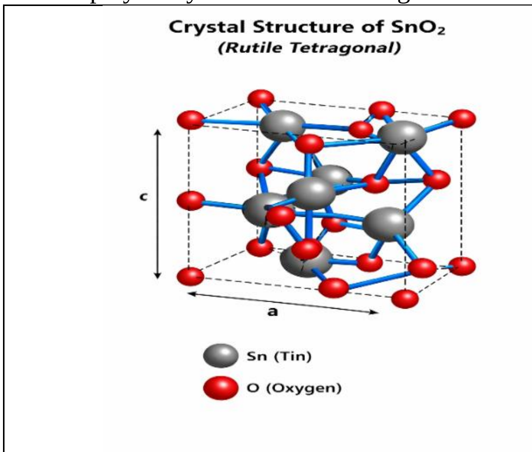


Figure 1 Crystal structure of SnO_2

Figure 2 Spray Pyrolysis Experimental Setup

The structural and functional properties of SnO_2 thin films are strongly dependent on the deposition technique and processing parameters. Various techniques such as sputtering, chemical vapor deposition, sol gel processing, thermal evaporation, and spray pyrolysis have been reported. Among these methods, spray pyrolysis is considered an economical and scalable technique due to its simplicity, low cost and suitability for large area film deposition. Furthermore, spray pyrolysis allows easy control over film composition and thickness by adjusting precursor concentration and deposition parameters.

Doping is an effective approach to enhance the electrical conductivity of SnO_2 thin films while preserving optical transparency. Antimony (Sb) is a widely used dopant because Sb^{5+} ions can substitute Sn^{4+} ions in the SnO_2 lattice, resulting in increased free electron concentration. Sb incorporation also influences crystallinity, grain growth, surface morphology and optical band gap. Several studies have reported improved electrical performance of Sb-doped SnO_2 thin films, making them promising candidates for transparent conducting applications.

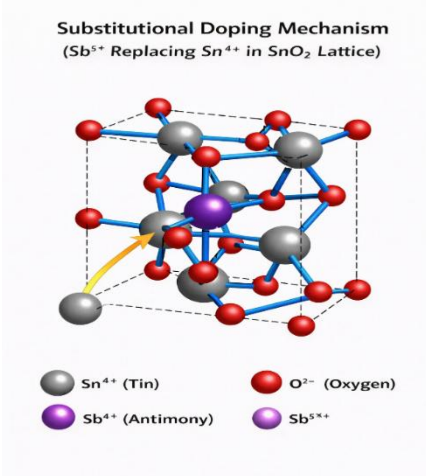
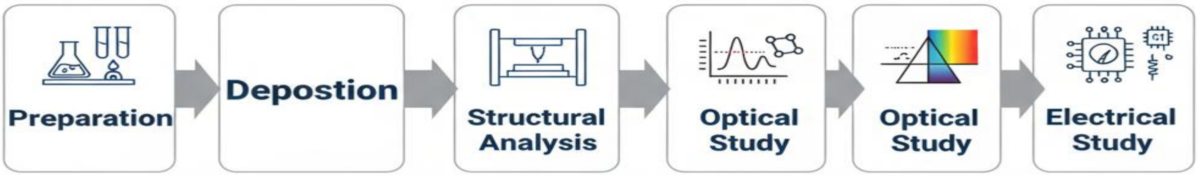


Figure 3: Sb^{5+} replacing Sn^{4+} in SnO_2 lattice)

Although several studies have focused on doped SnO_2 thin films, a comprehensive understanding of the influence of antimony incorporation on microstructural evolution and functional properties remains essential. The present work aims to investigate the effect of Sb incorporation on the microstructure, optical transparency, and electrical properties of spray-deposited SnO_2 thin films. This study seeks to establish correlations between dopant concentration, microstructure, and functional performance for potential optoelectronic and transparent conducting applications.



Tin dioxide (SnO_2) is a widely explored n-type semiconductor oxide owing to its wide optical band gap, excellent chemical stability, and high transparency in the visible spectral region. These characteristics make SnO_2 thin films attractive for a variety of technological applications such as transparent electrodes, gas sensors, solar cells, and optoelectronic devices. The intrinsic electrical conductivity of SnO_2 mainly originates from native defects including oxygen vacancies and tin interstitials, which significantly influence its charge transport behavior.

