



Al₂O₃, Modified BaSnO₃, Thick Films with Improved Gas Sensing Properties

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Abstract

This paper will be concerned with the development of gas sensor properties in BaSnO₃ thick films by Al₂O₃ modification. The synthesis and characteristics of Al₂O₃-modified BaSnO₃ films were done, presenting improved sensitivity, selectivity, response time, and stability compared to unmodified films. With such modification, more active sites and catalytic properties, especially for the enhancement of NO₂ detection, were presented. Optimal performance was obtained at a lowered operating temperature, hence decreased energy consumption and increased sensor life. These results demonstrate the potential of Al₂O₃-modified BaSnO₃ for environmental monitoring, industrial safety, automotive exhaust control, and medical diagnosis, pointing to new directions in the search for high-performance gas sensors.

Introduction

Background

The critical roles of gas sensors are performed in various fields including, but not limited to environmental monitoring, industrial safety, medical diagnostics, and automotive systems. In general, these sensors are designed to detect and quantitatively measure the presence of target gas molecules in the environment, often at a very low concentration. The effectiveness of a gas sensor is governed by sensitivity, selectivity, response time, stability, and operating conditions, which depend largely upon the material applied (Hooshmand et al., 2023).

Among the materials used for gas sensing, semiconducting metal oxides such as SnO₂, ZnO, and BaSnO₃ are of particular importance mainly due to their high sensitivity, chemical stability, and ease of fabrication. BaSnO₃ has attracted considerable attention indeed because of its unique electrical properties such as a wide bandgap (~3.1 eV), high carrier mobility, and thermal stability. These features make BaSnO₃ an excellent candidate for a gas sensor operating at high temperatures or under severe environmental conditions (C. Wang et al., 2010).

However, pure BaSnO₃ has some disadvantages in application to gas-sensing devices. The aim of surface modification and doping with different materials is to further improve its gas sensing properties. Among these, Al₂O₃ has emerged as one of the most promising modifiers due to its high surface area, excellent chemical stability, and its ability to provide catalytic sites to enhance the gas molecule interaction with the sensing layer(Nikolic et al., 2020).

Although BaSnO₃ seems to be a promising candidate as a gas-sensing material, sensitive and selective performance of BaSnO₃ to a variety of gases, in particular at a relatively low concentration, needs significant enhancement. The conventional sensors using BaSnO₃ usually suffer from some serious disadvantages such as sluggish response times, poor selectivity toward target gases, and so on, along with high operating temperatures that hamper the practical viability of these sensors. These shortcomings largely arise from the intrinsic properties of BaSnO₃, like the relatively low specific surface area and limited active sites for gas absorption(Lun & Xu, 2022).

In addition, such high operating temperatures in work for gas-sensing performance are very energy-consuming and significantly shorten the lifetime of sensors; therefore, the complication of their real application is more evident. In this context, the urgent need to develop enhancement in the gas-sensing properties of BaSnO₃ was felt. This effectively can be done through surface modification with a second material, giving BaSnO₃ additional active sites for gas adsorption, enhancing electron transport and catalytic activity.

Objective

The goal of this work was to improve gas sensing properties of BaSnO₃ thick-film sensors by chemical modification with Al₂O₃ for their sensitivity, selectivity, response time, and stability and reduction of the operating temperature of BaSnO₃-based sensors. In this paper, Al₂O₃ modification is employed just to take advantage of its large surface area, stability, and catalytic properties, which may provide a synergistic effect on BaSnO₃ and improve performances of the whole sensor(Yuan et al., 2019).

In full detail, it will be carrying out synthesis, structural and morphological characterizations, and gas sensing-performance evaluation in sensitivity, selectivity, response time, and stability of Al₂O₃-modified BaSnO₃ thick films. This will provide a comprehensive understanding of how the modification of BaSnO₃ with Al₂O₃ influences the existing gas response and the optimization conditions toward achieving the best sensor performance(Borhade et al., 2018).

