Recent Advances in Metal Oxides and Metal Oxide Nanocomposites for Chemiresistive Detection of Hazardous Gases

UJWALKUMAR D. PATIL[1], CHETAN P. BHADANE[2], HARSHAL S. GAVALE[3], HARISHCHANDRA B. PATIL[4], KAMLESH B. DEORE[5]
[1,2,4]*Department of Physics, R. C. Patel Arts, Commerce & Science College, Shirpur (MS), India.*
[3,5]*Department of Physics, JET's Z. B. Patil College, Dhule (MS), India.*

Abstract- The rapid and reliable detection of hazardous gases is essential for environmental monitoring, industrial process control, public safety, and healthcare diagnostics. Among various sensing materials, nanostructured metal oxides (MOs) and their nanocomposites have emerged as the most promising candidates for chemiresistive gas sensors owing to their excellent chemical stability, tunable electronic properties, high surface area, and cost-effective fabrication. This mini-review summarizes recent developments in the synthesis, sensing mechanisms, and gas-sensing performance of pristine MOs and MO-based nanocomposites for hazardous gas detection. Various synthesis approaches, including sol-gel, hydrothermal, chemical precipitation, spray pyrolysis, combustion, chemical vapor deposition, and microwave-assisted methods, are critically discussed with respect to their influence on morphology, crystallinity, defect engineering, and sensing characteristics. The review further highlights the fundamental chemiresistive sensing mechanism and key performance parameters such as sensitivity, selectivity, response/recovery time, detection limit, and long-term stability. Recent advances in heterostructures, noble metal decoration, graphene- and polymer-based composites, and hybrid nanomaterials are comprehensively evaluated, demonstrating remarkable improvements in sensing performance through synergistic interfacial interactions and enhanced charge transfer. Finally, current challenges, including high operating temperature, humidity interference, and limited selectivity, are discussed along with future strategies for developing low-power, room-temperature, high-performance chemiresistive gas sensors.

Keywords: Metal Oxide Nanostructures, Chemiresistive Gas Sensors, Metal Oxide Nanocomposites, Hazardous Gas Detection, Gas Sensing Mechanism

I. INTRODUCTION

Metal oxides (MOs) have garnered significant attention in recent decades due to their versatile properties and wide-ranging applications in various technological domains [1]. Among these applications, gas sensing stands out as a critical field where the unique properties of MOs have been extensively exploited [2]. The increasing demand for efficient, reliable, and cost-effective gas sensors arises from their critical roles in environmental monitoring, industrial safety, healthcare, and domestic applications [3]. Gas sensors based on MOs have demonstrated exceptional performance in detecting toxic, flammable, and hazardous gases with high sensitivity, selectivity, and stability, making them indispensable in addressing modern societal challenges [4-6].

The synthesis of MOs plays a pivotal role in determining their structural, morphological, and physicochemical properties, which directly influence their gas-sensing performance [7]. MOs, including both single-MOs and bimetallic oxides, possess unique characteristics such as semiconducting behavior, tunable band gaps, high surface area, and robust chemical stability [8]. These features enable effective interaction between the gas molecules and the sensing material, leading to detectable changes in electrical or optical signals [9]. The synthesis methods employed for MOs, such as sol-gel processes, hydrothermal techniques, chemical vapor deposition, combustion methods, etc. significantly impact the material's properties, including particle size, crystallinity, porosity, and surface defects [10-12]. An in-depth understanding of these synthesis techniques is crucial for tailoring MOs for specific gas-sensing applications.

The fundamental chemiresistive sensing mechanism of MOs is predominantly governed by surface reactions, where the adsorption and desorption of gas molecules alter the electrical conductivity of the material [7, 13, 14]. When exposed to a target gas, MOs exhibit changes in resistance due to charge transfer between the gas molecules and the surface states of the material [15]. The sensitivity of this process is highly dependent on factors such as the type of gas, operating temperature, surface morphology, and the presence of catalytic additives or dopants [16]. In particular, bimetallic oxides and composite materials have shown promise in overcoming the limitations of single-MOs by offering synergistic effects that enhance gas-sensing performance [17]. These materials often exhibit improved sensitivity, reduced operating temperatures, and enhanced selectivity due to the combination of multiple active sites and catalytic functionalities [18]. The applications of metal oxide-based gas sensors are diverse and continue to expand with advancements in synthesis techniques and material design [19]. Environmental monitoring, for instance, relies heavily on gas sensors for detecting pollutants such as nitrogen dioxide (NO2), sulfur dioxide (SO2), carbon monoxide (CO), and volatile organic compounds (VOCs) [20]. In the industrial sector, gas sensors are crucial for detecting explosive gases like methane (CH4) and hydrogen (H2), ensuring safety and compliance with regulatory standards [21]. Additionally, in healthcare, these sensors play a vital role in non-invasive diagnostics, such as breath analysis for disease detection [22]. The development of portable, low-power, and miniaturized gas sensors further broadens their utility in consumer electronics and smart devices [23]. Despite their advantages, metal oxide-based gas sensors face several challenges that necessitate further research and innovation. Issues such as high operating temperatures, limited selectivity, response and recovery times, and susceptibility to humidity interference must be addressed to achieve optimal performance [24]. Emerging strategies, including the incorporation of nanostructures, doping, hybrid composites, and functionalization with noble metals or polymers, offer promising pathways to overcome these limitations [25]. Moreover, advancements in theoretical modeling and computational techniques provide valuable insights into the underlying mechanisms, enabling the rational design of next-generation gas-sensing materials.

This review aims to provide an in-depth analysis of the synthesis methods, structural characteristics, and functional properties of MOs with a particular emphasis on their applications in gas sensing. By exploring recent advancements and identifying current challenges, this article seeks to contribute to the growing body of knowledge in the field and pave the way for the development of innovative solutions to address the evolving demands of chemiresistive gas sensing technologies. The review highlights not only the scientific and technological aspects but also the interdisciplinary nature of the field, which integrates chemistry, materials science, physics, and engineering to create efficient and sustainable chemiresistive sensing platforms.

II. SYNTHESIS METHODS OF MOS FOR GAS SENSING APPLICATIONS

MOs are among the most extensively studied materials for gas sensing due to their remarkable chemical and physical properties, including high sensitivity, selectivity, and stability [7, 26]. The performance of metal oxide-based gas sensors is significantly influenced by their synthesis methods, which determine key material characteristics such as particle size, crystallinity, morphology, surface area, and defect structure [27]. This section provides a detailed overview of various synthesis approaches used for metal oxide preparation, emphasizing their scientific principles, advantages, limitations, and examples from the literature [28].

