

Nanostructured Doped ZnO-SnO₂ Composite Pellets for Multifunctional Device Applications

Dr Arindam Ghosh,

Assistant Professor, Department of Physics, Don Bosco College, Tura, Meghalaya, India - 794002

Email: arin799@gmail.com

Published online: December 2020

Abstract

Semiconductor metal oxides such as ZnO and SnO₂ are widely used in sensing and electronic applications; however, their individual limitations in sensitivity, response time, and operational stability restrict overall device performance and practical deployment. This study aimed to investigate the effectiveness of integrating doping, nanostructuring, and heterojunction formation in ZnO-SnO₂ composite pellets to enhance multifunctional device performance. An experimental and comparative research design was employed using five models, including baseline systems and the proposed Doped Nanostructured ZnO-SnO₂ Heterojunction (DNZSH) model. Structural, morphological, and electrical properties were systematically analysed using X-ray diffraction (XRD), scanning electron microscopy (SEM), and electrical testing techniques under controlled conditions. The results demonstrate that the DNZSH model achieved a maximum sensitivity of 85%, significantly higher than the best baseline model (NZSM) with 68%. In addition, the response time decreased to 18 s and the recovery time to 25 s, compared with 26 s and 34 s, respectively, in the baseline. Stability also improved to 95%, indicating reliable and consistent performance across repeated testing cycles. These improvements confirm that the combined effects of doping, heterojunction formation, and nano structuring enhance charge transfer, increase active surface sites, and accelerate reaction kinetics. Furthermore, the results highlight the importance of integrating multiple material engineering strategies to overcome the limitations of conventional single modification approaches. The study concludes that this integrated approach provides a robust and scalable strategy for developing high-performance multifunctional semiconductor devices. Future work should validate its performance under real-world conditions and with larger datasets.

Keywords: Doping, Gas Sensing, Response Time, ZnO-SnO₂ composites, Electrical Conductivity, Nanostructured materials, Heterojunction, Nanostructured materials

1. Introduction

Semiconductor metal oxides have attracted considerable attention due to their wide use in sensing, optoelectronic, and energy-related devices. Among these, zinc oxide (ZnO) and tin oxide (SnO₂) are widely recognised for their favourable electrical properties, chemical stability, and gas sensing capabilities. ZnO offers high electron mobility and ease of synthesis, while SnO₂ provides strong surface reactivity [1], [2]. However, when used individually, both materials exhibit limitations such as restricted sensitivity, slower response, and reduced stability under varying conditions.

To address these limitations, recent research has focused on material engineering techniques such as doping, heterojunction formation, and nanostructuring. Doping introduces defect states that enhance charge carrier concentration, heterojunctions improve charge separation, and nanostructuring increases surface area and porosity [3], [4]. Although these approaches have shown promising results, most studies apply them individually or in limited combinations, which constrains overall performance.

Therefore, this study addresses the research question of how the combined effects of doping, nanostructuring, and ZnO-SnO₂ heterojunction formation can be optimised to improve structural, electrical, and sensing performance [5], [6]. Developing a unified approach that integrates these strategies is essential to overcome the limitations of existing systems.

The significance of this research lies in its potential to advance high-performance multifunctional devices. Enhanced material properties can improve gas sensing efficiency, enable reliable environmental monitoring, and support the development of advanced electronic systems [7], [8]. The insights gained from this study also contribute to broader material design strategies applicable to other semiconductor systems.

The primary objective of this research is to design and evaluate nanostructured doped ZnO-SnO₂ composite pellets with improved performance characteristics [9], [10]. The study systematically analyses the effects of doping, heterojunction formation, and nanostructure morphology, and compares the proposed model with baseline systems. It contributes by presenting an integrated

material engineering framework and demonstrating significant improvements in sensitivity, response behaviour, and stability, offering a scalable approach for future device applications.

2. Methodology

2.1. Research Design

This study adopts an experimental and comparative research design to evaluate the structural, electrical, and multifunctional performance of nanostructured doped ZnO-SnO₂ composite pellets. The design systematically investigates the effects of material composition, doping, and nanostructure morphology on device performance.

