An overview of hetero-structured nanomaterials based on metal oxides for gas sensing applications

Smruti Dhola[1], Ankit Patel[2]
[1]*Teaching Assistant, Applied Science & Humanity Department, School of Engineering, P P Savani University, Kosamba, Gujarat, India*
[2]*Associate Teacher, Mauni International School, Surat, Gujarat, India*

Abstract- Nanomaterial based heterostructures have become a promising avenue for enhancing gas sensing technologies due to their unique structural and electronic properties. This review paper provides a comprehensive overview of recent advances in the synthesis methods and gas sensing applications of nanomaterial heterostructures. Various synthesis techniques, including chemical vapor deposition, hydrothermal methods and sol-gel processes, are discussed, highlighting their impact on the structural and functional attributes of the heterostructures. The paper emphasizes the importance of interface engineering, morphology control and material composition in optimizing the gas sensing performance. Key gas sensing mechanisms, including adsorption-desorption dynamics, charge transfer processes, and the role of heterojunctions are elucidated. Furthermore, the review explores the sensitivity, selectivity, response time, and stability of different nanomaterial-based heterostructures in detecting gases such as ammonia, nitrogen dioxide, and volatile organic compounds. Finally, the paper identifies current challenges and future research directions in the field, aiming to direct the creation of the upcoming generation of gas sensors with improved performance metrics.

Key Words: Nanomaterial Heterostructure, gas sensor, Sensing material and sensing mechanism

I. INTRODUCTION

The detection and monitoring of gases are crucial for variety of uses, such as medical diagnostics, industrial safety, environmental monitoring. Even though they work well, traditional gas sensors sometimes have problems with stability, sensitivity, selectivity, and reaction time. The advent of nanotechnology has opened new horizons for the development of advanced gas sensors, particularly through the use of nanomaterial-based heterostructures.

Nano materials, due to their high surface area-to-volume ratio, tunable electronic properties[1], and enhanced surface activity, have shown significant potential in gas sensing applications. Among them, heterostructures-comprising two or more different nanomaterials-stand out due to their ability to synergistically combine the advantages of each constituent material. This synergy often results in improved gas sensing performance, better selectivity and sensitivity than single-component sensors, for example.

This review aims to provide an all-encompassing overview of the recent advancements in the synthesis and application of nanomaterial-based heterostructures for gas sensing. We begin by discussing various synthesis such as CVD, sol-gel, hydrothermal methods which play a critical role in determining the structural and functional properties of the heterostructures.

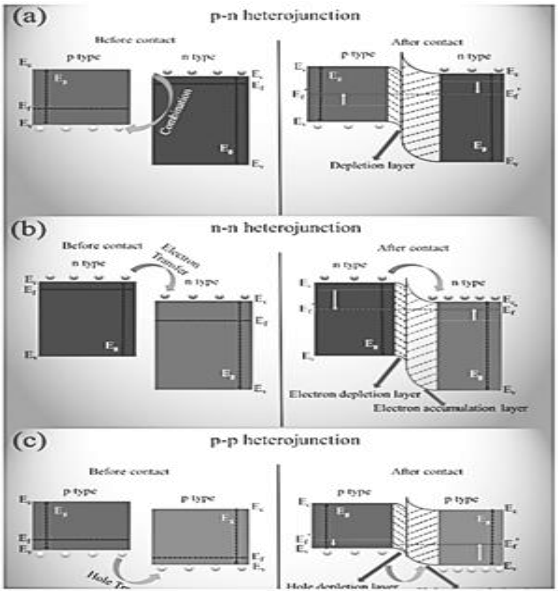

Fig.I Diagrams showing the hetero-junction contacts of the energy band[2] structures at the three main types of heterojunctions: p–n, n–n, and p–p.

They possess exceptional electrical, optical, thermal, and chemical activity, as well as high specific surface areas. Its most effective properties is to purge wastewater of biological and chemical impurities.