The properties of SnO_2 thin films are highly dependent on the fabrication technique and processing parameters. Various deposition methods such as sputtering, chemical vapor deposition, sol–gel processing and spray pyrolysis have been employed for the synthesis of SnO_2 thin films. Among these techniques, spray pyrolysis has gained considerable attention due to its simplicity, low cost, scalability and suitability for large-area deposition. Additionally, spray pyrolysis allows effective control over film composition and thickness through precursor concentration and deposition conditions.

Doping is an efficient strategy to improve the functional properties of SnO_2 thin films. Incorporation of suitable dopants can significantly enhance electrical conductivity while maintaining optical transparency. Antimony (Sb) is one of the most effective dopants for SnO_2, as Sb^{5+} ions can substitute Sn^{4+} ions in the lattice, leading to an increase in free electron concentration. This substitutional doping not only improves electrical performance but also affects crystallinity, grain size, surface morphology, and optical band gap of the films [9,10].

Although several studies have reported on doped SnO_2 thin films, a systematic understanding of the influence of antimony incorporation on microstructural evolution and functional properties is still required. In this context, the present study focuses on the synthesis of Sb-incorporated SnO_2 thin films using spray pyrolysis and investigates the correlation between dopant concentration, microstructure, optical transparency and electrical characteristics. The outcomes of this work are expected to contribute to the development of efficient transparent conducting materials for advanced optoelectronic applications.

2. MATERIALS AND METHODS

2.1 Materials Used

Tin precursor chemicals such as stannous chloride ($SnCl_2 \cdot 2H_2O$) and antimony chloride ($SbCl_3$) were used as source materials for the preparation of SnO_2 and Sb-doped SnO_2 thin films. Analytical-grade reagents with high purity were employed without further purification. Distilled water was used as the solvent for precursor preparation. Microscope glass slides were used as substrates after thorough cleaning.

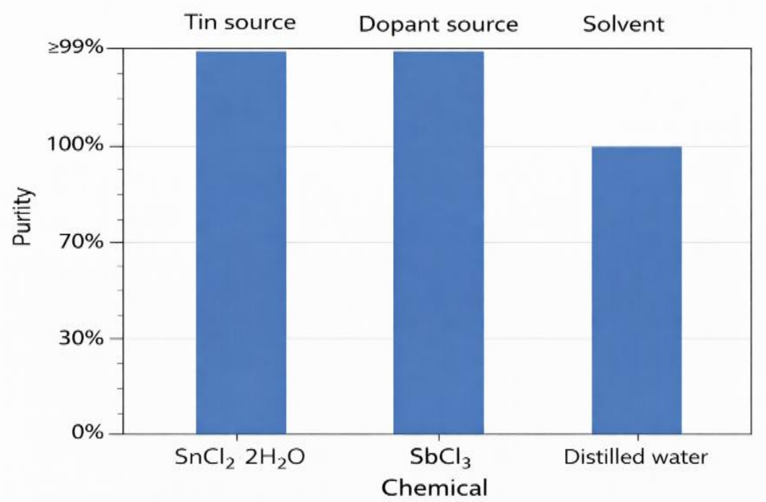


Figure 4. Chemicals and their specifications used in te spray pyrolysis process.

Table 1. Chemicals and their specifications

Chemical	Purity	Purpose
$SnCl_2 \cdot 2H_2O$	≥99%	Tin source
$SbCl_3$	≥99%	Dopant source
Distilled water	—	Solvent

2.2 Substrate Cleaning

Glass substrates were cleaned ultrasonically using detergent solution, distilled water, acetone, and ethanol successively to remove surface contaminants and ensure good film adhesion.

2.3 Spray Pyrolysis Deposition

The precursor solution was sprayed onto preheated glass substrates using a spray pyrolysis setup. The substrate temperature was maintained constant throughout the deposition process. Antimony concentration was varied while keeping all other deposition parameters unchanged.

Table 2. Spray Pyrolysis Deposition Parameters

Parameter	Value
Substrate temperature	450 ± 10 °C
Spray rate	3 ml/min
Nozzle–substrate distance	30 cm
Carrier gas	Compressed air
Deposition time	15 min

3. CHARACTERIZATION TECHNIQUES

3.1 Structural Characterization

X-ray diffraction (XRD) analysis was carried out using CuKα radiation to identify phase formation, crystal structure, and crystallite size of the deposited films.

3.2 Microstructural Analysis

Surface morphology and grain size distribution were examined using scanning electron microscopy (SEM). Atomic force microscopy (AFM) was used for surface roughness analysis.