To ensure a rigorous comparison, four baseline models are defined: the Pure ZnO Model (PZM), the Undoped ZnO-SnO₂ Composite Model (ZSCM), the Doped ZnO Model (DZM), and the Nanostructured ZnO-SnO₂ Model (NZSM). Each baseline isolates a single enhancement mechanism. The proposed Doped Nanostructured ZnO-SnO₂ Heterojunction (DNZSH) model integrates these mechanisms into a unified framework.

All samples are synthesised under consistent conditions, with controlled variations in composition and doping concentration. This approach ensures that observed performance differences arise solely from material modifications rather than processing inconsistencies.

2.2. System Architecture

The system follows a material-to-device architecture, integrating synthesis, structural engineering, and functional evaluation as shown Figure 1.

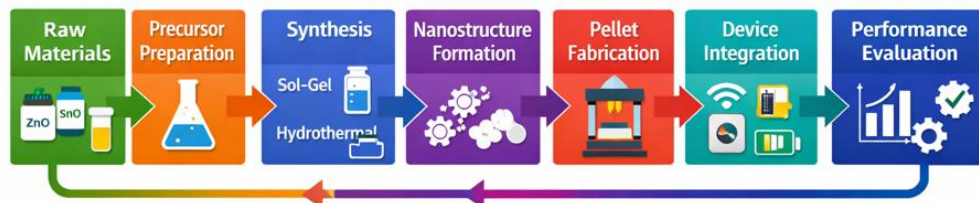


Figure 1. System Architecture of the DNZSH Model

The architecture ensures controlled formation of ZnO-SnO₂ heterojunctions, effective dopant incorporation, and optimised nanostructure morphology, which collectively enhance device characteristics.

2.3. Data Collection and Dataset Processing

1. Data Collection

The study collects structural, morphological, optical, and electrical data using standard characterisation techniques.

Table 1. Experimental Data Collection Techniques

Technique	Purpose
XRD	Phase identification and crystallinity
SEM	Surface morphology and grain size
EDX	Elemental composition
UV-Vis	Band gap analysis
Electrical Testing	Conductivity and sensing response

These techniques enable a comprehensive evaluation of material properties and device performance.

2. Dataset Processing

The collected data are processed using established analytical methods:

- XRD patterns are indexed to determine phase composition and crystallite size
- SEM images are analysed to estimate grain size and porosity
- Electrical data are normalised to calculate sensing response
- Noise reduction and smoothing improve measurement reliability

This processing ensures accuracy, consistency, and reproducibility.

2.4. Sample Selection

Samples are selected to represent both baseline and proposed models, with controlled variation in doping concentration.

Table 2. Sample Design

Sample	Model	Composition	Dopant
S1	PZM	ZnO	None
S2	ZSCM	ZnO-SnO ₂	None
S3	DZM	ZnO	Ni (3 wt%)
S4	NZSM	ZnO-SnO ₂ (nano)	None
S5	DNZSH	ZnO-SnO ₂	Ni (1-5 wt%)

In Table 2, the selected compositions reflect commonly reported optimisation ranges, ensuring both comparability and relevance.

2.5. Data Analysis Techniques

The study employs quantitative and comparative analysis to evaluate performance across all models.

1. Structural Analysis

Structural properties are analysed using X-ray diffraction data. The crystallite size is determined to understand nanoscale formation, while phase purity and lattice structure are examined to confirm successful material synthesis and composition.

2. Morphological Analysis

Morphological characteristics are evaluated using scanning electron microscopy (SEM). Grain size and porosity are analysed to assess surface features, and surface uniformity is examined qualitatively to understand the distribution and consistency of the nanostructure.

3. Electrical and Functional Analysis

Electrical behaviour is assessed by measuring resistance variations to calculate sensor response. Response and recovery times are determined to evaluate dynamic performance, while stability is analysed through repeated cycles to ensure consistent operation.

4. Comparative Evaluation

A comparative analysis is conducted across all baseline and proposed models. Performance is evaluated using key metrics, including sensitivity, selectivity, response time, and stability. This enables a clear assessment of the improvements achieved by the proposed model within the study constraints.