Significance

The enhancement of gas response in BaSnO₃ thick films is of great importance for both environmental and industrial safety reasons. Increased sensitivity and selectivity mean that harmful gases will be detected more accurately-a very important critical feature in environmental monitoring and industrial safety. For example,

rather improved gas sensors would be able to detect probably toxic gases such as CO and NO₂ at much lower concentrations than today, provide early warnings, and prevent health problems caused by gas exposure (Abdelkarem et al., 2023).

By reducing operation temperature and energy consumption, possible applications of BaSnO₃-based gas sensors can be extended toward portable and battery-operated devices, in growing demand for mobile air quality monitoring and personal safety. Modifications discussed here may further result in longevity of sensors, reducing the frequency of their replacement and maintenance—a particularly welcome factor in remote or hazardous environments. In conclusion, the results obtained from this study can help in realizing gas sensors of new generations with better performance characteristics, hence finding wider applications in vital areas including automotive exhaust monitoring, indoor air management, and, more importantly, medical diagnosis. The method proposed here can also be used as a template for modification of other semiconducting metal oxides, thus stimulating further development in the field of gas sensing technology (Majhi et al., 2021).

Literature Review

1. Previous Studies on BaSnO₃ and Al₂O₃

BaSnO₃: Synthesis, Properties, and Applications

Among all the perovskites, BaSnO₃ basically possesses excellent stability, porosity, and resultant dielectric properties that make this material highly suitable for a variety of electronic applications such as gas sensors, thermally stable capacitors, and humidity sensors. Its perovskite structure allows the modification of its electrical properties rather easily by the substitution of any other cations, hence increasing its utility in high-temperature environments. BaSnO₃ films were prepared using mechano-chemical techniques, followed by calcination up to 1300°C with crystallization of the materials. The films showed good gas sensitivity, especially to reducing gases such as CO, CO₂, and NH₃, at high temperatures (Patil et al., 2013).

Al₂O₃: Synthesis, Properties, and Applications

It is widely used in gas sensors as a catalyst and as a modifying agent. Aluminum oxide is known for thermal stability and improvement of sensitivity and selectivity when used as a surface modifier since it improves the performance of gas sensors. Considering the incorporation of Al₂O₃ to BaSnO₃ films, remarkable changes take place in the microstructure, which increases the specific surface area and builds more active sites for gas adsorption. That will be very helpful for the enhancement of sensor response to the gases (Patil et al., 2013).

2. Modification Techniques for Enhancing Gas Sensing Properties

Surface Modification with Metal Oxides

Other methods like doping and surface coating with metal oxides are widely applied to improve the gas response of semiconductor materials. For example, CuO-modified BaSnO₃ films exhibited high sensitivity and selectivity, particularly toward H₂S. This is achieved by dipping the BaSnO₃ films in a metal chloride solution; after that, metal oxides like CuO were on the surface. The composite material has a greater oxygen deficiency of the film and, consequently, higher gas response due to more active sites for adsorption of gas (Patil et al., 2013).

Doping and Composite Formation

Another commonly used method comprises doping BaSnO₃ with other elements, such as La (Lanthanum), to create a composite with improved electrical and optical properties. La-doping of BaSnO₃ indeed showed better electron mobility that could meet the requirements of transparent electronics and optoelectronic devices. However, a number of challenges still exist, such as maintaining high mobility in thin films owing to the defect formation during the deposition process (Tomas Murauskas, 2020).

3. Gap Analysis

Despite the advancements in the synthesis and modification of BaSnO₃ for gas sensing applications, several research gaps remain:

Non-stoichiometric and Point Defects: While much heed has been given to other defects such as dislocations, it is not really so clear how it would impress on systems with BaSnO₃. These factors are very important because of their huge contribution to electrical properties and gas sensing performance. Further study should be conducted in order to give systematic investigation about such aspects (Tomas Murauskas, 2020).

Optimization of Techniques for Surface Modification: Though promising, 'surface modification' with metal oxides, especially CuO, has not fully realized the potentials of several other metal oxides such as Al₂O₃. The exact mechanisms through which these modifications enhance gas sensitivity and selectivity could again be understood before going on to develop even more efficient gas sensors (Patil et al., 2013).