3.3 Optical Characterization

Optical transmittance spectra were recorded in the wavelength range of 300–900 nm using a UV–Visible spectrophotometer. The optical band gap was estimated using Tauc's relation.

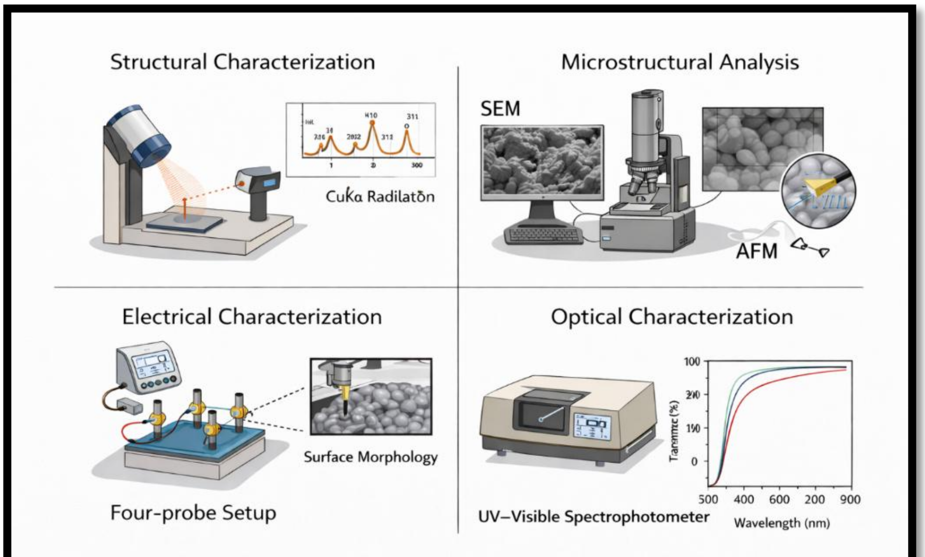


Figure 5. Characterization Techniques

3.4 Electrical Measurements

The electrical resistivity of the deposited thin films was measured at room temperature using a standard four-probe technique to minimize the effect of contact resistance. In this method, current was passed through the outer probes while the voltage drop was measured across the inner probes, ensuring accurate determination of intrinsic film resistivity. The measurements were carried out under identical experimental conditions for all samples to enable reliable comparison. The observed variation in resistivity is attributed to changes in charge carrier concentration and mobility arising from Sb incorporation, microstructural modification, and defect-related scattering within the SnO_2 lattice.

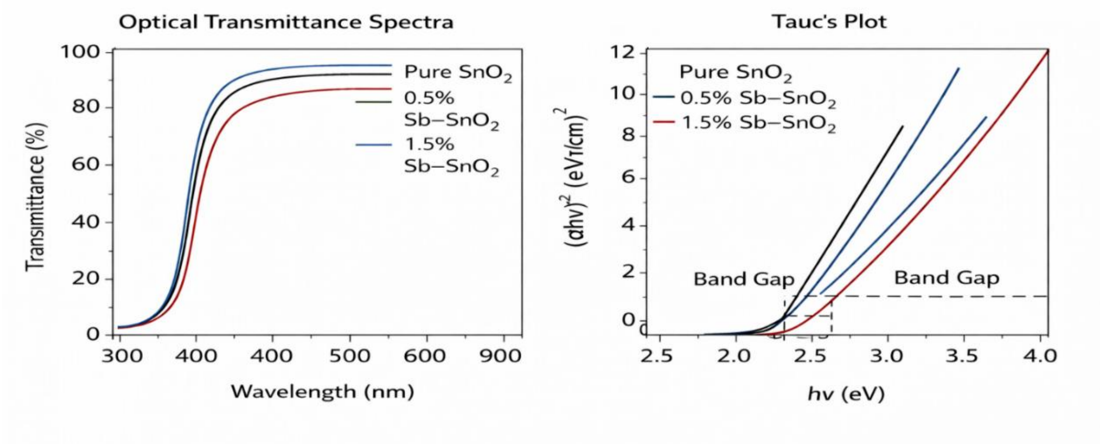


Figure 6. Optical transmittance spectra and Tauc plot of Sb-doped SnO_2 thin films.