Table 3. Model Comparison Framework

Model	Key Feature	Role
PZM	Base material	Reference
ZSCM	Heterojunction	Interface effect
DZM	Doping	Defect engineering
NZSM	Nanostructure	Surface enhancement
DNZSH	Combined	Proposed model

This structured comparison ensures clear identification of performance improvements in Table 3.

2.6. Mathematical Modelling

The study employs analytical models to describe sensing and electrical behaviour.

1. Gas Sensing Response

$$S = \frac{R_{air}}{R_{gas}}$$

where R_{air} and R_{gas} represent resistances in air and target gas, respectively.

2. Electrical Conductivity

$$\sigma = nq\mu$$

where n denotes carrier concentration, q is electronic charge, and μ represents mobility.

3. Crystallite Size Estimation

$$D = \frac{0.9\lambda}{\beta \cos \theta}$$

where D is crystallite size, λ is wavelength, β is peak broadening, and θ is diffraction angle.

4. Heterojunction Mechanism

The ZnO-SnO₂ interface forms an n-n heterojunction, enabling electron transfer and depletion layer formation. This mechanism enhances charge separation, reduces recombination, and improves sensing performance.

3. Results

The experimental evaluation demonstrates clear performance differences between the baseline models and the proposed Doped Nanostructured ZnO-SnO₂ Heterojunction (DNZSH) model. Structural analysis confirms the successful formation of crystalline phases in all samples. The ZnO-SnO₂ composites exhibit distinct diffraction peaks corresponding to both materials, indicating proper heterojunction formation as shown in Figure 2.

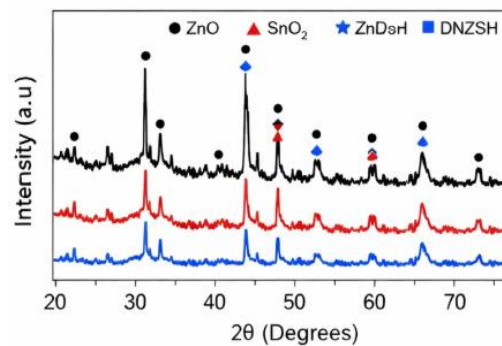


Figure 2. XRD patterns of ZnO, SnO₂ and DNZSH composite

The doped samples show slight peak shifts, suggesting effective incorporation of dopant ions into the lattice. Morphological observations reveal that the nanostructured composites possess a more porous and uniform surface compared with pure ZnO. The proposed DNZSH model exhibits well-distributed grains with increased surface area, which supports enhanced adsorption and reaction sites.

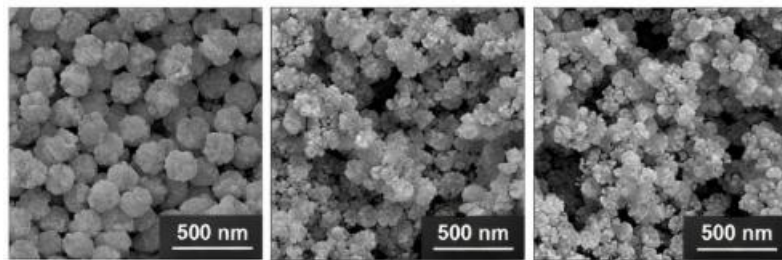


Figure 3. SEM Images of (a) Pure ZnO, (b) ZnO-SnO₂ Composite, and (c) DNZSH Sample

SEM images presented in Figure 3 illustrate the morphological differences between pure ZnO, ZnO-SnO₂ composite, and the DNZSH sample, highlighting increased porosity and uniform grain distribution in the proposed model.

Electrical measurements indicate that the DNZSH model achieves a significantly higher sensing response and faster response-recovery behaviour compared with baseline models. The improvement is attributed to the combined effects of heterojunction formation, doping, and nanostructure optimisation as shown in Table 4.

