

Original Paper

Development of Cu-doped SnO₂ thin film sensors for enhanced ammonia detection at room temperature

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ABSTRACT

In this study, Cu-doped tin dioxide (SnO₂) thin films were successfully synthesized using the thermochemical decomposition method at a deposition temperature of 350 °C and a precursor concentration of 0.02 M. Copper was introduced at doping levels of 3%, 5%, and 7% to systematically investigate its effects on the structural, morphological, electrical, and gas-sensing characteristics of the SnO₂ films. X-ray diffraction (XRD) confirmed the retention of the tetragonal rutile structure in all samples, with Cu incorporation leading to a reduction in crystallite size and peak shifts indicative of strain and defect formation. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) analyses revealed progressive grain refinement and increased surface roughness with increasing Cu content. Hall-effect measurements demonstrated that Cu doping enhanced carrier mobility and electrical conductivity, with the 5% Cu-doped film exhibiting the most favorable transport properties. Room-temperature gas-sensing measurements using ammonia (NH₃) showed that the 5% Cu-doped SnO₂ film achieved the highest response, with a sensor response (Ra/Rg) of approximately 3.4 at 150 ppm, a response time of 22 s, a recovery time of 35 s, and excellent cyclic stability. Compared with the undoped film, this result corresponds to an estimated 160% improvement in sensing performance. These findings highlight the potential of moderately Cu-doped SnO₂ thin films for use in high-performance NH₃ sensors operating at room temperature (25 °C).

Keywords: Copper-modified SnO₂ films, Electrical conductivity, NH₃ gap sensor response, Structural and morphological analysis

1 INTRODUCTION

Tin dioxide (SnO₂) is a well-established n-type semiconductor with a wide band gap (~3.6 eV), known for its high chemical stability, optical transparency in the visible range, and excellent thermal robustness [1, 2]. Owing to these properties, SnO₂ has been extensively explored for various applications, including gas sensors, transparent conducting electrodes, solar cells, and lithium-ion batteries [3, 4]. Despite its potential, the practical implementation of pristine SnO₂ in gas sensing is often hindered by its relatively low sensitivity, poor selectivity, and limited response and recovery characteristics,

particularly at room temperature [5].

To overcome these limitations, various strategies have been proposed to enhance the sensing characteristics of SnO₂, with chemical doping emerging as a particularly effective approach [6, 7]. Doping with transition metals, especially those with variable oxidation states, can modulate the electronic band structure, increase the concentration of defects such as oxygen vacancies, and facilitate grain-boundary engineering, all of which play crucial roles in gas-adsorption and charge-transport mechanisms [8, 9].

Copper (Cu) has been identified as a promising dopant because its ionic radius is similar to that of Sn⁴⁺ (0.73 for

Cu^{2+} vs. 0.69 for Sn^{4+}), which facilitates its substitution into the SnO_2 lattice without the formation of major secondary phases at low concentrations [10]. Cu doping has been reported to reduce crystallite size, enhance surface roughness, and introduce localized energy states within the band gap, which collectively improve gas adsorption and charge-carrier dynamics [11].

Particularly for ammonia (NH_3) sensing, which is of significant environmental and occupational concern, Cu-doped SnO_2 has demonstrated enhanced sensitivity and selectivity because of the increased chemisorption of NH_3 molecules and greater modulation of the depletion layer at the semiconductor surface [12,13]. Optimal doping levels are crucial: low Cu concentrations can enhance sensitivity by promoting grain-boundary formation and increasing defect density, whereas excessive doping may lead to phase separation, Cu-cluster formation, and degraded electronic-transport properties [14].

Although Cu-doped SnO_2 films have been investigated for gas sensing, gaps remain in understanding the interplay between doping concentration and structural evolution and their cumulative effects on electrical and sensing behavior, particularly when the films are synthesized using low-cost, scalable methods such as thermochemical decomposition [15]. Most previous studies have focused on either bulk materials or nanopowders, with relatively few examining thin-film geometries under ambient conditions using simple deposition techniques [16].