2.1 Sol-Gel Method

The sol-gel method is a widely employed and highly adaptable technique for the synthesis of MOs, owing to its ability to produce materials with remarkable uniformity, high purity, and controlled microstructure [10]. This method involves the conversion of a liquid precursor, referred to as the sol, into a solid gel through a sequence of hydrolysis and condensation reactions [29]. Fundamentally, the sol-gel process begins with the hydrolysis of metal alkoxides or inorganic salts to generate hydroxylated intermediates, which subsequently undergo polycondensation, forming a robust three-dimensional network of metal-oxygen bonds [30]. Key chemical steps include hydrolysis, where metal precursors react with water to form hydroxides, and condensation, which facilitates the linkage of hydroxyl groups, resulting in the development of the solid gel matrix [31]. This technique has been extensively explored in the synthesis of functional materials for gas sensing applications, as highlighted in the literature. For instance, M. Jabeen et al., synthesized ZnO nanoparticles using the sol-gel process demonstrated exceptional ethanol gas sensitivity, attributed to their uniform particle size and enhanced surface area [32].

Similarly, Y He et al., prepared SnO_2 thin films via sol-gel method exhibited superior CO detection performance due to their engineered porosity and well-defined crystallinity [33]. The sol-gel method offers several advantages, such as precise control over particle size, morphology, and composition, as well as the ability to incorporate dopants or functional additives at relatively low synthesis temperatures, thereby preserving their activity [34]. However, this method also has limitations, including the lengthy processing time required for aging and drying steps and the potential for cracking or shrinkage during gel formation, which can impact material integrity [29]. Despite these challenges, the sol-gel approach remains a cornerstone in the field of metal oxide synthesis, offering unparalleled opportunities for tailoring materials to meet the specific requirements of gas sensing applications.

2.2 Hydrothermal and Solvothermal Methods

Hydrothermal and solvothermal methods are widely employed for the synthesis of MOs, leveraging elevated temperatures and pressures within sealed reaction vessels to facilitate controlled crystal growth and the formation of unique morphologies [35]. These techniques are particularly advantageous for producing nanoscale structures such as nanorods, nanowires, and nanosheets, which exhibit enhanced properties tailored to specific applications. The underlying principle of these methods involves the dissolution of precursors, followed by nucleation and crystal growth under high-pressure conditions, with water acting as the reaction medium in hydrothermal synthesis or organic solvents being utilized in solvothermal processes [36]. The temperature and pressure parameters play a pivotal role in determining the crystal phase, size, and morphology of the resulting materials [37]. For instance, hydrothermally synthesized Au/TiO_2 nanocomposite have demonstrated superior sensing performance detecting gases including CO and H_2, NO, etc, gaseous, attributed to their high aspect ratio and increased surface area (Zhang et al. Haiyang Liu et al., 2016) [38]. Similarly, hydrothermally prepared WO_3 nanoflakes exhibited remarkable NH_3 sensitivity, which can be linked to their controlled crystal orientation and optimized pore structure, as highlighted (PS Kolhe et al., 2020) [39]. The primary advantages of these methods include precise control over particle size and morphology, high crystallinity, and minimal structural defects, making them highly suitable for advanced gas-sensing applications [40]. However, these methods also present certain limitations, such as the need for specialized equipment, such as autoclaves, and the often lengthy reaction times, which may pose challenges for large-scale production [41]. Despite these constraints, hydrothermal and solvothermal techniques remain indispensable tools for the synthesis of high-performance MOs, offering unparalleled control over material properties critical to gas-sensing technologies.

2.3 Chemical Precipitation

Chemical precipitation is widely recognized as a simple, cost-effective, and scalable method for the synthesis of MOs, making it particularly attractive for large-scale applications [42]. The process involves the reaction of metal salt solutions with a suitable precipitating agent, such as ammonia or sodium hydroxide, to form insoluble metal hydroxides. These hydroxides are subsequently subjected to calcination at elevated temperatures to yield the desired metal oxide products [43]. This method has been extensively utilized in the preparation of various gas-sensitive materials due to its simplicity and cost-efficiency [44]. T. Doan et al. reported that MOFderived ZnO/CuO nanoparticles synthesized via a precipitation method exhibit remarkable sensitivity toward hydrogen sulfide (H_2S) gas, which is mainly attributed to their uniform and well-controlled particle size [45]. Similarly, M. Shoaib et al. reported that ZnO nanoparticles and their corresponding thin films synthesized using this method exhibited excellent methane sensing performance, which can be attributed to their intrinsically porous structure [46]. Despite its advantages, including economic viability and scalability, chemical precipitation is not without limitations. Challenges such as limited control over particle morphology and size distribution often arise, which can affect the uniformity and performance of the synthesized materials [40]. Additionally, the calcination step required to convert hydroxides to oxides can lead to particle agglomeration, thereby compromising the surface area and gas sensing performance of the final product. Nevertheless, the method remains a cornerstone in the synthesis of MOs, offering a balance between simplicity, cost, and functionality, which is critical for their application in gas sensing technologies.

2.4 Spray Pyrolysis

Spray pyrolysis is a versatile and widely used technique for the synthesis of metal oxide particles, involving the atomization of a precursor solution into fine droplets that are subsequently thermally decomposed to form MOs [47]. The fundamental principle of this process is the rapid evaporation and decomposition of these droplets as they enter a high-temperature furnace, leading to the deposition of uniform and porous metal oxide layers. This method has been extensively applied in the fabrication of thin films for gas sensing applications, as evidenced by various studies [48]. However, spray pyrolysis also presents certain limitations, such as the high energy consumption required to maintain elevated temperatures and the challenge of achieving precise control over particle size during synthesis [49]. Despite these limitations, its adaptability and efficacy in producing high-quality MOs render spray pyrolysis an indispensable method for advancing gas sensing technologies, particularly in the development of sensitive and reliable sensors for environmental and industrial monitoring [50].