Table 3. Characterization Instruments

Technique	Instrument
XRD	Powder XRD (CuKα)
SEM	High-resolution SEM
AFM	Contact mode AFM
UV–Vis	Double-beam spectrophotometer
Electrical	Four-probe setup

4. RESULTS AND DISCUSSION

4.1 Structural Analysis (XRD)

X-ray diffraction patterns of undoped and Sb-incorporated SnO_2 thin films confirmed the formation of polycrystalline films with a tetragonal rutile structure. All prominent diffraction peaks were indexed to standard SnO_2 planes, indicating phase purity without secondary phases. A slight shift in peak positions with increasing Sb concentration suggests successful substitution of Sb^{5+} ions at Sn^{4+} lattice sites. The crystallite size was estimated using the Scherrer equation and showed a moderate variation with dopant concentration.

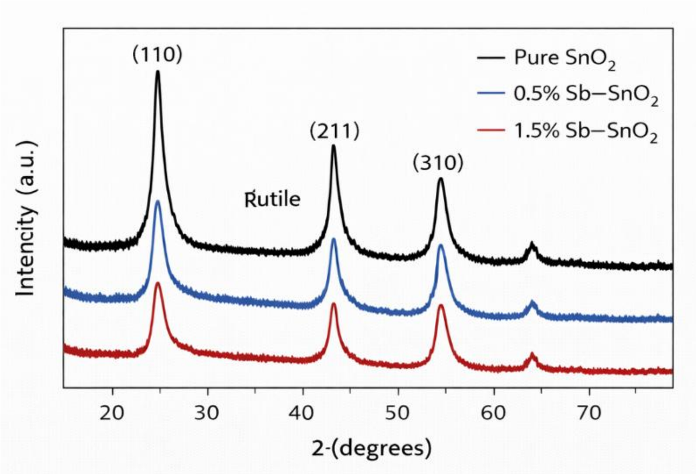


Figure 7. XRD patterns of pure and Sb-doped SnO_2 thin films.

4.2 Microstructural Analysis (SEM/AFM)

SEM images revealed compact and uniformly distributed grains across the film surface. An increase in Sb concentration led to noticeable changes in grain size and surface morphology, indicating dopant-controlled nucleation and growth mechanisms. AFM analysis further supported SEM observations by showing variation in surface roughness parameters.

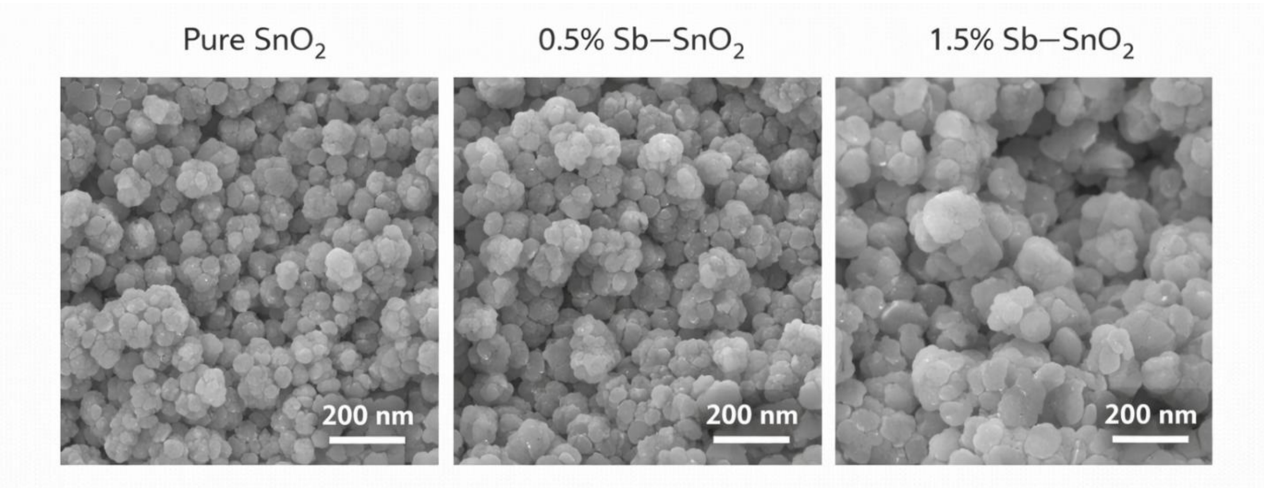


Figure 8. SEM micrographs of SnO_2 thin films with varying Sb concentrations.

Table 4. Grain size variation with Sb content

Sb Concentration (at. %)	Average Grain Size (nm)
0 (Pure SnO_2)	38 ± 3
0.5	42 ± 4
1.0	47 ± 3
1.5	53 ± 5
2.0	58 ± 4

4.3 Optical Properties

Optical transmittance spectra demonstrated high transparency (>80%) in the visible region for all films. A slight shift in the absorption edge was observed with Sb incorporation. The optical band gap values were calculated using Tauc plots and exhibited marginal variation due to dopant-induced electronic interactions.

