

Novel Au-modified Nano-SnS₂: synthesis, structural analysis, and enhanced gas sensing properties

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ABSTRACT

This study reports a facile synthesis of Au-modified Nano-SnS₂ composites through a combined water-thermal and in situ chemical reduction method, aimed at advancing low-temperature gas sensing technology. Comprehensive structural analyses using X-ray diffraction, scanning electron microscopy, transmission electron microscopy, and X-ray photoelectron spectroscopy confirmed that incorporation of Au nanoparticles significantly alters the nanostructure. The results reveal that optimal Au loading at 0.5 wt% refines the crystallite size from approximately 25 nm to 20–23 nm, while uniformly distributed Au particles with diameters of 3–5 nm effectively form Schottky junctions that enhance interfacial charge transfer. Gas sensing measurements demonstrate that the sensor response increases from 4.7 at 1 ppm to 22.6 at 10 ppm NO₂, and a linear correlation ($R^2 = 0.998$) was observed in the lower concentration range of 1–4 ppm. Furthermore, the optimal operating temperature decreased from 140°C for the unmodified sensor to 120°C, contributing to reduced power consumption. The transient response characteristics also improved markedly, with a response time of 42 s and a recovery time of 127 s, in contrast to 220 s and 520 s for the pristine material. Long-term stability tests over 40 days revealed less than 4% variation in sensor performance, and selectivity experiments confirmed a strong preference for NO₂ over other interfering gases. Overall, the synergistic effects of Au-induced electronic sensitization and catalytic activity result in enhanced sensitivity, faster kinetics, and excellent durability. These significant findings offer valuable insights for designing highly efficient sensors for environmental monitoring, paving the way for future sensor technology.

Keywords: Nanocomposite; Low-power; Schottky junction; Catalytic activity; Environmental monitoring.

1. INTRODUCTION

Novel Au-modified Nano-SnS₂ holds significant promise as a next-generation material for low-temperature gas sensors, addressing both the pressing environmental challenges and the technical limitations of current sensor technologies. In recent decades, increasing industrialization and the widespread use of fossil fuels have led to a surge in atmospheric pollutants, among which nitrogen dioxide (NO₂) is particularly notorious [1]. NO₂ not only contributes to smog and acid rain but also poses serious risks to human health by triggering respiratory ailments and other systemic disorders [2, 3]. Given this backdrop, the development of highly sensitive and selective NO₂ sensors that operate efficiently at low temperatures has emerged as a critical need in the fields of environmental monitoring and public health protection [4, 5]. From a materials science perspective, two-dimensional semiconductors such as tin disulfide (SnS₂) have garnered considerable interest due to their unique structural and electronic properties. SnS₂ is characterized by its layered architecture, which imparts a high specific surface area and an abundance of active sites for gas adsorption. These features are advantageous for gas sensing applications because they promote efficient interaction between the sensing material and target gas molecules [6, 7]. However, while SnS₂-based sensors have demonstrated promising sensitivity at low operating temperatures, their performance is often hindered by relatively slow response and recovery times. This limitation primarily arises from the intrinsic properties of the pristine material, which necessitates further modification to enhance its gas sensing kinetics [8, 9].

The introduction of noble metals, particularly gold (Au), onto SnS₂ surfaces offers an attractive strategy to overcome these limitations. Gold nanoparticles are well-known for their excellent catalytic properties and their ability to facilitate rapid electron transfer, phenomena that are critical for improving sensor performance [10, 11].

When Au is integrated with SnS_2 , several beneficial effects occur at the material interface [12]. First, the formation of Schottky junctions between Au and SnS_2 leads to a redistribution of charge carriers, which can effectively narrow the conduction channel and thereby amplify the sensor response upon NO_2 exposure. Second, the presence of Au nanoparticles induces an “electronic sensitization” effect, wherein the Au acts as an electron sink, promoting more efficient electron transfer from the SnS_2 conduction band to the adsorbed gas molecules [13]. Additionally, the catalytic activity of Au enhances the dissociation of oxygen molecules on the sensor surface, a process that further increases the density of active sites available for gas adsorption [14]. Together, these mechanisms not only improve the sensitivity but also accelerate the response and recovery times of the sensor. Despite the numerous studies investigating SnS_2 and its composites for gas sensing applications, significant gaps remain [15, 16]. Many previous investigations have focused on optimizing the morphology of SnS_2 —ranging from nanosheets to nanoflowers—to maximize surface area [17–19]. However, the precise interplay between Au nanoparticle size, distribution, and the resulting interfacial electronic properties has not been thoroughly explored. In particular, there is a need to better understand how the structural modulation of Au nanoparticles on SnS_2 can be leveraged to achieve an optimal balance between sensitivity, selectivity, and speed. Furthermore, the mechanisms underlying the enhanced gas sensing performance, especially in terms of interfacial charge transfer and catalytic effects, require more in-depth study from a materials engineering standpoint [20].

In this work, we aim to address these challenges by employing a straightforward water-thermal synthesis method combined with an in situ chemical reduction process to produce novel Au-modified Nano- SnS_2 . Our approach is designed to precisely control the deposition of Au nanoparticles onto the SnS_2 substrate, allowing us to tailor the interfacial properties and optimize the gas sensing performance [21]. By systematically varying the Au content, we investigate the effect of nanoparticle size and dispersion on both the structural characteristics and the gas sensing behavior. Our goal is to achieve a sensor that exhibits a significantly enhanced response to NO_2 at low operating temperatures, with markedly improved response and recovery times compared to pristine SnS_2 sensors [22]. The innovation of our study lies in three aspects: (i) the strategic use of an in situ chemical reduction method to achieve highly uniform and size-controlled Au nanoparticle deposition ($\sim 3\text{--}5\text{ nm}$) on SnS_2 nanoflowers, forming robust and reproducible Schottky junctions; (ii) the integration of comprehensive characterization techniques (XRD, SEM, TEM, BET, XPS) to systematically link nanoscale interfacial engineering with macroscopic sensing behavior; and (iii) the demonstration of superior gas sensing performance, including an ultralow detection limit ($<0.25\text{ ppm}$), significantly reduced response/recovery times ($42\text{ s}/127\text{ s}$), and long-term operational stability ($>40\text{ days}$), which collectively outperform previously reported Au/ SnS_2 systems. These innovations offer a new materials design strategy that addresses the persistent limitations in sensitivity, selectivity, and durability of low-temperature NO_2 sensors. Although room-temperature sensors have been developed, many still face challenges in achieving high sensitivity, fast response/recovery, and stability under real-world conditions. In contrast, our sensor operates effectively at a modest temperature of $120\text{ }^\circ\text{C}$, which is readily compatible with low-power microheaters, and demonstrates excellent sensing performance. This makes it highly applicable to air quality monitoring in urban settings, industrial leakage detection, and indoor environmental surveillance—scenarios where dependable sensitivity and response speed are more critical than ultra-low power operation.