2.5 Combustion Synthesis

Combustion synthesis is a widely utilized method for the preparation of MOs, characterized by its reliance on the highly exothermic reaction between a fuel, such as glycine or urea, and an oxidizer. This technique is well-regarded for its simplicity, cost-effectiveness, and rapid processing, making it an appealing choice for the synthesis of advanced materials [51, 52]. The fundamental principle of this method lies in the generation of substantial heat during the reaction, which facilitates the formation of highly crystalline MOs with porous structures that are advantageous for various applications [53]. For instance, magnesium oxide (MgO) nanoparticles synthesized using combustion techniques have demonstrated excellent performance in CO2 sensing due to their high surface area and enhanced adsorption properties [54]. Similarly, tungsten trioxide (WO3) nanostructures prepared through combustion synthesis have exhibited superior sensitivity to hydrogen gas, highlighting the versatility of this method in tailoring MOs for specific gas-sensing applications [55]. The method offers several advantages, including rapid synthesis, energy efficiency, and the ability to produce materials with a high degree of porosity, which is critical for improving gas diffusion and interaction with sensing surfaces [56]. However, it is not without limitations; challenges such as inhomogeneous particle distribution and limited control over the morphology of the synthesized materials can impact the reproducibility and performance of the resulting products [51]. Despite these limitations, combustion synthesis remains a highly promising approach for the development of MOs tailored for advanced gas-sensing technologies, contributing significantly to the growing field of functional materials.

III. MOS BASED CHEMIRESISTIVE GAS SENSING MECHANISM & EVALUATION

Chemiresistive gas sensing is a widely employed detection strategy that hinges on the variation in electrical resistance of semiconducting materials upon interaction with target gas molecules [57]. Among various materials, semiconducting metal oxides (SMOs) such as ZnO, SnO_2, TiO_2, WO_3, and In_2O_3 are extensively utilized due to their high chemical and thermal stability, tunable surface properties, and the ability to be synthesized in diverse nanostructured morphologies [58]. The fundamental sensing mechanism involves the adsorption of oxygen molecules on the metal oxide surface, especially under elevated temperatures, where these molecules extract electrons from the conduction band of n-type semiconductors to form chemisorbed oxygen species such as O_2^-, O^-, and O^{2-} [59]. This process results in the formation of an electron depletion layer (EDL), increasing the material's resistance. Upon exposure to reducing gases (e.g., CO, NH_3, H_2S), these gases react with the chemisorbed oxygen species, releasing electrons back to the conduction band, which narrows the EDL and decreases the resistance [60]. Conversely, exposure to oxidizing gases (e.g., NO_2, O_3) leads to further electron withdrawal and increased resistance. In p-type semiconductors (e.g., NiO, CuO), the mechanism is reversed: reducing gases decrease hole concentrations, increasing resistance, whereas oxidizing gases enhance hole accumulation, lowering resistance [61]. The overall performance of a chemiresistive gas sensor is governed by several key parameters, including operating temperature, nanostructure, surface area, defect concentration, and gas diffusion kinetics [62]. Nanostructures such as nanorods, nanowires, nanotubes, and porous architectures play a critical role by enhancing the surface-to-volume ratio, increasing the density of active sites for gas adsorption, and improving electron transport pathways [63]. The choice of operating temperature is crucial, as it affects the formation and reactivity of adsorbed oxygen species and the desorption kinetics of the gas molecules [64]. Additionally, oxygen vacancies and surface defects serve as active centers for gas adsorption, making defect engineering an effective strategy for enhancing sensitivity and response time. The dynamic response and recovery behavior, which reflect how quickly a sensor reacts to the presence and absence of a gas, are directly linked to the surface reaction rates and the reversibility of adsorption processes. Recent advancements have highlighted the importance of heterostructures, dopants, and nanocomposites in fine-tuning the chemiresistive response [57]. For instance, p–n and n–n heterojunctions at the interface of two semiconductors introduce additional energy barriers that modulate charge transfer, thereby amplifying the resistance change upon gas exposure. Similarly, doping with noble metals or transition elements can introduce catalytic activity, enhance surface reactivity, and shift the Fermi level, improving gas selectivity and lowering the activation energy for surface reactions [65]. Integration of SMOs with two-dimensional materials like graphene, MoS_2, or MXenes provides synergistic effects such as higher conductivity, enhanced gas adsorption, and improved sensor stability under ambient conditions [66]. Moreover, environmental factors such as humidity can significantly influence gas sensing behavior by altering surface interactions or blocking active sites, necessitating the development of moisture-tolerant sensing platforms. Altogether, the chemiresistive gas sensing mechanism is governed by a complex interplay between surface chemistry, electronic structure, and environmental parameters, and continuous innovations in material design and surface engineering are driving the development of next-generation sensors with ultra-low detection limits, rapid response-recovery, high selectivity, and long-term operational stability for practical applications [67, 68].

The performance of these sensors is evaluated based on key parameters such as sensitivity, selectivity, response time, recovery time, stability, reproducibility, and power consumption [69]. Sensitivity, which refers to the sensor's ability to detect low concentrations of gases, is influenced by material properties such as surface area, morphology, and crystallinity, with nanostructured MOs (e.g., nanoparticles, nanowires, and nanosheets) enhancing sensitivity due to their higher surface area [70]. Doping with foreign elements and creating composites, such as bimetallic oxide composites or MO/graphene hybrids, further boosts sensitivity by modifying electronic structures and catalyzing surface reactions. Selectivity, the ability of a sensor to distinguish between target and interfering gases, is a significant challenge, often addressed by optimizing the material composition, forming heterojunctions, or incorporating catalytic materials like noble metal nanoparticles [71]. Cross-sensitivity remains a concern, but signal processing techniques can mitigate this issue. Response time and recovery time, which are critical for real-time detection, depend on the surface interactions between the gas molecules and the sensing material, with nanostructured MOs enabling faster response and recovery [72]. Elevated operating temperatures, commonly required for high sensitivity and fast response, increase power consumption; however, research into room-temperature operation using advanced materials like graphene and light-assisted activation techniques offers potential solutions. Stability and reproducibility, key for long-term deployment, are influenced by factors like material degradation and environmental conditions, and can be enhanced by material optimization and protective coatings. Environmental robustness and miniaturization for integration into portable devices are additional concerns, with strategies such as using hydrophobic coatings and microfabrication techniques being explored to address these challenges [73]. Despite the need for improvements in selectivity and operating conditions, chemiresistive gas sensors based on metal oxides and their composites continue to be a dominant and promising choice for various applications in environmental monitoring, industrial safety, healthcare diagnostics, and beyond, due to their simplicity, scalability, and potential for widespread commercialization.