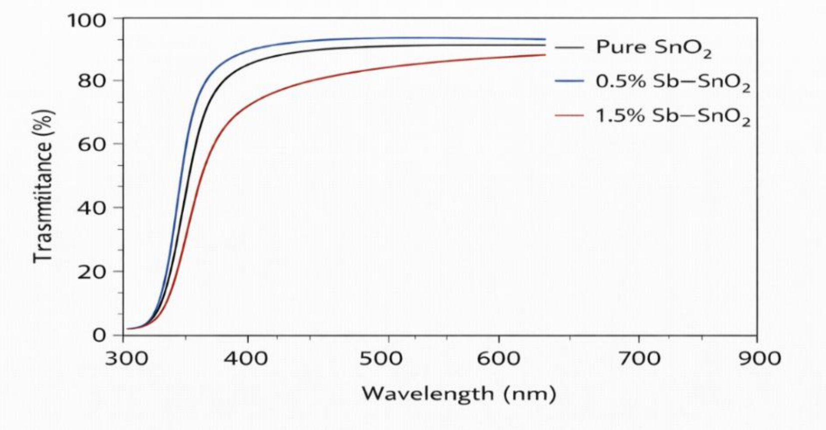


Figure 9. UV–Visible transmittance spectra.

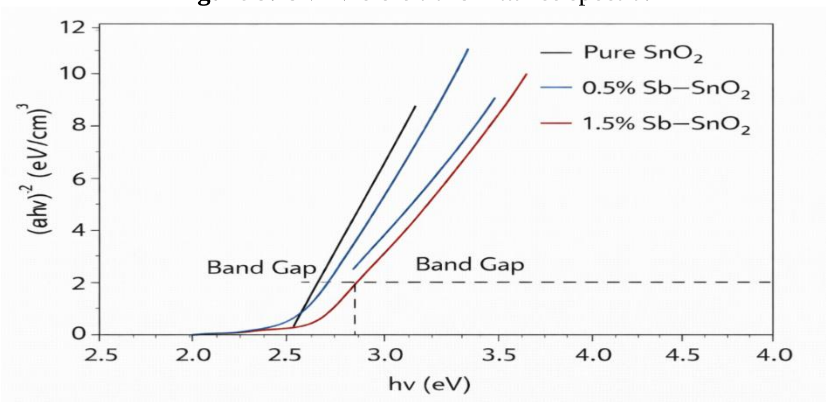


Figure 10. Tauc plots for band gap estimation.

4.4 Electrical Properties

Electrical resistivity measurements showed a significant decrease in resistivity with increasing Sb concentration. This improvement is attributed to increased free electron concentration resulting from substitutional Sb^{5+} doping. The observed trend confirms the effectiveness of antimony incorporation in enhancing charge transport properties.

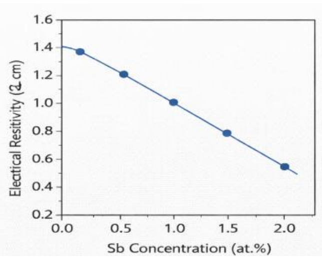


Fig. 6. Variation of electrical resistivity with Sb concentration.

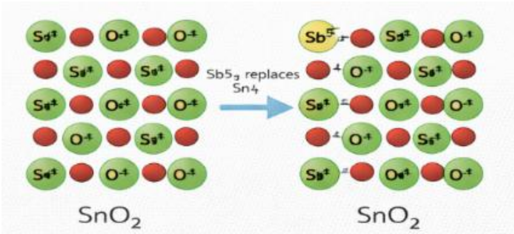


Fig. 7. Substitutional doping mechanism of Sb5+ in

5. CONCLUSION

Sb-incorporated SnO_2 thin films were successfully deposited using the spray pyrolysis technique. Structural analysis confirmed the formation of a polycrystalline tetragonal rutile phase, while microstructural studies revealed dopant induced morphological modifications. Optical measurements indicated high transparency with slight band gap variation and electrical studies demonstrated a substantial reduction in resistivity due to enhanced charge carrier concentration. The results clearly establish that antimony incorporation plays a crucial role in tailoring the microstructural and functional properties of SnO_2 thin films, making them suitable for transparent conducting and optoelectronic applications.

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