2. MATERIALS AND METHODS

Tin(IV) chloride pentahydrate ($\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$, analytical grade, from Sinopharm Chemical Reagent Co., Ltd.), thioacetamide (TAA, $\geq 99\%$, obtained from Aladdin Industrial Corporation), chloroauric acid ($\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$, analytical grade, purchased from Macklin Biochemical Co., Ltd.), sodium citrate dihydrate (analytical grade, from Sinopharm), and L-lysine (analytical grade, supplied by Aladdin) were utilized as received without further purification.

The synthesis of Nano- SnS_2 was carried out using a hydrothermal method. In a typical procedure, 1.50 g of $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ was dissolved in 40 mL of deionized water under constant magnetic stirring at room temperature until a clear solution was obtained. Simultaneously, 1.20 g of thioacetamide was dissolved in 20 mL of deionized water. The thioacetamide solution was then slowly added dropwise to the tin precursor solution under vigorous stirring. After complete mixing, the resulting homogeneous solution was transferred into a 100 mL Teflon-lined stainless-steel autoclave. The autoclave was sealed and maintained at $200\text{ }^\circ\text{C}$ for 12 hours to ensure complete reaction and crystallization. During the hydrothermal process, the controlled temperature and pressure conditions facilitated the nucleation and growth of layered SnS_2 nanosheets, which gradually assembled into flower-like nanostructures. Upon completion of the reaction, the autoclave was allowed to cool naturally to room temperature. The resulting yellow precipitate was collected by centrifugation at 6000 rpm for 10 minutes and subsequently washed several times with deionized water and absolute ethanol to remove any residual reactants.

and impurities. Finally, the cleaned product was dried in a vacuum oven at 60 °C for 12 hours, yielding pure Nano-SnS₂ powders.

For the decoration of Au nanoparticles on the Nano-SnS₂, an in situ chemical reduction method was employed. A predetermined amount (typically 100 mg) of the as-synthesized Nano-SnS₂ was dispersed in 30 mL of deionized water by ultrasonication for 30 minutes to ensure a uniform suspension. To this suspension, 0.05 mL of 0.01 M HAuCl₄ solution was added under continuous stirring. After 10 minutes, 0.15 mL of a 0.01 M L-lysine solution was introduced; L-lysine served as both a stabilizing agent and a mild reducing agent. The reaction mixture was then allowed to stir at room temperature for an additional 30 minutes to facilitate the initial nucleation of Au ions onto the SnS₂ surface [23]. In the subsequent step, 0.1 mL of 0.1 M sodium citrate solution was added dropwise to the mixture. Sodium citrate acted as a strong reducing agent and helped control the growth and dispersion of Au nanoparticles on the SnS₂ nanosheets. The overall Au content was varied by adjusting the volume of HAuCl₄ solution added, allowing the preparation of samples with nominal Au loadings of 0.1, 0.3, 0.5, and 1.0 wt%. After a further stirring period of 30 minutes, the resulting Au-modified Nano-SnS₂ composite was collected via centrifugation, washed repeatedly with deionized water and ethanol, and dried at 60 °C in a vacuum oven for 12 hours.

The fabrication of the gas sensor devices began with the preparation of the sensing films. The Au-modified Nano-SnS₂ powders were first mixed with a small amount of deionized water to form a uniform paste by mechanical grinding [24]. This paste was then deposited onto pre-fabricated interdigital electrodes (IDEs) on alumina ceramic substrates. The IDEs, fabricated by screen-printing a gold paste and sintering at 850 °C, featured finger widths and inter-finger spacings of approximately 200 µm. The deposition of the Nano-SnS₂ paste onto the IDEs was performed via a dip-coating method to ensure a uniform and adherent film over the electrode surface [25]. After coating, the sensors were dried in an oven at 60 °C for 12 hours, ensuring complete solvent evaporation and robust adhesion of the sensing layer. A post-deposition thermal treatment was then carried out at 120 °C for 1 hour to further improve the electrical contact between the Nano-SnS₂ film and the electrodes.

The gas sensing measurements were carried out using a fully automated gas testing system assembled in our laboratory. The system comprised a computer-controlled gas mixing chamber capable of accurately regulating the concentration of NO₂ in the test atmosphere [26]. The sensor devices were mounted inside a sealed test chamber, where the operating temperature was controlled by an integrated heating element and monitored via thermocouples. Test gases, including NO₂ at various concentrations, were introduced into the chamber using a mass flow controller system, while a constant background of dry air was maintained to ensure reproducibility. The electrical response of each sensor was measured using an Agilent 34465A digital multimeter connected to a data acquisition system. The sensor response (S) was defined as the ratio of the resistance in the target gas (R_g) to the resistance in the background air (R_a) for NO₂ detection. Response and recovery times were determined by measuring the time required for the sensor resistance to reach 90% of the total change upon exposure to and subsequent removal of NO₂, respectively. For the selectivity tests, interfering gases including NH₃, methanol, ethanol, formaldehyde, benzene, and acetone were introduced at a fixed concentration of 4 ppm. These vapors were generated using a static volumetric method based on the ideal gas law, wherein precise volumes of liquid-phase chemicals were injected into a sealed chamber. The required injection volume was calculated using the formula:

$$V_{\text{liquid}} = \frac{C \cdot V_{\text{chamber}} \cdot M}{\rho \cdot R \cdot T}$$

as described in previous studies [27–29]. This approach ensured accurate and reproducible gas concentrations for comparative analysis.