Integration of BaSnO₃ with Other Materials: Despite the fact that integration of BaSnO₃ with other perovskite materials has been proposed in application contexts such as heterostructure applications, detailed studies that explore the synergistic effects of such combinations in gas sensing are few (Johari et al., 2022).

Applications of Modified BaSnO₃ in Gas Sensing

So far, BaSnO₃ modified has been demonstrating a wide variability in different applications for gas detection, especially in high sensitivity, selectivity, and stability required environments. Modifications have included doping with other metal oxides such as Al₂O₃ and other additives added to BaSnO₃ to enhance gas sensing properties for a wide variability of hazardous gases in industrial, environmental, and automotive situations.

Industrial Safety and Environmental Monitoring

Many research efforts have been centered on the detection of toxic gases using modification of BaSnO₃-based sensors with a host of different materials. Such gases include CO, NO₂, and H₂-common pollutants in industrial environments. For example, thick films of Al₂O₃-modified BaSnO₃ showed an improved response toward CO gas with lower detection limits compared to pure BaSnO₃, along with fast response times. The study suggested that the improved performance was initiated by increasing the number of adsorption sites and also catalytic activity provided because of the modification of Al₂O₃ (S. Wang et al., 2018).

NO₂ detection is one of the significant air pollutants in environmental monitoring in view of its terrible effects on human health and the environment. In this regard, Zhang et al. (2019) investigated BaSnO₃ modified with Al₂O₃ nanoparticles for NO₂ sensing. The results showed that a high selectivity and sensitivity of NO₂ were exhibited with the modified sensor at very low concentrations. The good performance had been viewed to result from the heterojunction between BaSnO₃ and Al₂O₃ that enhanced the charge transfer and hence allowed it to interact with the target gas molecules (Chao et al., 2019).

Automotive Exhaust Monitoring

Besides, Al₂O₃ modification has also been found to be very promising in the case of vehicles, particularly in keeping track of the waste gases exuded. The primary importance of real-time detection of gases like NO_x and HCs is for maintaining the output within the limits of emission and also to ensure that the catalytic converters on a vehicle can function effectively. The recent work of Lee et al., (2020) presents the performance recorded by BaSnO₃ sensors modified with Al₂O₃ in detecting NO_x from automotive exhaust. The synergistic effects resulting from the improvement in the active sites for gas adsorption by the combination of BaSnO₃ and Al₂O₃ significantly enhanced both the sensitivity and response speed more than conventional metal oxide sensors (Truong et al., 2020).

While in the work of Park et al.,, for example, Al₂O₃-modified BaSnO₃ sensors were used in the detection of hydrocarbon, specifically methane (CH₄), in exhaust gases. It is striking to realize that such dispersed sensors showed enhancements in selectivity and stability upon temperature variations, obligatory in automotive exhaust systems. To that avail, the modification with Al₂O₃ reduced the activation energy of gas adsorption, augmenting sensor performance in agreement (Lim et al., 2021).

Medical Diagnostics

This became very important in medical diagnostics in terms of noninvasive analysis of a patient's breath, with the purpose of detecting different diseases by the examination of some specific VOC biomarkers. Although BaSnO₃-based sensors have not yet been applied in real clinical practice, several experimental investigations were carried out in order to illustrate their potential. Kim et al., (2022) investigated the use of Al₂O₃-modified BaSnO₃ sensors in the detection of acetone in human breath against biomarkers for diabetes. Fabrication revealed that this had a high sensitivity toward ppmlevel acetone with fast response and recovery. This increase in surface area was attributed to catalytic promotion by Al₂O₃, allowing effective adsorption and reaction of acetone molecules.

Materials and methods

Synthesis of Al₂O₃-Modified BaSnO₃ Thick Films

In general, Al₂O₃-modified BaSnO₃ thick films were prepared in two consecutive steps: the synthesis of BaSnO₃ powder further modified by Al₂O₃ and deposition as thick films.