In this study, we address these gaps by synthesizing Cu-doped SnO_2 thin films with doping concentrations of 3%, 5%, and 7% using a thermochemical decomposition route. We systematically evaluate the influence of Cu incorporation on the structural, morphological, and electrical properties of the films. Special emphasis is placed on their NH_3 -sensing performance at room temperature. Our findings aim to elucidate the optimal doping concentration and the mechanistic relationship between microstructure and gas-sensing efficacy, paving the way for the development of low-cost, high-performance SnO_2 -based sensors for environmental monitoring at low operating temperatures, particularly room temperature ($\sim 25^\circ\text{C}$).

2 MATERIALS AND METHODS

2.1 Materials

Tin(II) chloride dihydrate ($\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$; molecular weight: 225.63 g/mol) was used as the tin precursor. This material, supplied by Oxford Lab Chem (India),

was a white crystalline powder with a purity of 99.98% and high solubility in water. Copper(II) chloride dihydrate ($\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$; molecular weight: 170.48 g/mol) was used as the dopant source and was obtained from Alpha Chemika (India) with a purity of 99%. Ethanol (99.5%) was used as the solvent. Microscope glass slides ($25\text{ mm} \times 25\text{ mm}$) were used as substrates and were ultrasonically cleaned in acetone, ethanol, and deionized water before deposition.

2.2 Film preparation

A 0.02 M solution of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ was prepared in ethanol and magnetically stirred at room temperature for 1 h. For doping, $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ was added in stoichiometric amounts to achieve Cu-doping levels of 3%, 5%, and 7% relative to tin. Each solution was stirred further until fully homogenized. Deposition was performed using the chemical thermal decomposition (CTD) method. The cleaned glass substrates were heated and maintained at a constant surface temperature of 350°C . The precursor solution was sprayed onto the heated substrates using a fine atomizing nozzle positioned 25 cm above the surface at a constant spray rate of 1.5 mL/min. The thermal energy of the substrate induced the in situ decomposition of the precursor, leading to the direct formation of SnO_2 thin films without additional post-annealing. After deposition, the samples were allowed to cool naturally to room temperature. The resulting films exhibited high optical transparency, strong adhesion to the substrates, and uniform surface coverage, with estimated thicknesses ranging from 200 to 300 nm, depending on the precursor concentration.

2.3 Structural characterization

X-ray diffraction (XRD) analysis was performed using a Philips PW 1730 XRD system manufactured in the Netherlands. The system was operated at 40 kV and 30 mA using Cu K α radiation with a wavelength of 1.5406. Measurements were performed over a 2θ range of 20° – 80° , with a step size of 0.05° and an acquisition time of 1 s per step. The following standard equations were applied to estimate the microstructural parameters.

2.4 Surface morphology analysis

Surface topography was studied using a JPK NanoWizard II atomic force microscope (AFM) from Bruker (Germany), operating in tapping mode over a scan area of $0.49 \times 0.49\ \mu\text{m}^2$. This enabled the extraction of

quantitative surface parameters, including average grain size, mean roughness (Ra), and peak-to-valley height.

A TESCAN MIRA3 scanning electron microscope (SEM), manufactured in the Czech Republic, was used to examine surface morphology and particle distribution. SEM imaging was performed at a high magnification (100,000 $\times$) to assess film uniformity, grain connectivity, and size distribution.

2.5 Electrical measurements

A Keithley 2182A nanovoltmeter in a van der Pauw configuration was used to measure the electrical properties at room temperature. Ohmic contacts were formed using aluminum (Al) electrodes deposited by thermal evaporation under vacuum, with an average thickness of approximately 400 nm. Parameters including carrier type, Hall coefficient, carrier concentration, electrical resistivity, conductivity, and Hall mobility were determined for all samples.

2.6 Gas sensing measurements

NH₃ gas-sensing tests were conducted at room temperature using a dynamic-response system. The thin-film samples were integrated with interdigitated silver electrodes to enable resistance measurements. The sensors were sequentially exposed to NH₃ concentrations of 50, 100, and 150 ppm in dry air. Resistance variations were continuously recorded to determine the response magnitude, response time, and recovery behavior at each concentration. Multiple exposure-recovery cycles were performed to evaluate stability and repeatability.