IV. REVIEW OF PRISTINE NANOSTRUCTURED MOS FOR HIGH PERFORMANCE CHEMIRESISTIVE GAS SENSORS

Pristine nanostructured metal oxides (MOs) have garnered considerable attention for their potential in high-performance chemiresistive gas sensors due to their tunable morphologies, high surface-to-volume ratios, and surface reactivity. Both n-type and p-type MOs offer promising gas detection capabilities, with enhanced sensitivity, selectivity, and fast response/recovery dynamics under optimized conditions. Recent studies have explored various synthetic strategies such as hydrothermal, template-assisted, and surfactant-mediated methods to fine-tune particle size, crystallinity, and porosity, directly influencing gas adsorption and electron transport mechanisms. This section reviews key reports on pristine MO-based sensors, highlighting their structural attributes, detection limits, operating temperatures, and gas-specific sensing efficiencies. One of the noteworthy developments in this area was demonstrated by Hui-Bing Na et al., who utilized absorbent cotton as a bio-template to synthesize hierarchically porous ZnO hollow tubules. The resulting ZnO-600 sensor exhibited an ultra-low detection limit of 10 ppb for H_2S and a fast response time of 29 s to 50 ppb H_2S, operating efficiently across a broad concentration range. The superior performance was attributed to its high surface area (31 m^2/g), interconnected meso/macroporous network, and abundant surface-adsorbed oxygen species, which facilitated rapid gas diffusion and improved adsorption kinetics [74]. Building upon the morphological advantages of 1D nanostructures, Zhao et al. synthesized ZnO nanorods (ZNRs) via a complex-surfactant-assisted hydrothermal method and evaluated them for ethanol sensing [49]. Compared to zero-dimensional and two-dimensional counterparts, the ZnO nanorods demonstrated exceptional sensitivity (R_a/R_g = 45) to 100 ppm ethanol, with rapid response (6 s) and recovery (31 s) at 300 °C. The enhanced sensing was credited to the high aspect ratio of the ZNRs, which improved gas molecule transport and increased the density of surface oxygen vacancies [75]. Further exploring the impact of morphology on sensing performance, Cui et al. compared ZnO nanofibers, nanoplates, and nanoflowers for formaldehyde (HCHO) sensing under UV illumination [50]. Among these, ZnO nanofibers showed superior sensitivity, a fast response (32 s), and a quick recovery (17 s). These advantages were primarily due to their larger surface area and improved charge separation facilitated by UV activation, which accelerated electron–gas interactions and desorption processes [76]. To enhance selectivity and stability, several studies have focused on combining MOs to form heterojunctions. For instance, Ran Yoo et al. engineered a p–n heterojunction by depositing hydrothermally synthesized CuO nanoparticles onto flower-like ZnO structures [51]. The resulting CuO/ZnO composite sensor exhibited selective detection of dimethyl methylphosphonate (DMMP), with a rapid response time of 26.2 s and high sensitivity (response = 626.21 s) at 350 °C. The improved performance was attributed to the extended depletion region and modulated resistance due to heterojunction formation, enhancing charge carrier separation and adsorption efficiency [77]. A similar approach was adopted by Jiangyang Liu et al., who developed ZnO/SnO_2 hollow nanostructure composites through a solution-phase method [52]. Uniform dispersion of ZnO nanoparticles over SnO_2 hollow spheres was confirmed via XRD, TEM, and XPS. The heterostructure significantly boosted ethanol sensing response—sevenfold compared to pristine SnO_2 and enabled detection at ppb levels. These enhancements stemmed from the synergistic interaction at the heterojunction interface, which increased chemisorbed oxygen species and electron exchange [78]. Emphasizing the role of template-assisted synthesis, Jun Zhang et al. fabricated porous SnO_2 nanotubes using MnO_2 nanorods as a sacrificial template. This method resulted in high surface area structures that required no post-synthesis treatment. The SnO_2 nanotube-based sensors demonstrated high sensitivity, fast response-recovery cycles, and excellent repeatability for alcohol detection, underscoring the importance of porosity and structural integrity in enhancing chemiresistive behavior [79]. Another study focusing on ethanol sensing was presented by Shixiu Cao et al., who employed a one-step hydrothermal synthesis to produce WO_3 nanofibers with uniform morphology. The sensor achieved a notable response of 62 at 350 °C, which was attributed to the nanofiber's one-dimensional architecture that promoted electron transport and efficient gas adsorption. This work further highlighted the influence of dimensional control on sensing activity [80]. Complementing this, Ze-Xing Cai et al. synthesized single-crystalline WO_3 nanowires hydrothermally on FTO substrates and calcined them to yield an orthorhombic phase. With diameters between 15–20 nm, these nanowires exhibited a response of 37 and rapid response/recovery (68/88 s) to NO at 300°C. XPS and DRIFT analyses confirmed that surface oxygen defects played a critical role in the NO chemisorption and oxidation processes, pointing to the value of defect engineering in optimizing gas sensor functionality [81]. Park et al. synthesized nanograined ZnO nanowires (20–100 nm) via ZnSe thermal oxidation (650°C), achieving an exceptional 237, 263% response at 10 ppm NO_2 (300°C), far surpassing single-crystal ZnO (6.5%). The sensor exhibited shorter recovery time and enhanced sensitivity due to multiple grain boundaries increasing resistance modulation. These findings demonstrate the potential of nanograined ZnO nanowires for high-performance, cost-effective NO_2 sensing applications. The superior sensing behavior was attributed to the formation of multiple electrical barriers at the grain boundaries, which amplified resistance changes upon gas adsorption/desorption. Additionally, the sensor exhibited a shorter recovery time 180 s, making it highly effective for NO_2 detection [82]. In the domain of titanium-based oxides, Y. Kwon et al. reported the fabrication of TiO_2 nanotube arrays via anodization of Ti thin foils for ethanol gas sensing applications. The nanotube arrays exhibited diameters of 70–120 nm and lengths of 300–400 nm. The sensors demonstrated exceptionally high responses of 68,000% and 1,380,000% to 300 ppm and 1000 ppm ethanol at 250°C, respectively, surpassing most reported one-dimensional oxide nanostructures. The key sensing parameters such as LOD 50 ppm, response time 110 s, and fast recovery time 19 s [83]. Room-temperature operation remains a challenge for many MO-based sensors, but Y. Shen et al. reported the in-situ growth of mesoporous In_2O_3 nanorod arrays on a porous ceramic substrate via a one-step hydrothermal method for highly sensitive NO_2 detection at room temperature. The nanorods (120–200 nm in diameter, 0.5–1 μm in length) were assembled from aggregated In_2O_3 nanoparticles (10–30 nm), forming a mesoporous structure with a high surface area. The fabricated sensor demonstrated an exceptional response of 14.9 toward 800 ppb NO_2 at 25°C, with a rapid response time of 14 s and a UV-assisted recovery time of 32 s. The high sensing performance was attributed to the mesoporous architecture and the enhanced nucleation facilitated by the ceramic substrate. This work highlights a cost-effective strategy for fabricating highly efficient NO_2 gas sensors operating at room temperature [84]. Focusing on molybdenum-based oxides, B. Mandal et al. tailored MoO_3 nanostructures via frequency-dependent pulsed temperature hydrothermal growth, enhancing ethanol sensing performance. MoO_3 nanofibers exhibited higher crystallinity, surface area, and defect sites than nanobelts, leading to superior

© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1720065

sensitivity. The sensor operated at 275°C with a response time of 45 s, recovery time of 138 s, and a LOD of 21 ppm. These improvements make MoO_3 nanofibers promising for high-performance chemiresistive ethanol sensing [85]. Z. Li et al. reported the hydrothermal synthesis of CeO_2 nanowires without surfactants, demonstrating their efficacy in H_2S sensing at room temperature (25°C). The synthesized CeO_2 nanowires exhibited a uniform diameter of 12.5 nm with a cubic fluorite structure and [111] preferred orientation. The sensor based on these nanowires showed excellent performance, including a low detection limit of 50 ppb, fast response (24 s), and recovery time (15 s). Additionally, the sensor exhibited good sensitivity, long-term stability, and high selectivity towards H_2S gas [86]. Taken together, these studies illustrate the critical roles of nanostructure design, oxygen vacancy control, and heterojunction engineering in modulating gas sensing behavior. Strategies such as template-assisted synthesis, defect modulation, dimensional tuning, and hybridization have enabled remarkable improvements in sensitivity, selectivity, and stability. As summarized in Table 1, the comparative analysis of recent developments confirms that pristine nanostructured metal oxides remain at the forefront of next-generation chemiresistive gas sensor design, providing scalable, tunable, and efficient materials for diverse sensing applications.

Table 1: Summary of pristine nanostructured MOs for chemiresistive gas sensing without modification.

Sensing Material	Morphology	Synthesis Method	Target Analyte	Operating Temperature (°C)	Tres/Trec (Sec)	LOD	Ref.
WO_3	Nanofiber	Electrospinning	NH_3	200	1/5	–	[87]
V_2O_5	Nanowire	Melt quenching	Ethanol	330	–	–	[88]
NiO	Nanowire	Chemical Reduction	NH_3	–	–	–	[89]
CuO	Nanorod	Hydrothermal	Ethanol	210	13/17	5 ppm	[90]
WO_3	Nanofiber	Hydrothermal	Ethanol	350	–	10 ppm	[80]
CuO	Nanowire	Electrodeposition	H_2S	180	–	10 ppb	[91]
MoO_3	Nanofiber	Hydrothermal	Ethanol	275	45/138	21 ppm	[85]
MoO_3	Nanorod	Probe ultrasonic	NO_2	290	–	10 ppm	[92]
In_2O_3	Nanowire	Electrospinning	H_2S	25	–	–	[93]
In_2O_3	Nanorod	Hydrothermal	NO_2	25	14/32	100 ppb	[84]
TiO_2	Nanofiber	Electrospinning	CO	200	32/84	1 ppm	[94]
ZnO	Nanowire	Thermal Evaporation	NO_2	300	570/180	100 ppb	[82]
ZnO	Nanowire	Hydrothermal	H_2S	300	–	50 ppb	[95]
ZnO	Nanorod	Vapor phase transport	H_2S	Room temperature	320/3592	500 ppb	[96]
ZnO	Nanorod	Hydrothermal	Ethanol	320	47/50	1 ppm	[97]

ZnO	Nanofiber	Hydrothermal	CO	250	1/0.002	10 ppm	[98]
TiO_2	Nanotube	Electrochemical anodization	Ethanol	250	110/19	50 ppm	[83]
SnO_2	Nanowire	Chemical vapor deposition	NO_2	250	5/–	50 ppm	[99]
WO_3	Nanowire	Hydrothermal	NO_2	150	–	5 ppm	[100]
WO_3	Nanowire	Hydrothermal	NO	300	63/88	50 ppm	[81]
WO_3	Nanospheres	Hydrothermal	NO_2	300	–	1 ppm	[101]

V. REVIEW OF NANOSTRUCTURED MOS BASED COMPOSITES FOR HIGH PERFORMANCE CHEMIRESISTIVE GAS SENSORS

In recent years, composite materials based on metal oxides (MOs) have gained considerable attention for chemiresistive gas sensing applications due to their improved sensitivity, selectivity, stability, and tunable operating temperatures. The integration of nanostructured MOs with noble metals, conductive additives, and other semiconducting materials has led to the development of highly efficient sensors capable of detecting a broad range of hazardous gases at sub-ppm or even ppb levels. This section reviews recent advancements in the design and performance of such MO-based composite systems, highlighting their morphology, detection limits, operating temperatures, and gas-sensing mechanisms. One notable approach involves doping noble metals into metal oxide matrices to enhance catalytic activity and promote gas molecule adsorption. For instance, S. An et al. synthesized Au-doped In_2O_3 nanotube sensors using TeO_2 nanowire templates, yielding high surface area structures with significantly improved ethanol sensing performance. These sensors exhibited exceptional responses ranging from 187% to 1219% at 300 °C for ethanol concentrations between 50 and 250 ppm, clearly outperforming undoped counterparts. The observed enhancement was attributed to the Au-induced spillover effect and increased chemisorption, facilitating faster reaction kinetics and improved electron transfer [102]. Similarly, P. Jaroenapibal et al. introduced Ag-doping into WO_3 nanofibers via electrospinning. The optimized 3 mol% Ag-doped WO_3 sensor demonstrated a high response of 90.3 to 5 ppm NO_2 at 225 °C, nearly nine times greater than the undoped version. The porous nanofiber morphology coupled with Ag's electronic and catalytic effects contributed to improved sensitivity and selectivity. Although the response (6 min) and recovery (18 min) times were moderate, the doping level and material structure