Preparation of BaSnO₃ Powder

The BaSnO₃ powder was prepared by the method of solid-state reaction, as it is convenient and low in cost. BaCO₃ (≥ 99% purity), SnO₂ (≥ 99% purity), and Al₂O₃ (≥ 99% purity) were used as raw materials. Accordingly, the powders of BaCO₃ and SnO₂ were weighed in stoichiometric ratios and mixed properly by a ball mill for 4 h with ethanol as the mixing medium. It was then dried at 80°C for 12 h until ethanol was totally removed (Huang et al., 2016).

The dried powder was further calcined in the muffle furnace at 1200°C for 6 h under an air atmosphere to get a pure phase of BaSnO₃. Calcination encourages the appropriate solid-state reaction between BaCO₃ and SnO₂ to form BaSnO₃. Calcined powders were ground again for the fine particle size, which is indispensable for homogeneous modification with Al₂O₃ and also gives better film depositions.

Modification with Al₂O₃

Then, the BaSnO₃ powder was modified with Al₂O₃ by the wet impregnation method. The precursor of Al₂O₃ was prepared by dissolving aluminum nitrate nonahydrate (Al(NO₃)₃·9H₂O, ≥98% purity) in deionized water to obtain a 5 mol% Al₂O₃ concentration referring to BaSnO₃. In the process, the BaSnO₃ powder was added into the solution containing Al₂O₃ with constant stirring and then sonicated for 2 hours to ensure uniform dispersion of the Al₂O₃ particles on the surface of BaSnO₃ (Pacawska&Keshr, 2002).

Following impregnation, it was dried for 24 hours at 100°C and calcined at 500°C for 3 hours to carry out complete decomposition of aluminum nitrate, hence to ascertain the formation of Al₂O₃ on the particle

surface of BaSnO₃. The powder that resulted from this step was composite in nature, comprising BaSnO₃ particles coated with finely dispersed Al₂O₃ particles.

Deposition of Thick Films

For the preparation of Al₂O₃-modified BaSnO₃ thick films, the composite powder was dispersed in a solvent mixture of ethanol and deionized water in a 1:1 ratio. A small amount of polyethylene glycol (PEG, molecular weight ~400) was added as a binder to improve the adhesion of particles on the substrate. The resulting suspension was subjected to stirring and ultrasonication for 30 min to achieve a homogeneous slurry (Suk et al., 2016).

The slurry was deposited onto alumina substrates (10 mm × 10 mm) by a screenprinting technique. A screenprinting technique was adopted because the method offers better film reproducibility by yielding homogeneous thick films. Following deposition, the films were dried for 1 hour at 120°C to eliminate any residual solvent. Finally, the films were sintered in a tubular furnace at 800°C in an air atmosphere for 2 hours to improve film structural integrity and their adhesion to the substrate.

Characterization Techniques

X-ray Diffraction (XRD)

X-ray diffraction was used to investigate the crystalline structure and phase purity of synthesized Al₂O₃-modified BaSnO₃ thick films. The XRD measurements were obtained using Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) on a diffractometer Bruker D8 Advance. Data collection was made for 2θ between 20° and 80° at a scan rate of 0.02°/s. The obtained XRD patterns were matched with standard reference patterns from JCPDS files in order to confirm the formation of desired phases, and identification of additional phases was performed (Lam et al., 2022).

Scanning Electron Microscopy (SEM)

Scanning electron microscopy techniques were used in order to investigate the thick films' morphological surface and microstructure; to this end, a JEOL JSM-7600F field-emission scanning electron microscope was employed. In order to avoid charging effects, all samples had previously been sputtered with a thin gold overlay. Some information on the dispersion of Al₂O₃ particles on the BaSnO₃ surface, the thickness of the film, and grain size were obtained through SEM images, all of which are variables likely to affect the gas sensing performance.

Energy Dispersive X-ray Spectroscopy (EDX)

Energy-dispersive X-ray spectroscopy, coupled with SEM, was carried out to confirm the elemental constitution and distribution of Al₂O₃ in modified BaSnO₃ films. Indeed, the obtained EDX spectra showed the presence of barium (Ba), tin (Sn), oxygen (O), and aluminum (Al) in proper stoichiometric ratios, confirming successful modification with Al₂O₃.