3 RESULTS AND DISCUSSION

3.1 XRD analysis results

X-ray diffraction (XRD) analysis was performed to evaluate the structural characteristics of undoped and Cu-doped SnO₂ thin films deposited via thermochemical decomposition at 350°C. The XRD patterns of all samples (Figure 1) confirmed the presence of a polycrystalline tetragonal rutile SnO₂ phase (ICDD card No. 00-041-1445), with no detectable secondary phases, such as CuO or Cu₂O. In the undoped sample, the observed diffraction peaks corresponding to the (110), (101), (200), and (211) crystallographic planes were located at approximately 26.580°, 34.282°, 37.976°, and 51.795°, respectively. The dominant (110) peak in all compositions indicates a preferred orientation in that direction, which is typical of solution-derived SnO₂ films. This trend has also

been observed in Cu-doped SnO₂ systems prepared using sol-gel and spray-pyrolysis methods [15, 17].

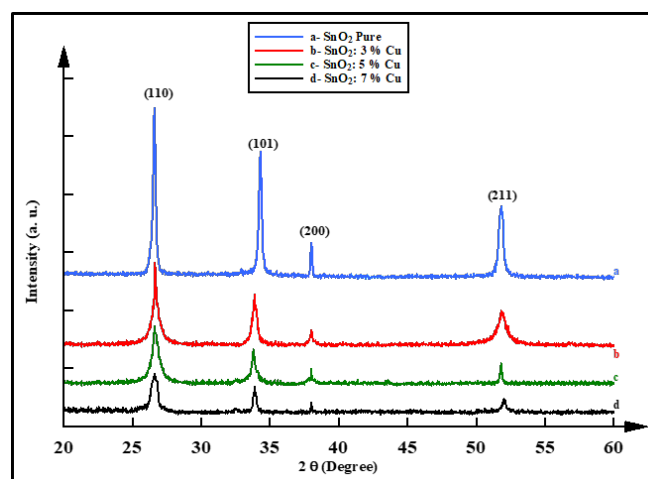


Fig. 1 XRD patterns of SnO₂ thin films with 0%, 3%, 5%, and 7%Cu doping

Upon Cu doping, notable shifts in the peak positions were observed. For instance, the (110) reflection exhibited a slight positive shift of +0.08° at both 3% and 5% Cu, followed by a marginal shift of +0.01° at 7%Cu, indicating a contraction in lattice spacing and the emergence of compressive strain. In contrast, the (101) peak exhibited a negative shift of up to -0.48° at 5% Cu, revealing tensile strain along this direction. Such anisotropic shifts can be attributed to the substitution of Sn⁴⁺ ions (0.69) by slightly larger Cu²⁺ ions (0.73), generating local lattice distortions and oxygen vacancies for charge compensation. Similar peak shifts and strain effects have been reported in doped SnO₂ thin films using both XRD and Williamson-Hall analyses [18, 19]. The crystallite size associated with each plane was estimated using the Scherrer equation [20].

$$D = \frac{K\lambda}{\beta \cos \theta}$$

Copper doping induced a substantial reduction in crystallite size across all reflections at 3% Cu, suggesting uniform grain refinement driven by dopant-induced inhibition of crystal growth. The crystallite size associated with the (110) reflection decreased from 36.9 nm in the undoped film to 26.6 nm at 3% Cu, whereas those associated with the (101) and (211) reflections decreased to 19.1 and 10.2 nm, respectively. At 5% Cu, a unique bimodal distribution was observed: while the crystallite

size associated with the (110) reflection continued to decrease to 14.1 nm, that associated with the (211) reflection increased to 49.2 nm because of recrystallization. This transition is indicative of strain relaxation and preferential regrowth along selected orientations. Similar strain-relaxation and recrystallization trends in Cu-doped SnO₂ systems have been attributed to thermal annealing and substrate-facilitated reordering effects in previous studies [11, 21].

At 7% Cu, the (200) plane exhibited remarkable regrowth, reaching a crystallite size of 226.5 nm. This unusually large size suggests epitaxial realignment or texture reordering, a phenomenon often observed during defect-driven grain-boundary migration and possible spinel-phase formation. These transformations were further reflected in the evolution of the full width at half maximum (FWHM) values. The FWHM values of the major reflections varied significantly with increasing Cu content. For instance, the (200) peak exhibited a dramatic broadening of 314% at 3% Cu, indicating severe defect proliferation. At 5% Cu, the FWHM of the (110) peak increased by 160%, indicating partial amorphization and a high dislocation density. Conversely, the narrowing of the (211) peak at 5% and 7% Cu suggests crystallographic recovery and strain relaxation in selected domains. At 7% Cu, reductions of 25% and 11% in the FWHM values of the (200) and (101) peaks, respectively, were observed. These reductions may be attributed to the stabilization of Cu-Sn-O nanocomposites, such as Cu₂SnO₂. Similar trends in FWHM with Cu content have been reported under different deposition and annealing conditions, further corroborating the relationship between strain dynamics and structural modulation induced by Cu doping [15, 17].