played critical roles in enhancing sensing capability [103]. Beyond doping, hybrid nanocomposites have shown excellent results in tailoring surface and electronic properties for gas sensing. L. Guo et al. fabricated Pt-loaded ZnO–In_2O_3 nanofibers using a ZIF-8 framework, introducing ultra-small Pt nanoparticles as active catalytic sites. This hybrid composite demonstrated ultra-low detection limits (0.5 ppm) for acetone at 300 °C with extremely fast response and recovery times (1 s and 44 s, respectively). The unique heterojunction interface and catalytic activity of Pt facilitated rapid gas molecule dissociation and charge transfer, boosting sensitivity and long-term stability [104]. To operate at room temperature, polymer-inorganic hybrid composites have been explored. A. Seif et al. developed UV-assisted PANI/TiO_2 core–shell nanofibers via in situ polymerization on electrospun TiO_2 scaffolds. These sensors displayed excellent NH_3 sensitivity with a detection limit of 50 ppb and stable operation under ambient conditions. The anatase–rutile TiO_2 core provided a semiconducting backbone, while the porous PANI shell offered enhanced conductivity and interaction with target gases. The hybrid also displayed good humidity tolerance, making it suitable for practical breath analysis applications [105]. Graphene-based hybrid structures also play a pivotal role in enhancing chemiresistive properties. Wang et al. integrated 1 wt% graphene oxide (GO) into hollow SnO_2 nanofibers to enhance formaldehyde sensing. The resulting composite exhibited a fourfold increase in sensitivity compared to pure SnO_2 nanofibers, achieving a detection limit of 500 ppb and a rapid response/recovery time at a relatively low temperature of 120 °C. The synergistic interaction between GO's high surface area and SnO_2's semiconducting behavior led to an efficient electron modulation and gas adsorption interface [106]. Heterojunction-based nanofibers have emerged as a reliable strategy for tuning sensing behaviors. C. Li et al. synthesized p–n NiO/ZnO heterojunction nanofibers with an optimized NiO content of 4 mol%. These sensors delivered a high response (892) to 100 ppm trimethylamine (TMA) at 260 °C, with a low detection limit of 0.5 ppm and fast response/recovery times (<30 s/<35 s). The formation of p–n junctions enhanced carrier modulation and depletion layer width, enabling improved sensitivity and selectivity for amine-based gas detection [107]. Similarly, J. H. Lee et al. reported the fabrication of Co_3O_4-loaded ZnO nanofibers through electrospinning. The Co_3O_4 inclusion (5%) led to a significant increase in hydrogen gas response (~133 at 10 ppm H_2) with excellent selectivity and a low detection threshold (1 ppm). The nanofiber morphology supported efficient gas transport, while the Co_3O_4 loading induced surface electronic effects and oxygen vacancy generation, resulting in superior performance [108]. The incorporation of sulfide phases has also proven beneficial. R. Li et al. developed SnO_2/SnS_2 nanotube composites via an in situ hydrothermal sulfuration process. These composites, flexible and operable at room temperature, exhibited a remarkable NH_3 response of 2.48 at 100 ppm. The formation of a heterostructure with enhanced charge separation and extended depletion regions contributed to this improvement. The hollow tubular architecture also ensured sufficient active sites and rapid gas diffusion [109]. In another hybrid design, S. Shao et al. synthesized Au@WO_3–SnO_2 nanoporous nanofibers through post-synthetic hydrothermal treatment. These sensors achieved a low detection limit of 0.5 ppm and a high acetone response of 79.6 at 150 °C. The inclusion of gold nanoparticles and dual-phase oxides led to enhanced catalytic effects, selective adsorption, and better stability over extended use. Such systems are highly promising for applications in non-invasive health monitoring [110]. Carbon-based additives further enrich MO sensing matrices. J. Fan et al. incorporated carbon nanotubes (CNTs) into CuO/SnO_2 composites for detecting H_2S at low concentrations. The resulting sensor demonstrated superior sensitivity (0.1 ppm LOD), rapid response (8.3 s), and recovery (11.5 s) at a low operating temperature of 40 °C. The CNTs improved electron pathways and formed p–n junctions with metal oxides, significantly enhancing sensing characteristics [111]. To further elevate performance, noble metal-decorated rGO-ZnO composites were proposed by Z. U. Abideen et al. using sol–gel and electrospinning. These composites, functionalized with either Au or Pd, exhibited excellent gas responses for CO and benzene (C_6H_6) with LODs as low as 1 ppm, along with rapid kinetics and low-temperature operation. The synergy between 1D ZnO nanofibers, conductive rGO sheets, and noble metals amplified adsorption sites and catalytic breakdown of analytes, showing potential for sensitive and selective detection in industrial or environmental monitoring scenarios [112]. Collectively, these studies highlight the potential of nanostructured MO-based composites in enhancing chemiresistive gas sensors through strategic modifications like noble metal doping, heterojunctions, polymer/carbon integration, and sulfide incorporation. These designs improve sensitivity, response/recovery times, and temperature adaptability by enhancing surface area, charge transport, and catalytic activity. As summarized in Table 2, the comparative analysis reveals key structure–property–performance relationships crucial for developing next-generation gas sensing materials.

Table2: Summary of composite of nanostructured MOs for chemiresistive gas sensing.

Sensing Material	Synthesis Method	Target Analyte	Operating Temperature (°C)	Tres/Trec (Sec) Composite	Tres/Trec (Sec) Pristine	Ref.
Au/WO_3	Electrospinning	*n*-butanol	250	55/–	76/–	[113]
Au/ZnO	Hydrothermal	Ethanol	380	3/1	5/6	[114]
Au/ZnO	Hydrothermal	Toluene	340	36/45	–	[115]
Au/In_2O_3	Thermal evaporation	Ethanol	300	50/100	15/90	[102]
Ag/WO_3	Electrospinning	NO_2	225	11.9/8.7	12.4/6	[103]
Pt/In_2O_3	Electrospinning	Acetone	180	6/9	≈15/19	[116]
Pd/SnO_2	Electrospinning	Formaldehyde	160	2/7	12/22	[117]
Pd/WO_3	Electrospinning	Toluene	350	10.9/16.1	28.6/56.6	[118]
$PANI/SnO_2$	Electrospinning	H_2	48	≈3/4	–	[119]
GO/WO_3	Electrospinning	Acetone	375	4/10	8/13	[120]
GO/SnO_2	Electrospinning	Formaldehyde	120	66/10	70/7	[106]
rGO/Co_3O_4	Electrospinning	NH_3	20	4/300	–	[121]
$rGO/\alpha\text{-}Fe_2O_3$	Electrospinning	Acetone	375	3/9	25/30	[122]
$NiO\text{-}WO_3$	Electrospinning	Acetone	375	10/15	6/11	[123]
$CuO\text{-}WO_3$	Electrospinning	DMMP	RT	9.2/15.5	8.7/13.7	[124]
$In_2O_3\text{-}ZnO$	Electrospinning	Ethanol	225	53/3.7	105/7	[125]
NiO-ZnO	Electrospinning	Trimethylamine	260	18/20	5/13	[107]
NiO/SnO_2	Electrospinning	Ethanol	300	2.9/4.7	–	[126]
CuO/SnO_2	Electrospinning	H_2S	200	23/15	–	[127]
$\alpha\text{-}Fe_2O_3\text{-}SnO_2$	Electrospinning	Ethanol	300	22.46/20	–	[128]
$MoS_2\text{-}SnO_2$	Electrospinning	Methane	180	150/20	–	[129]
$MoS_2\text{-}ZnO$	Hydrothermal	NO_2	200	–	–	[130]
$MoS_2\text{-}TiO_2$	Hydrothermal	Ethanol	150	≈20	–	[131]
Au/rGO/ZnO	Electrospinning	CO	400	177.3/76.1	–	[112]
$Pt/ZnO/In_2O_3$	Electrospinning	Acetone	300	1/44	2/32	[104]
$CNT/CuO/SnO_2$	Electrospinning	H_2S	40	8.3/11.5	–	[111]