The crystalline structure of the samples was analyzed using an X-ray diffractometer (Bruker D8 Advance) with Cu Kα radiation (λ = 1.5406 Å). The measurements were performed over a 2θ range of 10° to 80°, with a scanning step of 0.02° and a scanning speed of 2°/min. The tube voltage and current were set at 40 kV and 40 mA, respectively. The surface morphology of the synthesized samples was examined using a scanning electron microscope (JEOL JSM-7610F) operated at an accelerating voltage of 10 kV. Prior to SEM observation, the powdered samples were mounted on conductive carbon tape adhered to aluminum stubs and were sputter-coated with a ~5 nm thick layer of gold using a Quorum SC7620 sputter coater to prevent charging and enhance image contrast. Transmission electron microscopy (TEM) analysis was conducted using a JEOL JEM-2100 instrument operating at an accelerating voltage of 200 kV. For sample preparation, a small quantity of Au-modified Nano-SnS₂ powder was ultrasonically dispersed in ethanol, and a few drops of the suspension were deposited onto copper TEM grids coated with a lacey carbon film and dried under ambient conditions before analysis.

3. RESULTS AND DISCUSSION

3.1. Structure and morphology characterization

The XRD patterns (Figure 1) of the pristine Nano-SnS₂ sample exhibit distinct diffraction peaks at approximately 15.03°, 28.20°, 32.10°, 41.95°, and 49.90°, which correspond to the (001), (100), (101), (110), and (111) crystal planes, respectively, in agreement with the standard hexagonal phase (JCPDS #23-0677). Upon modification with Au nanoparticles, the overall pattern remains similar; however, subtle changes are evident. Specifically, the (001) diffraction peak shifts slightly from 15.03° in the pristine sample to approximately 15.12° in the sample with 0.5 wt% Au loading [30]. Similarly, the (101) peak exhibits a minor shift of 0.1° toward higher angles [31]. These peak shifts are indicative of lattice distortion, most likely caused by the incorporation of Au into the SnS₂ lattice or by strain effects induced at the interface between the Au nanoparticles and the SnS₂ nanosheets [32].

Moreover, in the XRD pattern of the sample with 1.0 wt% Au, a weak peak is observed at around 38.1°, which can be attributed to the (111) plane of metallic Au. The full width at half maximum (FWHM) values for the main peaks in the Au-modified samples are marginally broader than those for the pristine Nano-SnS₂, suggesting a reduction in the average crystallite size. Using the Scherrer equation, the average crystallite size for the pristine sample was calculated to be approximately 25 nm, while the Au-modified samples exhibited crystallite sizes in the range of 20 to 23 nm. These results support the notion that Au decoration induces a slight refinement in the crystallite dimensions, potentially due to localized strain and defects introduced during the reduction process [33].

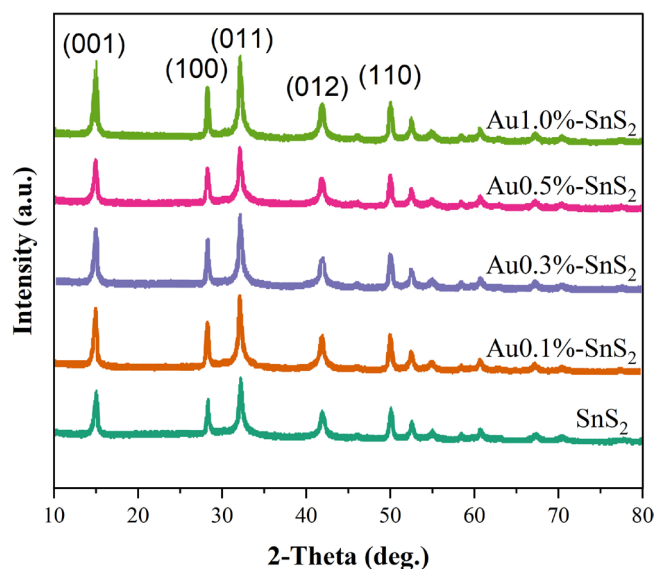


Figure 1: XRD patterns of pristine Nano-SnS₂ and Au-modified Nano-SnS₂ samples.

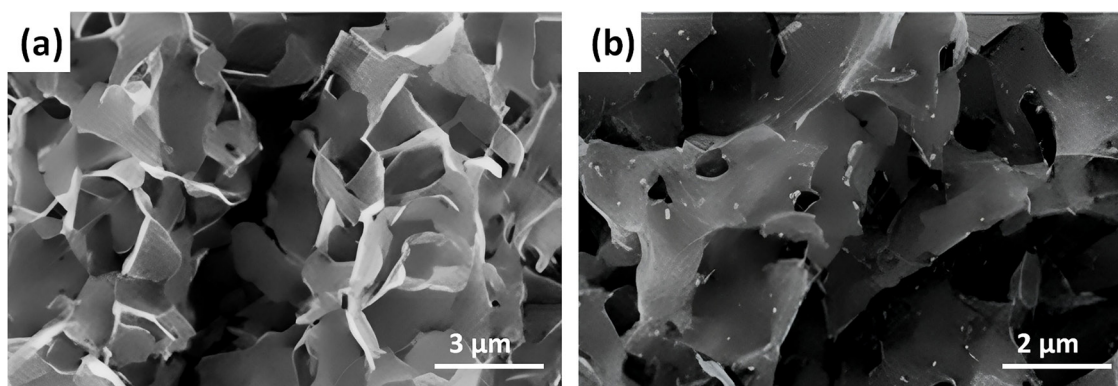


Figure 2: SEM images of (a) pristine Nano-SnS₂ at 20,000× magnification and (b) Au-modified Nano-SnS₂ at 50,000× magnification, showing a change in morphology after Au decoration.

The surface morphology of the synthesized samples was examined using SEM. Figure 2a shows the SEM image of pristine Nano-SnS₂, which reveals a well-defined flower-like structure. The nanoflowers are composed of numerous thin nanosheets that radiate outward, creating a hierarchical architecture with an average lateral dimension of approximately 3 μm and individual nanosheet thicknesses around 40 nm. This morphology is particularly beneficial for gas sensing applications as it offers a high specific surface area and numerous active sites for gas adsorption. In contrast, the SEM image of the Au-modified Nano-SnS₂ sample, as shown in Figure 2b, retains the overall flower-like morphology. However, a closer inspection reveals that the surfaces of the nanosheets are decorated with uniformly distributed nanoparticles [34]. These nanoparticles are not visible in the low-resolution SEM images of the pristine sample, suggesting that their presence is directly related to the Au modification process [35].