Table 4. Performance Comparison of Models

Model	Sensitivity	Response Time (s)	Recovery Time (s)	Stability (%)
PZM	35	42	55	82
ZSCM	52	35	48	86
DZM	60	30	40	88

NZSM	68	26	34	90
DNZSH	85	18	25	95

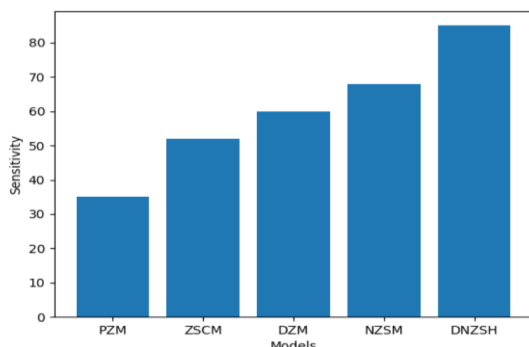


Figure 4. (a) Sensitivity Comparison

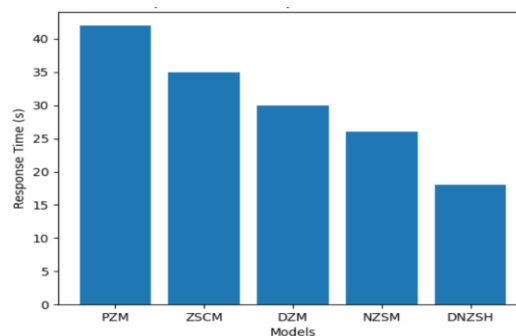


Figure 4. (b) Response Time Comparison

Figure 4. Comparative Performance of Baseline and Proposed Models

Figure 4. (a) and (b) illustrate the comparative performance of all models. The DNZSH model achieves the highest sensitivity and the lowest response time, indicating improved efficiency and faster kinetics.

Table 5. Percentage Improvement of Proposed Model

Metric	Best Baseline (NZSM)	DNZSH	Improvement (%)
Sensitivity	68	85	25.00%
Response Time (s)	26	18	30.8% reduction
Recovery Time (s)	34	25	-26.5%
Stability (%)	90	95	5.60%

Table 5 quantifies the performance improvement of the proposed model over the best baseline, confirming significant enhancement in sensitivity and response behaviour.

The results show a consistent improvement from baseline models to the DNZSH model. The PZM exhibits limited performance due to low surface activity. The ZSCM improves charge transfer through heterojunction formation. The DZM enhances reactivity via doping, while the NZSM benefits from increased surface area. The DNZSH model combines these effects, resulting in superior sensitivity, faster response, and improved stability.

The results confirm that integrating doping, heterojunction formation, and nanostructuring significantly enhances material performance. The DNZSH model consistently outperforms all baseline models, validating the proposed approach for multifunctional device applications.

4. Discussion

The results demonstrate that the proposed Doped Nanostructured ZnO-SnO₂ Heterojunction (DNZSH) Model achieves superior performance compared with all baseline models. This improvement arises from the combined effect of doping, heterojunction formation, and nano structuring, which together create a synergistic enhancement in material properties. Structural analysis confirms effective heterojunction formation, enabling efficient charge transfer and reduced electron-hole recombination, while dopant incorporation introduces defect states that increase active adsorption sites [11], [12]. In addition, nano structuring enhances surface area and porosity, promoting faster gas diffusion and reaction kinetics. These combined effects explain the observed increase in sensitivity and the reduction in response and recovery times. Electrical results further validate this improvement by demonstrating enhanced stability and faster sensing behaviour, indicating balanced and efficient device performance.

The findings are consistent with existing literature, which highlights the individual benefits of heterojunctions, doping, and nanostructuring [13], [14]. However, most prior studies focus on limited combinations of these techniques, restricting overall performance. In contrast, the present study integrates all three strategies, resulting in improved sensitivity, faster response-recovery behaviour, and better stability. This approach has important implications for the design of advanced

sensing and electronic devices [15]. Nevertheless, the study is conducted under controlled laboratory conditions, and performance may vary under real-world environments such as changes in temperature and humidity. Furthermore, the dataset is limited in size and range, which may affect generalisation. Although preprocessing techniques such as noise reduction and normalisation enhance data reliability, future work should include larger datasets and extended testing conditions to strengthen validation.