VI. SUMMARY

Metal oxide (MO)-based chemiresistive gas sensors have emerged as one of the most promising technologies for the detection of hazardous gases because of their high sensitivity, simple device architecture, low fabrication cost, and excellent chemical and thermal stability. This review comprehensively discussed recent advances in the synthesis, sensing mechanisms, and performance of pristine metal oxides and metal oxide-based nanocomposites for hazardous gas detection. It was demonstrated that the sensing characteristics of MOs are strongly influenced by their synthesis routes, which govern critical material properties such as morphology, crystallinity, particle size, porosity, surface defects, and oxygen vacancies. Conventional synthesis techniques, including sol-gel, hydrothermal, chemical precipitation, spray pyrolysis, combustion, chemical vapor deposition, and microwave-assisted methods, provide versatile approaches for tailoring these properties to achieve superior sensing performance.

Furthermore, the review highlighted the fundamental chemiresistive sensing mechanism based on surface adsorption–desorption reactions and charge transfer processes, emphasizing the importance of nanostructure engineering, defect modulation, and heterojunction formation in enhancing sensor response. Comparative analysis of recent literature revealed that pristine nanostructured metal oxides exhibit excellent gas sensing characteristics; however, the incorporation of noble metals, graphene derivatives, conductive polymers, transition metal oxides, and other functional nanomaterials significantly improves sensitivity, selectivity, response/recovery characteristics, and detection limits through synergistic catalytic and electronic effects. Despite remarkable progress, several challenges remain, including high operating temperatures, humidity interference, limited selectivity, and long-term operational stability. Future research should focus on developing room-temperature sensing materials, multifunctional heterostructures, flexible and wearable sensor platforms, low-power devices, and intelligent sensor systems integrated with artificial intelligence and the Internet of Things (IoT). Overall, nanostructured metal oxides and their composites continue to provide a versatile and scalable platform for next-generation chemiresistive gas sensors, offering significant potential for applications in environmental monitoring, industrial safety, food quality assessment, and non-invasive healthcare diagnostics.

REFERENCES

[1] Hajra, K., D. Maity, and S. Saha, Recent advancements of metal oxide nanoparticles and their potential applications: A review. Adv. Mater. Lett, 2024. 15(1): p. 2401-1740.

[2] Yang, X., et al., Functionalization of mesoporous semiconductor metal oxides for gas sensing: Recent advances and emerging challenges. Advanced Science, 2023. 10(1): p. 2204810.

[3] Panda, S., et al., Comprehensive review on gas sensors: Unveiling recent developments and addressing challenges. Materials Science and Engineering: B, 2024. 308: p. 117616.

[4] Alam, M.W., et al., The recent development in chemoresistive-based heterostructure gas sensor technology, their future opportunities and challenges: A review. Membranes, 2022. 12(6): p. 555.

[5] Gautam, Y.K., et al., Nanostructured metal oxide semiconductor-based sensors for greenhouse gas detection: Progress and challenges. Royal Society open science, 2021. 8(3): p. 201324.

[6] Jana, R., et al., Recent advances in multifunctional materials for gas sensing applications. Journal of Environmental Chemical Engineering, 2022. 10(6): p. 108543.

[7] Sun, Y.-F., et al., Metal oxide nanostructures and their gas sensing properties: a review. Sensors, 2012. 12(3): p. 2610-2631.

[8] Huang, A., et al., A review of recent applications of porous metals and metal oxide in energy storage, sensing and catalysis. Journal of Materials Science, 2019. 54(2): p. 949-973.

[9] Potyrailo, R.A., et al., Materials and transducers toward selective wireless gas sensing. Chemical reviews, 2011. 111(11): p. 7315-7354.

[10] Ayuk, E., M. Ugwu, and S.B. Aronimo, A review on synthetic methods of nanostructured materials. Chemistry Research Journal, 2017. 2(5): p. 97-123.

[11] Ashik, U., S. Kudo, and J.-i. Hayashi, An overview of metal oxide nanostructures. Synthesis of inorganic nanomaterials, 2018: p. 19-57.

[12] Hachem, K., et al., Methods of chemical synthesis in the synthesis of nanomaterial and nanoparticles by the chemical deposition method: a review. BioNanoScience, 2022. 12(3): p. 1032-1057.

[13] Wang, C., et al., Metal oxide gas sensors: sensitivity and influencing factors. sensors, 2010. 10(3): p. 2088-2106.

[14] Staerz, A., U. Weimar, and N. Barsan, Current state of knowledge on the metal oxide based gas sensing mechanism. Sensors and Actuators B: Chemical, 2022. 358: p. 131531.

[15] Mirzaei, A., S.S. Kim, and H.W. Kim, Resistance-based H2S gas sensors using metal oxide nanostructures: A review of recent advances. Journal of hazardous materials, 2018. 357: p. 314-331.

[16] Patial, P. and M. Deshwal, Selectivity and sensitivity property of metal oxide semiconductor based gas sensor with dopants variation: A review. Transactions on Electrical and Electronic Materials, 2022. 23(1): p. 6-18.

[17] Cuong, N.D. and D.T. Quang, Progress through synergistic effects of heterojunction in nanocatalysts-Review. Vietnam Journal of Chemistry, 2020. 58(4): p. 434-463.

[18] Ray, C. and T. Pal, Retracted Article: Recent advances of metal–metal oxide nanocomposites and their tailored nanostructures in numerous catalytic applications. Journal of Materials Chemistry A, 2017. 5(20): p. 9465-9487.