TEM analysis provides further insight into the nanostructural features. Figure 3 illustrates TEM and HRTEM images of the Au-modified Nano-SnS₂ sample. The TEM image confirms that the overall morphology of the nanoflowers remains intact after Au decoration. At higher magnification, the HRTEM images clearly show discrete nanoparticles, with diameters ranging from 3 to 5 nm, attached to the SnS₂ nanosheets [36]. The lattice fringes observed in the HRTEM images are well-resolved: one set of fringes with an interplanar spacing of 0.31 nm corresponds to the (001) plane of SnS₂, while another set, with a spacing of approximately 0.24 nm, is consistent with the (111) plane of metallic Au. These observations verify that Au nanoparticles have been successfully deposited on the SnS₂ surfaces and that they exhibit a crystalline structure. In samples with lower Au loading (e.g., 0.1 and 0.3 wt%), the Au nanoparticles are present but are sparser and occasionally tend to form small clusters; however, at an optimal Au content of 0.5 wt%, the nanoparticles are uniformly dispersed, minimizing agglomeration and ensuring maximal interface area between Au and SnS₂.

To further elucidate the correlation between morphology and sensing performance, BET and BJH analyses were conducted on both Nano-SnS₂ and Au-modified Nano-SnS₂ samples. As shown in Figure 4A, both samples exhibited type IV isotherms with H3 hysteresis loops, indicating mesoporous characteristics. The specific surface area of the pristine Nano-SnS₂ was calculated to be $\sim 73.22 \text{ m}^2/\text{g}$, whereas Au-modified Nano-SnS₂ showed a significantly higher value of $\sim 105.05 \text{ m}^2/\text{g}$, attributed to the uniform distribution of Au nanoparticles which prevent restacking of SnS₂ nanosheets and generate additional porosity. The BJH pore size distribution (inset of Figure 4B) revealed that both samples possess mesopores mainly centered around 3.2 nm (pristine) and 3.6 nm (Au-modified), which facilitate gas diffusion and active site accessibility. These structural enhancements play a critical role in the superior gas sensing performance of the Au-modified sample. Furthermore, bulk density measurements using the Archimedes method revealed that the density of pristine Nano-SnS₂ was $3.27 \text{ g}/\text{cm}^3$, while that of the Au-modified sample (0.5 wt%) was slightly reduced to $3.12 \text{ g}/\text{cm}^3$. This reduction in density aligns with the observed increase in surface area and porosity, indicating a less compact, more permeable nanostructure. The lower density is beneficial for gas sensing, as it promotes rapid gas diffusion

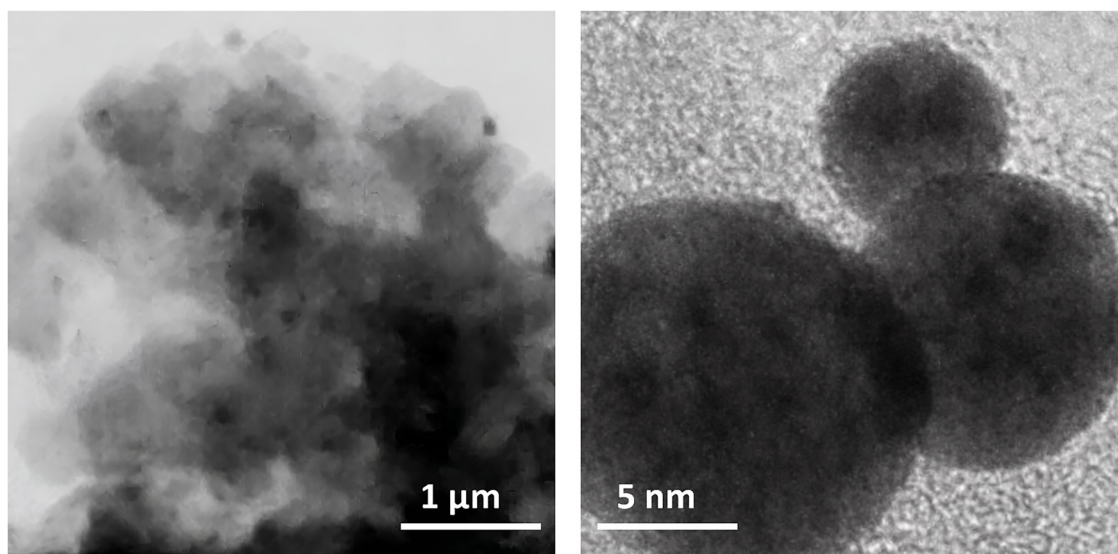


Figure 3: TEM and HRTEM images of Au-modified Nano-SnS₂.

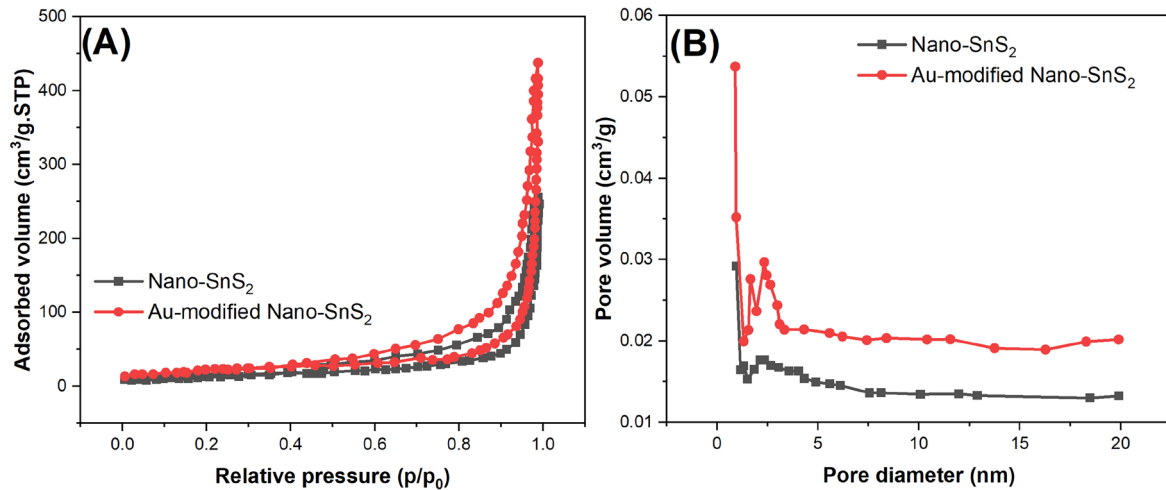


Figure 4: (A) Nitrogen adsorption-desorption isotherms of pristine Nano-SnS₂ and Au-modified Nano-SnS₂. (B) BJH pore size distribution curves showing mesoporous structures in both materials.