To visualize these trends, the variation in crystallite size as a function of Cu-doping level is presented in Figure 2. The graph clearly illustrates the pronounced reduction in crystallite size at 3% and 5% Cu, followed by a sharp increase in the crystallite size associated with the (200) reflection at 7% Cu, corroborating the proposed mechanism of dopant-induced structural modulation followed by orientation-selective epitaxial regrowth.

3.2 SEM analysis results

The SEM micrographs presented in Figure 3 provide insight into the effects of Cu doping on particle-size distribution, surface uniformity, and grain agglomeration.

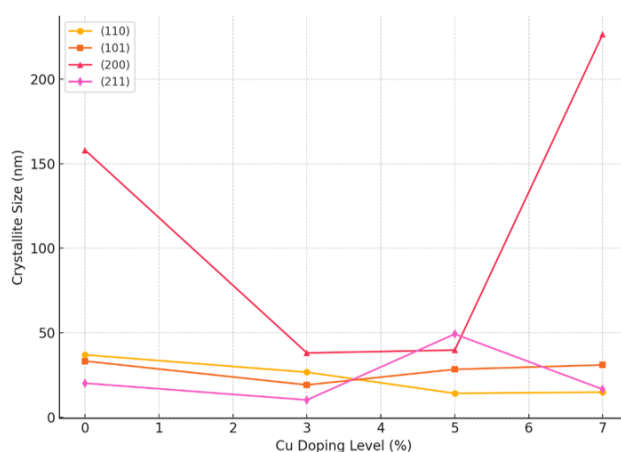


Fig. 2 Crystallite size versus Cu doping for (110), (101), (200), and (211) reflections

In the undoped SnO₂ sample (Figure 3a), the particles exhibited a relatively uniform granular morphology with moderate agglomeration. Based on direct SEM measurements processed using ImageJ software (NIH, USA), the particle sizes ranged from approximately 21.2 to 30.1 nm, with an average of approximately 26.5 nm, in good agreement with the crystallite sizes derived from XRD. The morphology suggests isotropic growth with minimal lattice constraint and dense packing, characteristic of pure-phase SnO₂ formed via thermochemical decomposition.

Upon the introduction of 3% Cu doping (Figure 3b), the surface exhibited more tightly packed grains with refined and slightly smaller particle sizes, ranging from 20.1 to 25.7 nm. The average particle diameter decreased slightly to approximately 22.8 nm. The reduction in particle size and enhanced homogeneity can be attributed to the Cu-induced inhibition of grain growth and enhanced nucleation during the thermal-treatment stage. Additionally, the grain boundaries appeared less diffuse, indicating improved phase integrity.

At a Cu-doping level of 5% (Figure 3c), a more heterogeneous microstructure was evident. The film contained both small spherical grains and occasional larger grains, indicating a bimodal distribution. The measured grain sizes ranged from 20.1 to 26.9 nm, with an average of approximately 23.5 nm. This morphological pattern corroborates the XRD results, which showed simultaneous crystallite-size reduction associated with the (110) reflection and recrystallization associated with the (211) reflection, implying stress-assisted reorientation or local recovery phenomena.