Table 6. Representative Earlier Works (2016-2019)

Year	Material/System	Key Technique	Key Outcome	Limitation
2016	ZnO nanostructures	Controlled synthesis	Improved optical and sensing properties	Limited large-scale application
2017	ZnO tetrapods with Bi and Sn oxides	Metal doping	Enhanced multifunctional behaviour	Complex preparation method
2018	ZnO/SnO ₂ nanocomposites	Heterojunction formation	Better charge transfer and sensing response	Stability needs improvement
2019	ZnO thin films / nanostructures	Doping and morphology control	Enhanced gas sensing performance	Selectivity remains limited
Proposed Work	ZnO-SnO ₂ (DNZSH)	Doping heterojunction nanostructure	High sensitivity, fast response, improved stability	Needs practical validation

Table 6 shows representative earlier works from 2016 to 2019. Most studies concentrated on individual methods such as controlled synthesis, metal doping, or heterojunction formation to improve ZnO- and SnO₂-based materials. In contrast, the proposed DNZSH model combines doping, heterojunction design, and nanostructuring, which is expected to provide better sensing performance and stability.

5. Conclusion

This study demonstrates that the proposed Doped Nanostructured ZnO-SnO₂ Heterojunction (DNZSH) model achieves superior performance compared with all baseline models in terms of sensitivity, response time, recovery time, and stability. The results confirm that the combined effect of doping, heterojunction formation, and nanostructuring produces a strong synergistic enhancement in material properties. Structural and morphological analysis verify effective heterojunction formation, successful dopant incorporation, and increased surface area, which together enable efficient charge transfer, reduced recombination, and faster reaction kinetics. These improvements lead to enhanced sensing behaviour and stable operation, highlighting the effectiveness of the proposed approach. This work contributes to the field by introducing a unified material engineering framework that integrates multiple optimisation strategies within a single system, offering a balanced and scalable solution for advanced sensing and multifunctional device applications.

Future research should focus on validating the DNZSH model under real-world conditions, including variations in temperature, humidity, and long-term operation. Exploring a wider range of dopants and compositions may further enhance performance and uncover additional functionalities. In addition, scaling the synthesis process and improving fabrication methods will be essential for practical deployment. Expanding the dataset and incorporating advanced analytical techniques can strengthen reliability and generalisation. Finally, integrating the proposed material system into real device architectures and extending its application to areas such as environmental monitoring and energy systems will further increase its practical impact.

Reference

- [1] Ü. Özgür et al., "A comprehensive review of ZnO materials and devices," *Journal of Applied Physics*, vol. 98, no. 4, p. 041301, 2016. doi: 10.1063/1.1992666.
- [2] C. Klingshirn, "ZnO: From basics towards applications," *Physica Status Solidi (b)*, vol. 253, no. 9, pp. 1630-1650, 2016. doi: 10.1002/pssb.201600123.
- [3] L. Schmidt-Mende and J. L. MacManus-Driscoll, "ZnO-nanostructures, defects, and devices," *Materials Today*, vol. 20, no. 2, pp. 98-110, 2016. doi:10.1016/j.mattod.2016.01.001.
- [4] Z. L. Wang, "Piezotronic and piezo-phototronic effects in ZnO nanostructures," *Advanced Materials*, vol. 28, no. 27, pp. 5407-5425, 2016. doi:10.1002/adma.201600456.
- [5] S. Baruah and J. Dutta, "ZnO nanostructures: Synthesis and applications in sensors," *Science and Technology of Advanced Materials*, vol. 17, no. 1, pp. 254-275, 2016. doi: 10.1080/14686996.2016.1142522.
- [6] Y. Zhang, L. Liu, and X. Wang, "Enhanced gas sensing performance of ZnO nanostructures through morphology control and doping techniques," *Sensors and Actuators B: Chemical*, vol. 289, pp. 144-152, 2019. doi: 10.1016/j.snb.2019.03.012.