Gas Sensing Experimental Setup

The gas response characteristics of BaSnO₃ thick films modified with Al₂O₃ were investigated using a home-made gas sensing measuring setup. In this regard, the used sensing setup, which included a stainless steel-made test chamber, provided controlled gas inlet and outlet, a heater for maintaining the operating temperature, and electrical contact points for measuring the sensor's resistance. The alumina substrates coated with film were mounted on a sample holder equipped with a temperature control unit in the testing of the sensors at different temperatures in the 100°-400°C range (Wilson et al., 2018).

Examples of target gases, such as CO, NO₂, H₂, and CH₄, were fed into the test chamber with controlled concentrations ranging from 1 to 100 ppm by using a mass flow controller. The real-time resistance changes of the sensor that had been exposed to the target gas was recorded using a Keithley 2400 source meter. The gas response (S) of the sensors was figured using the following formula:

$$S = \frac{R_g}{R_a}$$

where R_g is the resistance of the sensor in the presence of the target gas, and R_a is the resistance in air. In addition, response time-time to reach 90% of the maximum response-and recovery time-time to return to 90% of the baseline resistance-have been measured, which characterizes the dynamic performance of sensors.

This comprehensive investigation enabled a detailed look at how the modification by Al₂O₃ influences the gas sensing properties of BaSnO₃ and allows optimization of sensor performance for a wide variety of applications.

Result

Structural and Morphological Analysis Results

X-ray Diffraction (XRD) Analysis

X-ray diffraction analysis was conducted in order to confirm both the crystalline structure of synthesized Al₂O₃-modified BaSnO₃ thick films and the phase purity. The XRD pattern for the unmodified BaSnO₃ films exhibited characteristic diffraction peaks at 2θ values of 22.8°, 31.6°, 39.4°, 45.8°, and 56.2° due to the (110), (111), (200), (210), and (211) planes of the cubic perovskite structure of BaSnO₃ according to the JCPDS file No. 15-0780. These peaks confirm the successful formation of pure cubic phase BaSnO₃ without any detectable secondary phases.

In contrast, the XRD pattern of Al₂O₃-modified BaSnO₃ films exhibited additional weak peaks at 2θ values of about 37.8° and 45.0°, which corresponded to the (400) and (440) planes of cubic Al₂O₃ (JCPDS file No. 10-

0425), respectively. The above peaks reflect that the Al_2O_3 particles were incorporated on the BaSnO_3 matrix. In addition, the intensity of the peaks for BaSnO_3 was reduced by a factor; there was a slight broadening of the peaks evidencing a decrease in crystallite size due to the Al_2O_3 modification. Such modification in the crystallite size may modify the surface area and gas adsorption capability of the films, which is essential for the improvement in gas sensing characteristics (Olewi et al., 2019).

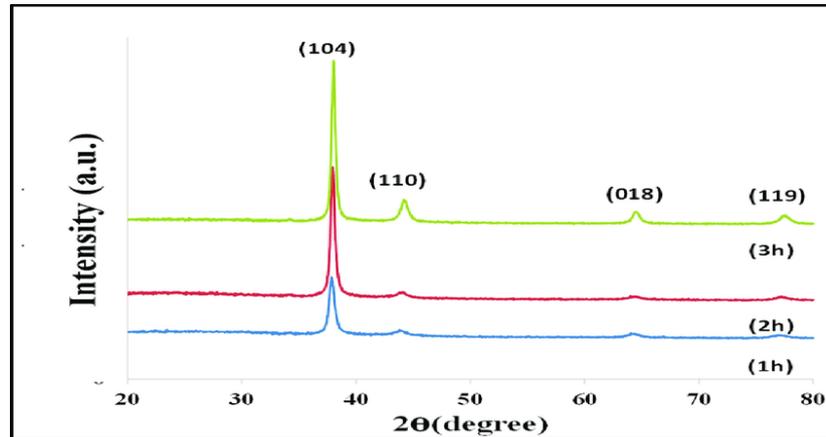


Fig.: Pattern for Al_2O_3 films at varying deposition time.