By employing UV activation, high energy irradiation as a post-treatment technique, and nanocomposites made of various MOx (metal oxides) on ZnO[3]. MOs gas sensors are broadly used to detect inflammable and toxic gases in daily life and production of industrial aspect. Mos are mainly classified into two types, according to the different conductive behavior, which are referred as p-type[4] and n-type. SnO_2, ZnO_2, TiO_2, Fe_2O_3, In_2O_3 are widely investigated by researchers for studying their gas sensing behavior. In other hand p—type MOs NiO, CuO, Co_3O_4 and Cr_2O_3 have received less attention relatively due to their lower reaction to target gases as compared to n-type MOs.

II LITERATURE REVIEW

Below is an example table listing various metal oxide-based heterojunctions, their synthesis methods, and their characteristics of gas sensing[5,6,7,8,9,10]

No.	Heterojunction	Synthesis Method	Target Gas	Sensitivity	Selectivity	Response Time	Stability
1.	ZnO/SnO_2	Hydrothermal	NO_2	High	High	Fast	Good
2.	TiO_2/WO_3	Sol-gel method	NH_3	Moderate	Moderate	Moderate	Good
3.	CuO/ZnO	CVD	H_2S	High	High	Fast	Good
4.	Fe_2O_3/SnO_2	Hydrothermal	CO	High	Moderate	Fast	Moderate
5.	NiO/SnO_2	Electro spinning	H_2	High	High	Fast	Excellent
6.	MoO_3/TiO_2	Sol-Gel Method	VOCs	High	High	Moderate	Good
7.	ZnO/Fe_2O_3	Hydrothermal	NO_2	High	Moderate	Fast	Moderate
8.	SnO_2	CVD	CO	Moderate	Moderate	Fast	Good
9.	In_2O_3	Hydrothermal	O_3	High	High	Fast	Excellent
10.	V_2O_5	Sol-Gel	Ethanol	High	Moderate	Fast	Good

Notes:

- The term "*sensitivity*" describes the sensor's capacity to identify the target gas at low concentrations.
- *Selectivity* shows the sensor's performance can differentiate between the target gas and other gases.
- *Reaction Time* the sensor's time to reach a specific percentage of its ultimate reaction is measured.
- The capacity of the sensor to continue operating consistently throughout time is referred to as *stability*.

The table provides a comparative analysis of various metal oxide-based heterojunctions, highlighting their synthesis methods and gas sensing properties. Here are the key insights derived from the table:

Hydrothermal synthesis frequently used as compared to others because its ability to produce well-defined nanostructures with high surface areas, contributing to enhanced gas sensing properties. Sol-Gel method allows for fine control over the material composition and morphology, which is critical for optimizing gas sensor performance. CVD is known for producing high-purity and uniform thin films, essential for consistent gas sensing responses. Electrospinning used for NiO/SnO_2 , which provides a high surface to volume ratio and good porousness, leading to excellent gas sensing characteristics.

Heterojunctions like ZnO/SnO_2, CuO/ZnO, and NiO/SnO_2 exhibit high sensitivity to gases such as NO_2, H_2S and H_2 respectively. The high surface area and effective charge transfer at the interface enhance gas adsorption and sensitivity. Other heterojunctions like TiO2/WO3 and SnO2/WO3 show moderate sensitivity, indicating room for optimization tuning. Most heterojunctions exhibit fast response times , especially ZnO/SnO_2, CuO/ZnO, NiO/SnO_2, Fe_2O_3/SnO_2, In_2O_3/SnO_2 and V_2O_5/TiO_2. Quick response times are essential for real-time monitoring applications. Moderate response times in TiO_2/WO_3 and MoO_3/TiO_2 may require optimization in material synthesis or device architecture to enhance performance. Excellent stability is noted in NiO/SnO_2 and In_2O_3/SnO_2 heterojunctions, indicating their reliability for long term applications. Good stability in ZnO/SnO_2, TiO_2/WO_3 and MoO_3/TiO_2 heterojunctions suggests they are suitable for various application but may benefit from further improvements to ensure consistent performance over extended periods. Moderate stability in Fe_2O_3/SnO_2 and ZnO/Fe_2O_3 indicates potential degradation issues or sensitivity to environmental conditions, necessitating further research to enhance their robustness.