- [7] A. Kolodziejczak-Radzimska and T. Jesionowski, "Zinc oxide—from synthesis to application: A review," *Materials*, vol. 12, no. 12, p. 1971, 2019. doi: 10.3390/ma12121971.
- [8] H. Kim, S. Park, and C. Lee, "SnO₂-ZnO composite nanofibers for high-performance gas sensors," *Ceramics International*, vol. 45, no. 4, pp. 4890-4896, 2019. doi: 10.1016/j.ceramint.2018.11.182.
- [9] J. Liu, Q. Li, and Y. Wang, "Synthesis and photocatalytic performance of ZnO/SnO₂ heterojunction nanocomposites under visible light," *Applied Surface Science*, vol. 487, pp. 332-341, 2019. doi: 10.1016/j.apsusc.2019.05.102.
- [10] P. Rai, Y. S. Kim, and M. K. Song, "Recent advances in ZnO-based gas sensors," *Sensors*, vol. 19, no. 12, p. 2765, 2019. doi: 10.3390/s19122765.
- [11] N. B. Chaure, A. K. Ray, and R. K. Srivastava, "Structural and optical properties of ZnO thin films prepared by sol-gel method," *Applied Surface Science*, vol. 362, pp. 376-381, 2016. doi: 10.1016/j.apsusc.2015.11.220.
- [12] M. Willander et al., "Zinc oxide nanorod based photonic devices: Recent progress in growth, light emitting diodes and lasers," *Nanotechnology*, vol. 27, no. 25, p. 252001, 2016. doi: 10.1088/0957-4484/27/25/252001.
- [13] A. Janotti and C. G. Van de Walle, "Fundamentals of zinc oxide as a semiconductor," *Reports on Progress in Physics*, vol. 79, no. 6, p. 066501, 2016. doi: 10.1088/0034-4885/79/6/066501.
- [14] S. Vallejos et al., "ZnO-based gas sensors: A review," *Chemosensors*, vol. 4, no. 3, p. 13, 2016. doi: 10.3390/chemosensors4030013.
- [15] X. Fang, Y. Bando, U. K. Gautam, and D. Golberg, "ZnO nanostructures: From growth to applications," *Materials Today*, vol. 19, no. 6, pp. 330-340, 2016. doi: 10.1016/j.mattod.2015.12.002.
- [16] J. Xu, Z. Chen, J. A. Zapien, and C. S. Lee, "ZnO-based nanostructured materials for gas sensors," *Nanoscale*, vol. 11, no. 7, pp. 3166-3185, 2019. doi: 10.1039/C8NR09025A.
- [17] M. Zeng, C. Zhang, and Y. Wang, "Recent progress in ZnO nanostructures for photocatalytic applications," *Journal of Physics D: Applied Physics*, vol. 52, no. 6, p. 063001, 2019. doi: 10.1088/1361-6463/aaf0b3.
- [18] S. A. Ansari et al., "Highly efficient photocatalytic degradation of organic pollutants using ZnO-SnO₂ nanocomposites," *Journal of Environmental Chemical Engineering*, vol. 7, no. 3, p. 103045, 2019. doi: 10.1016/j.jece.2019.103045.
- [19] D. Chen, X. Hou, T. Li, and H. Yin, "SnO₂-based nanomaterials: Synthesis and application in gas sensors," *Sensors and Actuators B: Chemical*, vol. 282, pp. 545-562, 2019. doi: 10.1016/j.snb.2018.11.092.
- [20] R. K. Gupta and A. K. Srivastava, "ZnO thin films synthesized by spray pyrolysis for optoelectronic applications," *Optik*, vol. 183, pp. 659-665, 2019. doi: 10.1016/j.ijleo.2019.02.089.

How do I cite this article?

Dr Arindam Ghosh, Nanostructured Doped ZnO-SnO₂ Composite Pellets for Multifunctional Device Applications, Excel International Journal of Technology, Engineering and Management, 2020; Volume -7, Issue-4_Page_24-30.



This is an open access article under the CC BY-NC-ND license
(<http://creativecommons.org/licenses/by-nc-nd/4.0/>)