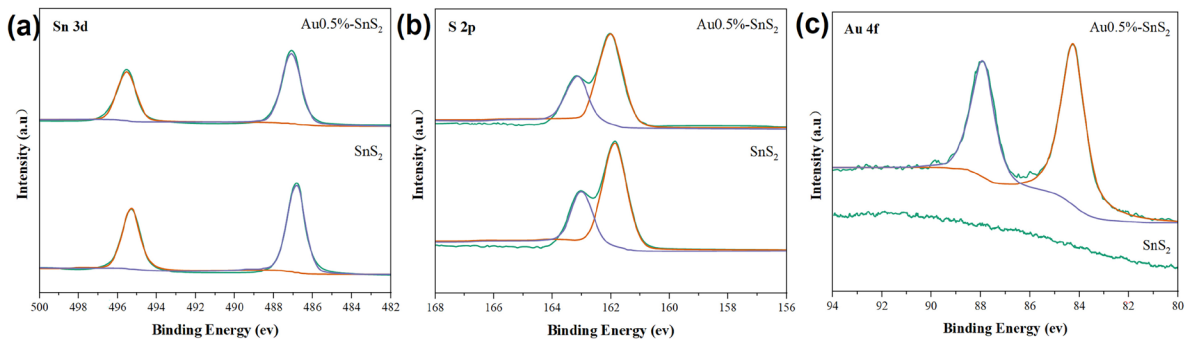


Figure 5: XPS spectra of Nano-SnS₂ and Au-modified Nano-SnS₂ samples showing the (a) Sn 3d, (b) S 2p, and (c) Au 4f regions.

and enhances the availability of active sites, thereby contributing to improved sensitivity and faster sensor dynamics.

To further understand the chemical composition and the electronic interactions within the composites, XPS measurements were conducted. Figure 5 shows the high-resolution XPS spectra for the pristine Nano-SnS₂ and the Au-modified Nano-SnS₂ samples. For the pristine sample, the Sn 3d spectrum displays two prominent peaks at binding energies of 486.4 eV (Sn 3d_{5/2}) and 494.8 eV (Sn 3d_{3/2}), which are characteristic of Sn⁴⁺ in SnS₂. The S 2p spectrum exhibits two peaks centered around 161.7 eV and 163.0 eV, corresponding to the S 2p_{3/2} and S 2p_{1/2} states, respectively. These binding energies confirm the formation of a stoichiometric SnS₂ phase. Upon Au modification, notable shifts in the binding energies are observed [37]. The Sn 3d peaks in the Au-modified sample shift by approximately 0.2 eV towards higher binding energies, while the S 2p peaks shift by about 0.15 eV towards lower binding energies. These shifts can be attributed to the strong electronic interaction between the Au nanoparticles and the SnS₂ nanosheets, suggesting a transfer of electrons from the SnS₂ to the Au, which is indicative of the formation of a Schottky barrier at the interface [38, 39]. Furthermore, the Au 4f spectrum for the Au-modified sample shows a clear doublet with peaks at 84.2 eV (Au 4f_{7/2}) and 87.8 eV (Au 4f_{5/2}), confirming the presence of metallic gold. The absence of any oxidized Au species implies that the reduction process was efficient and that Au exists predominantly in its zero-valent state.

EDS mapping analysis was employed to assess the elemental distribution in the composites. As illustrated in Figure 6, the EDS elemental maps of the Au-modified Nano-SnS₂ sample reveal a homogeneous distribution of Sn and S throughout the nanoflower structures. Additionally, discrete spots corresponding to Au are evenly distributed across the surface, with no evidence of significant agglomeration [40]. This uniform dispersion of Au nanoparticles supports the XPS findings and confirms that the in situ chemical reduction method employed for

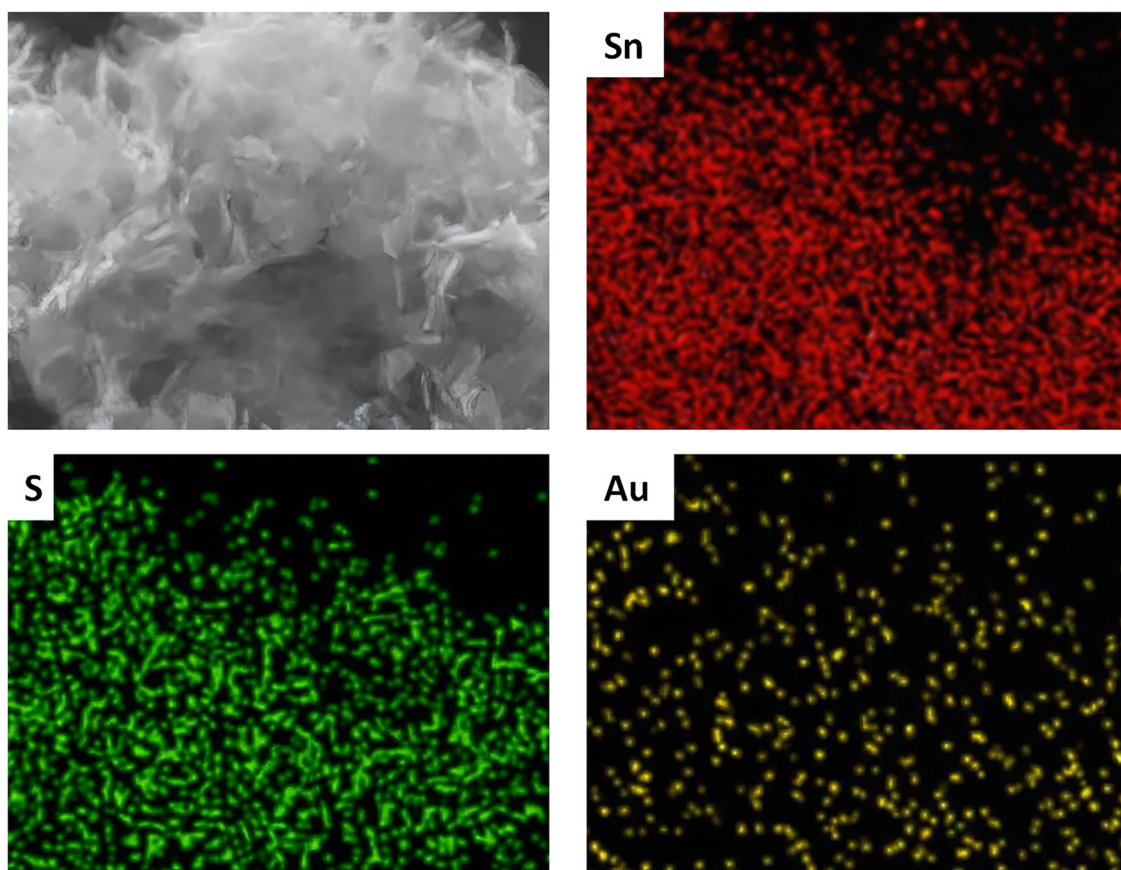


Figure 6: EDS elemental mapping images of an Au-modified Nano-SnS₂ sample, confirming the uniform distribution of Au, Sn, and S across the nanostructure.