The analysis of the table reveals that metal oxide based[11] heterojunctions offer diverse and promising options for gas sensing applications. The synthesis technique selection has a big impact on the structural and functional properties of the heterojunctions, which in turn affect their gas sensing performance. High sensitivity, selectivity, fast response time and stability re critical metrics for evaluating the effectiveness of these heterojunctions. While many heterojunctions demonstrate excellent performance in these areas, there is still room for improvement through material optimization and advanced synthesis techniques. Future research should focus on addressing these challenges to further enhance the capabilities of nanomaterial based heterojunctions in gas sensing applications.

CONCLUSION

Nanomaterial based heterostructures have shown significant possibilities in the area of gas detection, providing improved sensitivity, selectivity, response time, and stability compared to traditional gas sensors. This review has highlighted the diverse synthesis methods, including hydrothermal synthesis, sol-gel processes, chemical vapor deposition and electrospinning which are crucial for tailoring the structural and functional properties of these heterostructures. Nanomaterial based heterostructures hold great promise for the next generation of gas sensors, offering improved performance metrics essential for applications in industrial safety, healthcare, and environmental monitoring. Continued advancements in synthesis techniques and a deeper understanding of gas sensing mechanisms will drive the creation of additional efficient, reliable and versatile gas sensors, paving the way for broader adoption and innovative applications.

REFERENCE

[1] Deshpande MP, Patel KN, Gujarati VP, Patel K, Chaki SH. Structural, Thermal and Optical Properties of Nickel Oxide (NiO) Nanoparticles Synthesized by Chemical Precipitation Method. Adv Mat Res 2016; 1141: 65–71.
[2] Yunusa Z, Hamidon MN, Profile S, Awang Z, Kaiser A, Awang Z. Gas Sensors: A Review. 2014.
[3] Kumar R, Al-Dossary O, Kumar G, Umar A. Zinc oxide nanostructures for no2 gas–sensor applications: A review. Nano-Micro Letters 7 2015 97–120.
[4] Ahmed S, Sinha SK. Studies on nanomaterial-based p-type semiconductor gas sensors. Environmental Science and Pollution Research 2023; 30: 24975–24986.
[5] Chen X, Wong CKY, Yuan CA, Zhang G. Nanowire-based gas sensors. Sensors and Actuators, B: Chemical 177 2013 178–195.
[6] Wang H, Ma J, Zhang J et al. Gas sensing materials roadmap. Journal of Physics Condensed Matter 33 2021.
[7] Wang Z, Zhao C, Han T et al. High-performance reduced graphene oxide-based room-temperature NO2 sensors: A combined surface modification of SnO2 nanoparticles and nitrogen doping approach. Sens Actuators B Chem 2017; 242: 269–279.
[8] Gautam YK, Sharma K, Tyagi S, Ambedkar AK, Chaudhary M, Pal Singh B. Nanostructured metal oxide semiconductor-based sensors for greenhouse gas detection: Progress and challenges. Royal Society Open Science 8 2021.
[9] Chaiyo P, Makhachan C, Nutariya J, Thiabgoh O, Sumran S, Pukird S. Electrical and sensitivity properties of ZnO/TiO2 heterojunction nanocomposites for ammonia gas sensor. Journal of Physics: Conference Series, Institute of Physics Publishing 2019.
[10] Dhall S, Mehta BR, Tyagi AK, Sood K. A review on environmental gas sensors: Materials and technologies. Sensors International 2 2021.
[11] Isaac NA, Pikaar I, Biskos G. Metal oxide semiconducting nanomaterials for air quality gas sensors: operating principles, performance, and synthesis techniques. Microchimica Acta 189 2022.