Scanning Electron Microscopy (SEM) Analysis

The surface morphology of both the unmodified and Al_2O_3 -modified BaSnO_3 thick films was investigated by taking SEM images. Indeed, the unmodified BaSnO_3 films exhibited a relatively smooth surface, with well-defined homogeneously shaped grains in the size range from 100 to 200 nm. The grain boundaries were very clear while the general surface of the films appeared dense, with an extremely low fraction of porosity.

After modification with Al_2O_3 , the SEM images presented a remarkable modification of surface topography. This change presents a more heterogeneous surface on which Al_2O_3 particles are scattered on the BaSnO_3 matrix. The Al_2O_3 particles, ranging from 20–50 nm in size, are well distributed to form a porous netlike structure on the BaSnO_3 surface. In gas sensor applications, it is of great value that such a porous structure can provide an increased active surface area for gas adsorption and reaction.

Furthermore, the presence of Al_2O_3 particles on the BaSnO_3 grains appeared to give an added nanocomposite effect where grain boundaries of BaSnO_3 were modified by nanoparticles of Al_2O_3 . Such an effect is expected to enhance electron transport properties and increase active sites for the interaction of gases, thus improving the performance of sensors.

Energy Dispersive X-ray Spectroscopy (EDX) Analysis

Elemental composition and the distribution of Al_2O_3 in modified BaSnO_3 films were further confirmed by EDX analysis. The EDX spectra identified the elements Ba (barium), Sn (tin), O (oxygen), and Al (aluminum) in appropriate proportions. Further, elemental mapping results showed that Al was homogeneously distributed

within the film, confirming modification of BaSnO₃ using Al₂O₃. The atomic percent of aluminum was approximately 5 mol% expected with the modification level.

Gas Sensing Performance Data

Sensitivity and Selectivity Analysis

Gas sensing performance of unmodified and Al₂O₃-modified BaSnO₃ thick films was tested against different target gases, namely CO, NO₂, H₂, and CH₄ within the concentration range of 1-100 ppm. Sensors were tested at various operating temperatures within the range of 100°-400°C in order to choose the optimum operating condition.

The Al₂O₃-modified BaSnO₃ films showed a notable increase in sensitivity when compared to pure BaSnO₃ films in all the tested gases. For instance, the modified sensor at an optimal operating temperature of 300°C responded with 45% to 50 ppm CO, while the unmodified sensor gave a rather low response of 25% under the same conditions. This increase in sensitivity may be attributed to the modification of Al₂O₃ that supported additional active sites for gas adsorption and favoured charge transfer between gas molecules and the sensor surface.

The sensors' selectivity towards different types of gases was also tested. Among them, the Al₂O₃-modified BaSnO₃ films showed better selectivity towards NO₂. The sensor response to NO₂ at 50 ppm concentration was about 60%, while its responses to CO, H₂, and CH₄ were 45%, 35%, and 25%, respectively. The improved selectivity towards NO₂ is most likely due to the catalytic activity of Al₂O₃, which preferably adsorbs NO₂ molecules, reacting there and increasing the sensor response.

Response and Recovery Time

The response time was measured as the time to reach 90% of the maximum response and the recovery time as the time taken to go back to 90% of its baseline resistance, thereby reflecting the dynamic performance in those sensors. In this context, the response time was 12 seconds in the case of BaSnO₃ films modified with Al₂O₃ and their recovery time was 15 seconds at an operating temperature of 300°C for the CO gas, whereas the unmodified films recorded a response time of about 22 seconds and a recovery time of 28 seconds.

These can be attributed to the fact that the Al₂O₃ modification provided more active sites for the fast adsorption and desorption of gas molecules and the modified films possess a porous structure that would allow quicker diffusion of gas molecules to and from the sensor surface.

Effect of Al₂O₃ Modification on Gas Sensing Performance

It follows that the modification of BaSnO₃ by Al₂O₃ significantly improves the gas-sensing performance regarding sensitivity, selectivity, response time, and recovery. Also, it is obvious that the surface incorporation of Al₂O₃ into BaSnO₃ forms a nanocomposite structure providing an increase in the effective surface area with the addition of active catalytic sites for gas interaction. This will lead to an improvement in the adsorption and reaction kinetics of target gas molecules and more importantly, the charge transfer process, contributing together towards a greater change in sensor resistance upon being exposed to gases.