Au decoration was successful. The consistency in the elemental distribution further suggests that the interfacial interactions between Au and SnS₂ are uniform across the sample, which is expected to have a beneficial impact on the gas sensing properties of the material [41].

3.2. Gas sensing performance testing

The gas sensing performance of the synthesized Au-modified Nano-SnS₂ sensors was evaluated under controlled laboratory conditions. In this section, we discuss the dynamic response characteristics, temperature dependence, transient response behavior, long-term stability and repeatability, selectivity towards NO₂ against various interfering gases, and finally compare the key performance metrics with those reported in the literature.

Dynamic response measurements were performed by exposing the sensors to a series of NO₂ concentrations ranging from 1 to 10 ppm at the optimal operating temperature. Figure 7 illustrates the dynamic response curves recorded for the Au-modified Nano-SnS₂ sensor. The sensor response (*S*), defined as the ratio of the sensor resistance in NO₂ (*R_g*) to that in air (*R_a*), increased gradually with the NO₂ concentration. The response values of the Au-modified Nano-SnS₂ sensor at each NO₂ concentration are now explicitly labeled in Figure 7 to facilitate direct comparison. Specifically, the sensor exhibited responses of 4.7, 8.6, 10.6, 13.1, 15.5, and 22.6 at 1, 2, 3, 4, 5, and 10 ppm NO₂, respectively. These values are annotated at the respective response peaks in the figure to enhance visual clarity and emphasize the sensor's high sensitivity and excellent linearity. A linear regression analysis of the response versus NO₂ concentration (within the lower concentration range of 1–4 ppm) yielded a coefficient of determination (*R*²) of 0.998, indicating a strong linear relationship. Based on the slope of this calibration curve and the baseline noise level, the limit of detection (LOD) was estimated using the standard formula $LOD = 3\sigma/S$, where σ represents the standard deviation of the baseline signal and *S* is the slope of the response curve. The calculated LOD was approximately 0.21 ppm, which confirms the high sensitivity of the Au-modified Nano-SnS₂ sensor toward NO₂. The sensor's low detection limit is estimated to be

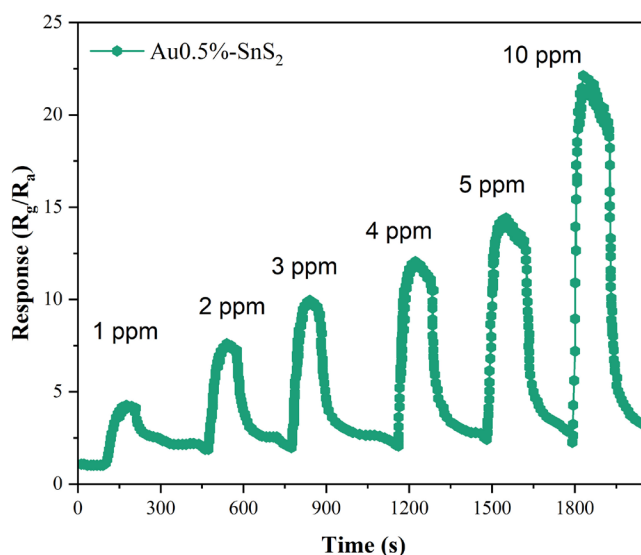


Figure 7: Dynamic response curves of Au-modified Nano-SnS₂ sensors to various concentrations of NO₂.

below 0.25 ppm based on the signal-to-noise ratio of the baseline resistance fluctuations. These results clearly demonstrate that the Au-modified Nano-SnS₂ sensor exhibits high sensitivity and excellent linearity over the tested concentration range [42]. To assess the influence of Au content on sensor performance, we systematically tested samples with Au loadings of 0.1, 0.3, 0.5, and 1.0 wt% under identical conditions. The results revealed a non-linear trend in sensing response. At 1 ppm NO₂, the response values were 3.1, 4.1, 4.7, and 3.5 for 0.1, 0.3, 0.5, and 1.0 wt% Au, respectively. At 10 ppm, the corresponding values were 14.3, 18.5, 22.6, and 17.2. While a moderate increase in Au content (0.3–0.5 wt%) significantly boosted the sensitivity due to enhanced catalytic activity and improved electron transfer via uniformly distributed Schottky contacts, excessive Au loading (1.0 wt%) resulted in a decline in response, likely due to nanoparticle agglomeration reducing effective surface area and electron mobility. Additionally, the optimal operating temperature for all Au-modified samples remained in the 120–130 °C range, but the 0.5 wt% sample displayed the fastest response/recovery times (42 s/127 s). These findings clearly demonstrate that 0.5 wt% Au provides the most favorable balance between catalytic activity, nanoparticle dispersion, and electronic sensitization. This optimal performance is attributed to the uniform dispersion and nanoscale size (3–5 nm) of Au particles at this composition, which ensures the formation of effective and evenly distributed Schottky junctions. These junctions facilitate enhanced electron depletion in SnS₂, thereby amplifying the sensor's response to NO₂. Simultaneously, the catalytic activity of finely dispersed Au promotes oxygen activation and accelerates NO₂ adsorption and desorption kinetics. Compared with lower Au contents (e.g., 0.1 and 0.3 wt%), 0.5 wt% provides a sufficient density of active Au sites; whereas higher loading (1.0 wt%) leads to particle agglomeration, which reduces interfacial contact and impairs both the electronic and catalytic enhancements. This interplay between structural uniformity and functional performance highlights 0.5 wt% Au as the most effective modification level in this study.