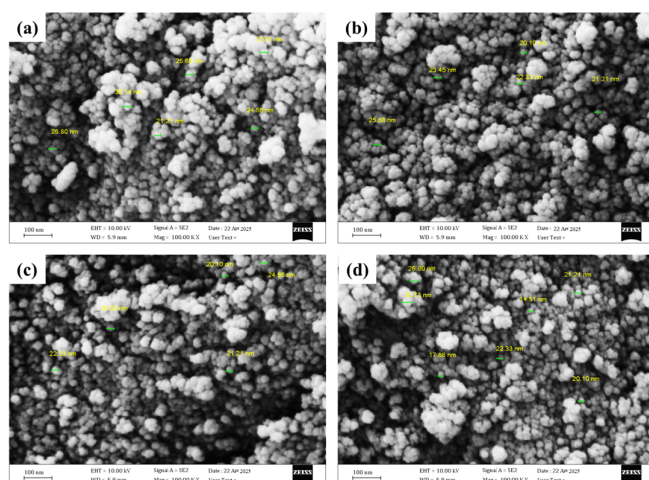


Fig. 3 SEM Images of SnO₂ Films at 100, 000× Magnification
(a) Pure SnO₂ (b) 3%Cu – SnO₂ (c) 5%Cu – SnO₂
(d) 7%Cu – SnO₂

Further doping with 7% Cu (Figure 3d) introduced notable textural changes. While some particles remained within the nanoscale range of 14.5 – 21.2 nm, others exceeded 35 nm, indicating incipient grain coalescence or spinel-phase nucleation. A similar phenomenon was reported by Bagheri-Mohagheghi et al. (2014) [22], who found that the grain size decreased and the morphology changed with increasing Cu content in SnO₂ thin films. Selleswari et al. (2019) [23] and Supu et al. (2022) [24] provided additional evidence of coalescence and secondary-phase-related morphological disorder, with both studies describing surface inhomogeneity and structural heterogeneity at higher Cu concentrations.

The surface became less homogeneous, possibly because of localized thermal strain and excessive oxygen-vacancy clustering. The measured average grain size was approximately 24.0 nm, showing a slight increase relative to the 5% Cu-doped sample. It is noteworthy that the crystallite size estimated by XRD for the (200) plane at 7% Cu reached 226.5 nm, contrasting with the smaller average grain size observed by SEM (approximately 24 nm). This difference arises because XRD measures the size of coherent diffracting domains, which may include preferentially oriented or deeply embedded crystallites that are not fully resolved by surface-level SEM imaging. Such selective crystallographic growth can result in localized large grains that are not dominant in the overall film morphology.

3.3 AFM analysis results

Atomic force microscopy (AFM) was used to further characterize the surface topography of the undoped and Cu-doped SnO₂ thin films. The AFM scans were performed in tapping mode over an area of $0.49 \times 0.49 \mu\text{m}^2$, and the resulting three-dimensional (3D) topographical maps are presented in Figures 4a-d. The data were quantitatively analyzed to determine the average grain size, maximum peak height, and mean surface roughness.

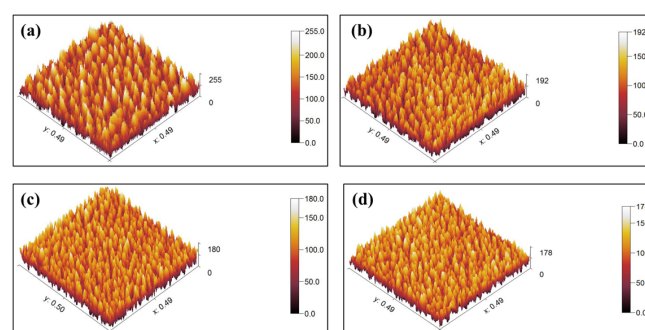


Fig. 4 AFM 3D Topography Maps ($0.49 \times 0.49 \mu\text{m}^2$) (a) Pure SnO_2 (b) $\text{SnO}_2 : 3\%\text{Cu}$ (c) $\text{SnO}_2 : 5\%\text{Cu}$ (d) $\text{SnO}_2 : 7\%\text{Cu}$

The undoped SnO₂ film (Figure 4a) exhibited a rough, granular surface with an average grain size of approximately 48.4 nm and a mean surface roughness (Ra) of 38.8 nm. Following doping with 3% Cu (Figure 4b), the grain size decreased to 37.5 nm, and Ra decreased to 32.1 nm, indicating a smoother surface morphology. With 5% Cu doping (Figure 4c), further refinement was observed, with the grain size decreasing to approximately 33.2 nm and Ra decreasing to approximately 27.8 nm, indicating improved film uniformity and densification. As the Cu content increased, the surface became even smoother, as shown in Figure 4d, with a grain size of approximately 25.6 nm and a further reduction in Ra to 20.9 nm.