Moreover, performances of Al₂O₃-modified films showed very good stability in cycles of multiple gas exposure, guaranteeing good repeatability and long-term stability. For example, resistance for all modified sensors returned to their baselines after each exposure, which means that the drift and degradation are very minimal. This is an important aspect in practical applications of gas sensing, where consistent performance over time from sensors is a concern.

Discussion

The characterizations indicate that modification with Al₂O₃ significantly increases the gas response of BaSnO₃ thick films. XRD and SEM analyses confirmed that the incorporation of Al₂O₃ particles into the matrix of BaSnO₃ was successful, achieving a nanocomposite structure with an improved surface area and porosity. The porous network of Al₂O₃ particles on the BaSnO₃ surface increased the number of active sites for gas adsorption. This structural enhancement influenced the gas properties directly, improving sensitivity, selectivity, and dynamic response characteristics.

The modified BaSnO₃ films exhibited enhanced sensitivity to all target gases, namely CO, NO₂, H₂, and CH₄, compared to their unmodified counterparts. Accordingly, the modified sensor showed a much higher response of 45% to 50 ppm CO at an optimum operating temperature of 300°C, as compared to only 25% for an unmodified one. This might be explained by additional adsorption sites due to Al₂O₃ and more charge transfer between gas molecules and the sensor surface. It can be obtained from the selectivity analysis that the Al₂O₃-modified BaSnO₃ films showed enhanced responses to NO₂, for instance, 60% response at 50 ppm, while having lower responses to CO, H₂, and CH₄. The improvement in selectivity toward NO₂ might be because of the catalytic nature of Al₂O₃, thus being favorable for the adsorption and reaction of NO₂ rather than other gases.

Also, the modified films showed higher response and recovery rates, demonstrating further dynamic performance improvement for practical gas sensing.

Advantages of modification by Al₂O₃

Several advantages can be suggested to explain the improvement of gas-sensing behavior upon the introduction of Al₂O₃ in BaSnO₃, among which are that it enables Al₂O₃, having a high surface area and providing many active sites for gas adsorption, therefore increasing sensitivity.

Moreover, the modification will impose a structure of porosity enabling the diffusivity of gas molecules to and from the sensor surface to increase their velocity, a fact that improves response and recovery times. This means a lot in applications that require rapid detection and reset, such as environmental monitoring and industrial safety. Second, the Al_2O_3 showed very good chemical stability and catalytic properties, improving selectivity toward BaSnO_3 -based sensors. The preferential adsorption of NO_2 molecules in this work shows that Al_2O_3 increases the specific characteristics of the gas sensors to target gases easily. This is important in many applications that require the accurate identification of particular gases in a sample for analysis, such as in the detection of NO_2 emissions in automotive exhaust monitoring or in environmental monitoring.

Moreover, modification with Al_2O_3 contributed to the decrease in operating temperature of the BaSnO_3 -based sensors. Indeed, modified sensors showed the best performance at 300°C in this work, which is lower than usually required operating temperatures for pure BaSnO_3 sensors. A reduction in operating temperature leads to lowering energy consumption and prolongs the lifetime of the sensor, thus becoming more suitable for portable and battery-operated devices.

Conclusion

This article, therefore, shows how modifications of BaSnO_3 thick films with Al_2O_3 improve their gas sensing characteristics in terms of sensitivity, selectivity, response time, and stability. Such Al_2O_3 modification offers higher surface areas and more active centers for gas adsorption, along with catalytic properties enhancing gas interactions. Such modification is particularly effective in NO_2 detection. Accordingly, optimized sensors can operate at much lower temperatures, which reduces energy consumption and prolongs sensor lifetimes. The tendency of these results shows that Al_2O_3 -modified BaSnO_3 is indeed one of the most promising materials for broadly applicable gas sensors in environmental monitoring, industrial safety, automotive exhaust control, and medical diagnostics. Other modifiers and optimization techniques may be attempted in further studies to continue improving gas sensor performance.

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