The sensor performance was further investigated as a function of operating temperature. Experiments were conducted at temperatures varying from 100 °C to 180 °C. Figure 8 presents the sensor response versus operating temperature curves for both pristine Nano-SnS₂ and Au-modified Nano-SnS₂ sensors. For the pristine sensor, the response to 4 ppm NO₂ peaked at around 140 °C. However, upon Au modification, the optimal operating temperature shifted significantly to approximately 120 °C, at which the response was maximized. This temperature shift can be attributed to the catalytic activity of the Au nanoparticles, which enhances oxygen activation and accelerates the gas adsorption process at lower temperatures [43, 44]. Additionally, the increase in carrier concentration with rising temperature is counterbalanced by the faster reaction kinetics induced by Au, leading to an overall improved sensor response at 120 °C. The data suggest that the Au modification not only increases sensitivity but also allows for lower power consumption by enabling operation at reduced temperatures.

Transient response measurements were performed to quantify the response and recovery times of the sensors. Figure 9 shows the transient response curves obtained when the sensors were exposed to 4 ppm NO₂. For the pristine Nano-SnS₂ sensor, the response time—defined as the time required for the sensor resistance to reach 90% of its total change—was measured to be approximately 220 seconds, while the recovery time was

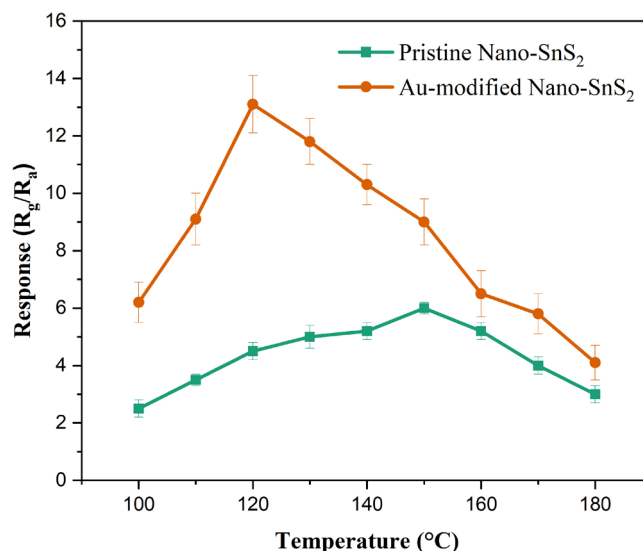


Figure 8: Response versus operating temperature curves for pristine and Au-modified Nano-SnS₂ sensors.

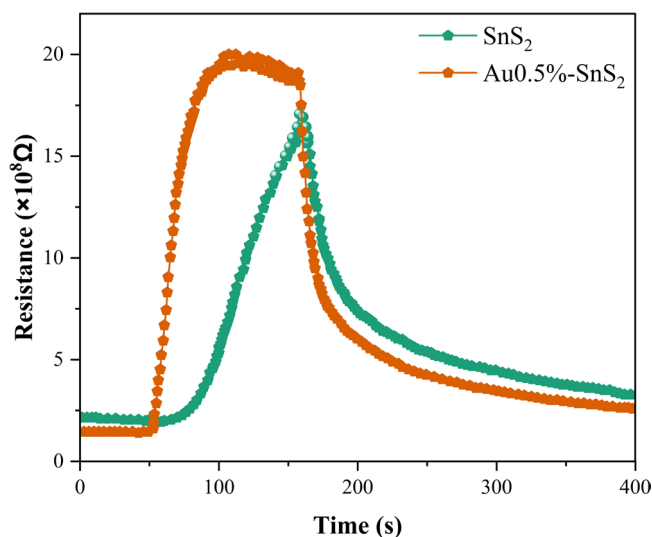


Figure 9: Transient response curves of Nano-SnS₂ and Au-modified Nano-SnS₂ sensors to NO₂.

around 520 seconds. In contrast, the Au-modified Nano-SnS₂ sensor exhibited markedly improved performance, with a response time of 42 seconds and a recovery time of 127 seconds. These improvements are indicative of the enhanced kinetics of gas adsorption and desorption processes facilitated by the Au nanoparticles [45]. The Au nanoparticles not only provide additional active sites for NO₂ adsorption but also promote rapid electron transfer through the formation of Schottky barriers, thus accelerating the overall sensor dynamics.

Long-term stability and repeatability are critical parameters for practical sensor applications. To assess these aspects, the Au-modified Nano-SnS₂ sensor was subjected to repeated exposure cycles to 4 ppm NO₂ over a period of 40 days. The sensor maintained a consistent response over multiple cycles, with deviation in the response value of less than 4% across all cycles. During the 40-day testing period, the sensor's baseline resistance and sensitivity remained stable, demonstrating excellent long-term reliability. This stability is likely due to the robust adhesion of the Au-modified Nano-SnS₂ film to the electrode substrate and the chemical stability of the composite material under continuous operation [46]. Such performance indicates that the sensor is well-suited for practical environmental monitoring applications where prolonged operation is required [47].

Selectivity is a crucial parameter in gas sensor performance, particularly in environments where multiple interfering gases are present. The selectivity of the Au-modified Nano-SnS₂ sensor was evaluated by exposing

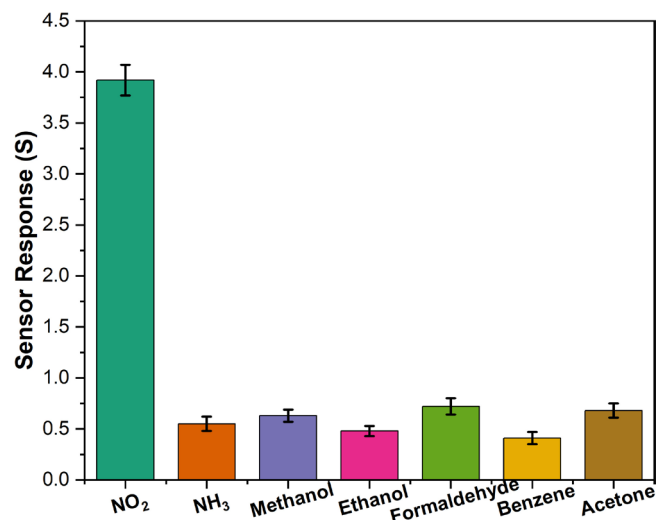


Figure 10: Selectivity of the Au-modified Nano-SnS₂ sensor, comparing its response to 4 ppm NO₂ with responses to various interfering gases at the same concentration.

it to several potential interfering gases, including ammonia (NH₃), various alcohols (such as methanol and ethanol), formaldehyde, benzene, and acetone, all at a concentration of 4 ppm. Figure 10 shows the selectivity, where the sensor response to NO₂ is compared with its response to these interfering gases. The Au-modified sensor exhibited a response of approximately 3.9 to 4 ppm NO₂, whereas the responses to NH₃, methanol, ethanol, formaldehyde, benzene, and acetone were significantly lower, typically ranging between 0.4 and 0.8. This marked difference underscores the sensor's high selectivity towards NO₂. The enhanced selectivity can be ascribed to the specific interactions between NO₂ molecules and the Au-modified surface, where the Au nanoparticles facilitate preferential adsorption and rapid charge transfer for NO₂, while the adsorption of other gases is comparatively less favorable [48].