This progressive smoothing trend can be attributed to dopant-induced lattice reordering and the suppression of uncontrolled grain growth. These findings are consistent with dopant-induced lattice rearrangement and growth inhibition. Benzitouni et al. (2016) [25] reported increased methanol sensitivity using smoother Cu -doped SnO₂ surfaces. Kwoka et al. (2007) [26] and Deepa et al. (2019) [27] also confirmed that lower surface roughness and optimal doping can substantially improve gas-sensing characteristics. These changes in roughness and grain size are associated with enhanced gas adsorption and electrical performance, particularly at the 5% doping level.

3.4 Electrical analysis results

The electrical transport characteristics of the undoped and Cu -doped SnO₂ thin films were systematically studied using Hall-effect measurements at room temperature. All samples exhibited n-type conduction behavior, consistent with the intrinsic nature of SnO₂ as a wide-band-gap oxide semiconductor and further influenced by oxygen-vacancy-related donor states.

The undoped SnO₂ film exhibited a carrier concentration of $3.939 \times 10^{12} \text{ cm}^{-3}$, a Hall mobility of $2.418 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, and a corresponding resistivity of $195.0 \Omega \text{ cm}$. This relatively low free-carrier concentration and high resistivity were attributed to the limited availability of intrinsic defects and the relatively large grain size, as evidenced by the XRD and SEM analyses. These findings agree with those reported for other oxide semiconductors, such as Cu -doped PbS and CdO [28,29]. Upon doping with 3%Cu, the carrier concentration increased substantially to $5.723 \times 10^{12} \text{ cm}^{-3}$, and the mobility increased to $3.856 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, resulting in a significant decrease in resistivity to $102.5 \Omega \text{ cm}$. This enhancement can be correlated with the observed grain refinement, increased surface area, and modest oxygen-vacancy generation, which collectively contributed to improved charge transport.

A more pronounced improvement in electrical conductivity was observed in the 5% Cu-doped sample. The carrier mobility reached $1.371 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, whereas the carrier concentration remained moderate at $2.561 \times 10^{11} \text{ cm}^{-3}$, resulting in a resistivity of $27.43 \Omega \text{ cm}$ and the highest conductivity of $3.645 \times 10^{-2} \Omega^{-1} \text{ cm}^{-1}$ among all samples. These results suggest an optimal doping concentration that maximizes charge-carrier mobility by minimizing grain-boundary scattering and facilitating electron delocalization through shallow defect levels. This finding agrees with the structural analysis, which indicated a bimodal grain distribution and crystallographic realignment at 5% Cu.

At a higher doping level of 7% Cu, a distinct shift in transport behavior was observed. Although the carrier concentration increased slightly to $4.312 \times 10^{11} \text{ cm}^{-3}$, the mobility increased significantly to $6.121 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, resulting in the lowest resistivity of $0.416 \Omega \text{ cm}$ and a corresponding conductivity of $2.401 \times 10^{-2} \Omega^{-1} \text{ cm}^{-1}$. This result suggests that, although the charge carriers remained moderately abundant, the transport pathways became more efficient, likely because of reduced trap density and partial grain coalescence, as

observed in the AFM and SEM micrographs.

The crystallite size of approximately 226.5 nm observed for the (200) XRD reflection was larger than the average grain size of approximately 24 nm measured by SEM for the 7% Cu-doped film. This difference could be explained by selective orientation and localized crystalline growth, which are more sensitively detected by XRD than by SEM. The low resistivity at a Cu-doping level of 7% could be due to increased carrier delocalization through these oriented domains and the development of highly conductive networks despite some grain coalescence.

However, the slight increase in resistivity compared with that of the 5% Cu-doped sample may indicate the onset of dopant saturation, possible Cu-cluster formation, or spinodal decomposition, which can locally disrupt the conduction network.

3.5 Gas sensing analysis results

The gas-sensing performance of the undoped and Cu-doped SnO₂ thin films toward ammonia (NH₃) was assessed at room temperature using dynamic response-recovery measurements. The sensor response was evaluated based on the change in resistance upon exposure to NH₃, a reducing gas, under atmospheric conditions. The sensing characteristics of each film are presented in Figure 5.