To further contextualize the performance of our Au-modified Nano-SnS₂ sensor, we compared its sensing parameters with those of previously reported NO₂ sensors. Our sensor exhibits a high response of 22.6 to 10 ppm NO₂ at a relatively low operating temperature of 120 °C, with fast response and recovery times (42 s and 127 s, respectively). In comparison, ZHU *et al.* [13] reported a response of 18.2 at 10 ppm NO₂ for Au-decorated 3D SnS₂ at 130 °C, but with longer response/recovery times of 60 s and 180 s. ZHANG *et al.* [24] demonstrated a response of ~12.4 at 10 ppm NO₂ for Au-modified SnS₂ sheet flowers, but required an operating temperature of 150 °C. Similarly, NGUYET *et al.* [22] achieved a response of ~15.6 at 10 ppm using ultrathin SnS₂ nanoplates, though their device operated at 140 °C and exhibited slower kinetics. These comparisons confirm that our Au-modified Nano-SnS₂ sensor achieves superior performance at lower temperatures with faster dynamics, validating the effectiveness of our synthesis strategy and interfacial engineering.

The enhancement in gas sensing performance of the Au-modified Nano-SnS₂ sensor is fundamentally attributed to the interfacial interactions between the Au nanoparticles and the SnS₂ nanosheets. To elucidate the gas sensing mechanism, it is essential to consider both the electronic sensitization effects introduced by Au and the surface chemical processes involved in NO₂ detection. In air, oxygen molecules are adsorbed onto the SnS₂ surface and ionized by capturing electrons from the conduction band, forming reactive oxygen species such as O₂⁻, O⁻, and O²⁻. These species generate an electron depletion layer (EDL) near the surface, increasing the sensor's resistance. When NO₂, a strong oxidizing gas, is introduced, it interacts directly with the adsorbed oxygen species or with surface electrons, extracting additional electrons from the semiconductor. This leads to a further widening of the EDL, resulting in a significant increase in resistance, which is detected as the sensor response.

Upon Au decoration, several synergistic effects enhance this process. First, Au nanoparticles form Schottky junctions with the n-type SnS₂ due to their higher work function (~5.1 eV for Au vs. ~4.3 eV for SnS₂). This induces band bending and establishes an additional EDL at the metal-semiconductor interface, which facilitates charge separation and electron depletion in the vicinity of the Au-SnS₂ contact. Consequently, the baseline resistance of the sensor increases, and its sensitivity to NO₂ improves. This phenomenon is supported by the XPS results, which show a shift in the binding energies of Sn and S after Au modification, indicating interfacial charge redistribution [49]. Second, the Au nanoparticles serve as catalytic sites for the adsorption and

dissociation of oxygen and NO₂ molecules. Au can enhance the chemisorption of NO₂ by lowering the activation energy required for surface reactions, thereby accelerating the reaction kinetics. Furthermore, the “spillover effect” enables oxygen species activated on the Au surface to migrate onto the SnS₂ surface, increasing the density of reactive sites available for gas interaction. This is especially critical at low operating temperatures, where catalytic assistance becomes essential for maintaining high reactivity. Third, the nanometric size and uniform dispersion of the Au particles (~3–5 nm) maximize the interfacial area and reduce the likelihood of particle aggregation, thereby ensuring consistent performance. The resulting Au–SnS₂ heterojunction structure facilitates fast electron transport, improves adsorption dynamics, and shortens response and recovery times.

Overall, the integration of Au nanoparticles onto the Nano-SnS₂ matrix results in a synergistic effect that significantly improves the gas sensing performance. The electronic sensitization provided by the Au nanoparticles, in combination with their catalytic action and the spillover effect, results in an increased density of active sites, a reduced energy barrier for charge transfer, and a more rapid response to NO₂ exposure. These effects collectively contribute to a higher response amplitude, reduced response and recovery times, and enhanced stability and selectivity of the sensor.

4. CONCLUSION

In conclusion, our study successfully demonstrated the synthesis, characterization, and enhanced gas sensing performance of Au-modified Nano-SnS₂ sensors, synthesized via a water-thermal method coupled with an in situ chemical reduction process. The incorporation of Au nanoparticles, with loadings ranging from 0.1 to 1.0 wt% and an optimal content of 0.5 wt%, resulted in a significant refinement of the crystallite size from approximately 25 nm in pristine Nano-SnS₂ to 20–23 nm, while uniformly dispersed Au particles exhibited diameters of 3–5 nm. XRD analysis revealed slight lattice distortions, with the (001) peak shifting from 15.03° to 15.12° and the (101) peak moving by 0.1°, confirming the formation of effective Schottky junctions that enhanced electron transfer at the Au/SnS₂ interface. Gas sensing tests showed that the sensor response increased from 4.7 at 1 ppm to 22.6 at 10 ppm NO₂, with a linear correlation ($R^2 = 0.998$) observed in the 1–4 ppm range. Furthermore, the optimal operating temperature was reduced from 140 °C for the pristine sensor to 120 °C for the Au-modified device, thereby lowering power consumption. Transient response measurements demonstrated a dramatic improvement, with the Au-modified sensor achieving a response time of 42 s and a recovery time of 127 s, compared to 220 s and 520 s for the unmodified sensor. Long-term stability tests conducted over 40 days exhibited less than 4% variation in response, while selectivity assessments confirmed a marked preference for NO₂ over interfering gases. Overall, the synergistic effects of electronic sensitization and catalytic activity introduced by the Au nanoparticles significantly boosted sensor performance, underscoring the potential of the Au-modified Nano-SnS₂ sensor for low-temperature environmental monitoring and advanced gas detection applications. These comprehensive findings validate our design strategy and pave the way for further optimization and commercialization of cost-effective, high-performance sensors effectively addressing diverse real-world environmental monitoring challenges.

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