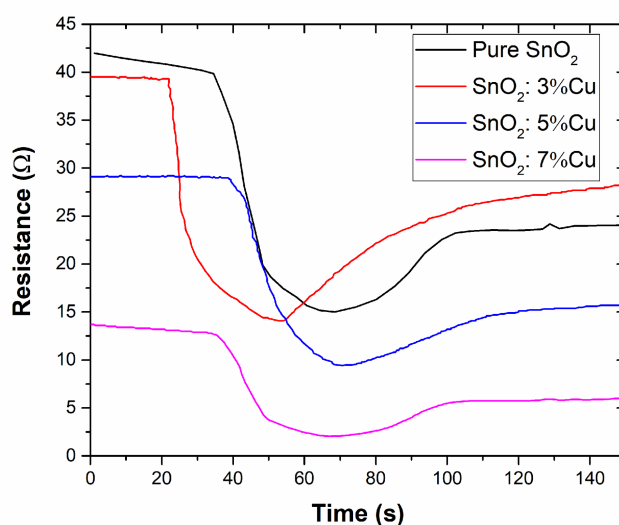


Fig. 5 NH₃ Gas Sensing Response-Recovery Curves of SnO₂ Thin Films (a) Pure SnO₂ (b) SnO₂ : 3%Cu (c) SnO₂ : 5%Cu (d) SnO₂ : 7%Cu

The undoped SnO₂ sample exhibited measurable but

moderate sensitivity to NH_3 gas (Figure 5). Upon gas exposure, a rapid decrease in resistance was observed, consistent with the behavior of an n-type semiconductor in the presence of a reducing gas. However, the response magnitude was relatively low, which was attributed to limited active surface sites and a lower density of oxygen vacancies. Recovery was slow, and the baseline resistance was only partially restored after gas removal, indicating sluggish adsorption-desorption dynamics, likely because of the larger crystallite size and smoother surface morphology observed in the previous SEM and AFM analyses.

Upon doping with 3% Cu (Figure 5), a substantial improvement in the gas-response and recovery characteristics was observed. The sensor exhibited enhanced sensitivity, characterized by a more pronounced and stable decrease in resistance upon NH_3 exposure. The improved performance was associated with enhanced surface roughness, reduced crystallite size, and higher carrier density, all of which promoted more efficient gas adsorption and faster charge transfer at the film-gas interface.

The 5% Cu-doped film (Figure 5) exhibited the highest sensing response among all compositions, with a sharp decrease in resistance and near-complete baseline recovery during the post-exposure phase. This superior performance was attributed to an optimized combination of surface-to-volume ratio, defect-induced active sites, and charge-carrier mobility. As discussed previously, this doping level also corresponded to the highest conductivity, reinforcing its role as the most structurally and electronically favorable composition for gas-sensing applications.

The 7% Cu-doped sample (Figure 5) showed a slight decline in sensor performance compared with the 5% Cu-doped film, although it maintained higher sensitivity than the undoped material. The reduced efficiency may result from the onset of dopant saturation, grain coalescence, and the possible formation of secondary Cu-based phases that partially block active sites or limit electrical conductivity [11, 30]. The larger grains and smoother surface texture observed by AFM may also contribute to reduced surface reactivity.

Among the investigated compositions, the 5% Cu-doped SnO_2 thin film emerged as the most promising candidate for gas-sensing applications. This selection was supported by a comprehensive evaluation of its physicochemical characteristics. Structurally, this film exhibited a bimodal crystallite-size distribution, with evidence of crystallographic reordering and moderate

strain relaxation, as revealed by XRD. Morphologically, the SEM and AFM analyses confirmed a high surface-area-to-volume ratio, improved grain uniformity, and reduced roughness, all of which enhanced surface interactions with gas molecules. Electrically, it exhibited the lowest resistivity and highest carrier mobility, facilitating efficient charge transfer. Collectively, these features indicate a favorable balance among surface reactivity, carrier transport, and structural integrity, making the 5% Cu-doped film an ideal candidate for detailed NH_3 -sensing evaluation.

The comparative cyclic response of the 5% Cu-doped SnO_2 thin film under successive exposures to NH_3 concentrations of 50, 100, and 150 ppm is presented in Figure 6. This response profile provides a detailed evaluation of the film's sensitivity, reproducibility, and operational stability under increasing analyte concentrations. Each exposure cycle exhibited a rapid, well-defined decrease in resistance upon NH_3 introduction, followed by a prompt and nearly complete return to baseline during the recovery phase. This behavior confirmed the reversible nature of NH_3 adsorption and desorption at the film surface, indicating robust gas-solid interface kinetics. As the NH_3 concentration increased from 50 to 150 ppm, the magnitude of the resistance change increased correspondingly in a linear and symmetric manner, reflecting consistent, concentration-dependent sensor behavior. The uniformity and repeatability of resistance modulation across the cycles demonstrated excellent sensing stability and minimal baseline drift, even at low gas concentrations. These features were attributed to the film's optimized microstructure, including its fine grain size, increased surface roughness, and enhanced carrier mobility, as previously confirmed by SEM, AFM, and Hall-effect measurements.

To quantify the sensitivity, the sensor response ($S = R_a/R_g$) was plotted against the NH_3 concentration, as presented in Figure 7. The response exhibited a clear linear trend over the tested range of 50–150 ppm, confirming predictable, concentration-dependent sensing behavior. This linearity is critical for accurate sensor calibration and indicates efficient modulation of the electronic-transport mechanism within the sensing layer.

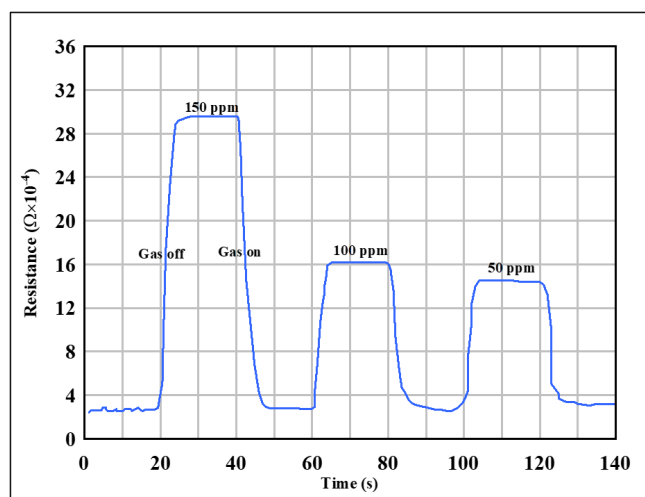


Fig. 6 Cyclic response of the 5% Cu-doped SnO₂ thin film under successive NH₃ exposures at concentrations of 50 ppm, 100 ppm, and 150 ppm

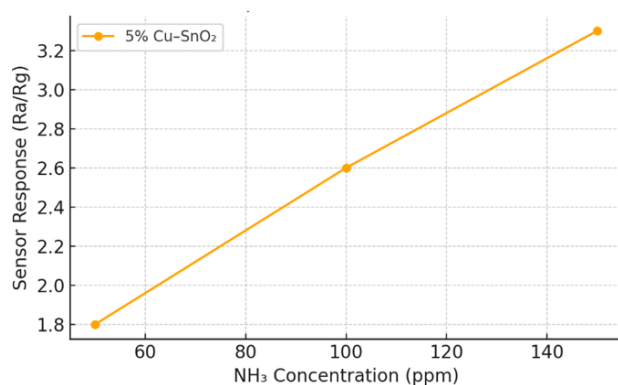


Fig. 7 Sensor response (R_a/R_g) of the 5% Cu-doped SnO₂ thin film as a function of NH₃ concentration (50, 100, and 150 ppm).

4 CONCLUSION

In the current study, Cu-doped SnO₂ thin films were synthesized via thermochemical decomposition and evaluated for their structural, morphological, electrical, and gas-sensing characteristics. Cu doping induced significant changes in crystallite size, lattice strain, and surface morphology. Electrical measurements confirmed enhanced carrier mobility and conductivity, especially at a Cu-doping level of 5%. Room-temperature gas-sensing tests revealed that the 5% Cu-doped film exhibited the highest sensitivity ($R_a/R_g \approx 3.9$ at 150 ppm), the fastest response (22 s), and stable cyclic behavior. These

combined results highlight the promising role of moderate Cu doping in optimizing SnO₂ films for high-performance NH₃ sensors operating at room temperature.

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Data availability

N/A

DECLARATIONS

Conflict of interest

The authors declare no competing interests

Consent to publish

N/A

Ethical approval

N/A

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