[19] Singh, A., et al., The recent development of metal oxide heterostructures based gas sensor, their future opportunities and challenges: a review. Sensors and Actuators A: Physical, 2021. 332: p. 113127.

[20] Saxena, P. and P. Shukla, A review on recent developments and advances in environmental gas sensors to monitor toxic gas pollutants. Environmental Progress & Sustainable Energy, 2023. 42(5): p. e14126.

[21] Moussa, N., et al., Hydrogen Sensing Technologies for the Safe and Reliable Decarbonization of Electric Power: A Review. Energies, 2024. 17(18): p. 4532.

[22] Das, S. and M. Pal, Non-invasive monitoring of human health by exhaled breath analysis: A comprehensive review. Journal of The Electrochemical Society, 2020. 167(3): p. 037562.

[23] Hou, L., et al., Low Power Gas Sensors: From Structure to Application. ACS sensors, 2024. 9(12): p. 6327-6357.

[24] Wawrzyniak, J., Advancements in improving selectivity of metal oxide semiconductor gas sensors opening new perspectives for their application in food industry. Sensors, 2023. 23(23): p. 9548.

[25] El-Naggar, M.E. and K. Shoueir, Recent advances in polymer/metal/metal oxide hybrid nanostructures for catalytic applications: A review. Journal of Environmental Chemical Engineering, 2020. 8(5): p. 104175.

[26] Moseley, P.T., Progress in the development of semiconducting metal oxide gas sensors: a review. Measurement Science and Technology, 2017. 28(8): p. 082001.

[27] Comini, E., Metal oxide nano-crystals for gas sensing. Analytica chimica acta, 2006. 568(1-2): p. 28-40.

[28] Baig, N., I. Kammakakam, and W. Falath, Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Materials advances, 2021. 2(6): p. 1821-1871.

[29] Bokov, D., et al., Nanomaterial by sol-gel method: synthesis and application. Advances in materials science and engineering, 2021. 2021(1): p. 5102014.

[30] Frenzer, G. and W.F. Maier, Amorphous porous mixed oxides: Sol-gel ways to a highly versatile class of materials and catalysts. Annu. Rev. Mater. Res., 2006. 36(1): p. 281-331.

[31] Danks, A.E., S.R. Hall, and Z. Schnepp, The evolution of 'sol–gel'chemistry as a technique for materials synthesis. Materials Horizons, 2016. 3(2): p. 91-112.

[32] Jabeen, M., R.V. Kumar, and N. Ali, A review on preparation of ZnO nanorods and their use in ethanol vapors sensing. Gas Sensors, 2020: p. 1-24.

[33] He, Y., et al., SnO2-BASED CO SENSORS: RECENT ADVANCES AND FUTURE DIRECTIONS. Ceramics–Silikáty, 2023. 67(4): p. 446-457.

[34] Myasoedova, T.N., R. Kalusulingam, and T.S. Mikhailova, Sol-gel materials for electrochemical applications: recent advances. Coatings, 2022. 12(11): p. 1625.

[35] Parthasarathy, S., et al., Nanoparticle Synthesis Methods, in Discovery, Disruption, and Future Implications of Nanomaterials. 2024, IGI Global. p. 33-68.

[36] Feng, S.-H. and G.-H. Li, Hydrothermal and solvothermal syntheses, in Modern inorganic synthetic chemistry. 2017, Elsevier. p. 73-104.

[37] Shandilya, M., R. Rai, and J. Singh, Hydrothermal technology for smart materials. Advances in Applied Ceramics, 2016. 115(6): p. 354-376.

[38] Liu, H., et al., Fabrication of lotus-like Au@ TiO2 nanocomposites with enhanced gas-sensing properties. Sensors and Actuators B: Chemical, 2016. 236: p. 490-498.

[39] Kolhe, P.S., et al., Synthesis of WO3 nanoflakes by hydrothermal route and its gas sensing application. Sensors and Actuators A: Physical, 2020. 304: p. 111877.

[40] Mandal, K., et al., Notes on useful materials and synthesis through various chemical solution techniques, in Chemical Solution Synthesis for Materials Design and Thin Film Device Applications. 2021, Elsevier. p. 29-78.

[41] Darr, J.A., et al., Continuous hydrothermal synthesis of inorganic nanoparticles: applications and future directions. Chemical reviews, 2017. 117(17): p. 11125-11238.

[42] Xia, X., et al., Solution synthesis of metal oxides for electrochemical energy storage applications. Nanoscale, 2014. 6(10): p. 5008-5048.

[43] Wang, L.K., et al., Chemical precipitation, in Physicochemical treatment processes. 2005, Springer. p. 141-197.

[44] Choudhuri, B. and P. Raturi, Fabrication of Gas Sensor Using Metal Oxide Semiconductor Nanostructures, in Hybrid Nanostructures as Solid-State Sensors for IoT. 2024, Chapman and Hall/CRC. p. 59-120.

[45] Doan, T.L.H., et al., Facile synthesis of metal-organic framework-derived ZnO/CuO nanocomposites for highly sensitive and selective H2S gas sensing. Sensors and Actuators B: Chemical, 2021. 349: p. 130741.

[46] Shoaib, M., et al., Synthesis and methane gas sensing study of uniform zinc oxide nanoparticles and thin film. Arabian Journal for Science and Engineering, 2024. 49(6): p. 7883-7892.

[47] Leng, J., et al., Advances in nanostructures fabricated via spray pyrolysis and their applications in energy storage and conversion. Chemical Society Reviews, 2019. 48(11): p. 3015-3072.

[48] Manea, R.S., Spray-pyrolysis technique for the synthesis of metal oxide nanostructures. Solution Methods for Metal Oxide Nanostructures, 2023: p. 155.

[49] Meierhofer, F. and U. Fritsching, Synthesis of metal oxide nanoparticles in flame sprays: review on process technology, modeling, and diagnostics. Energy & Fuels, 2021. 35(7): p. 5495-5537.

[50] Wang, J., et al., Chemiresistive gas sensors: materials, mechanisms, and applications on the road to intelligence and multifunctionality. Small, 2026. 22(13): p. e12547.

[51] Novitskaya, E., et al., A review of solution combustion synthesis: an analysis of parameters controlling powder characteristics. International Materials Reviews, 2021. 66(3): p. 188-214.

[52] Kopp Alves, A., C.P. Bergmann, and F.A. Berutti, Combustion synthesis, in Novel synthesis and characterization of nanostructured materials. 2013, Springer. p. 11-22.

[53] Varma, A., et al., Solution combustion synthesis of nanoscale materials. Chemical reviews, 2016. 116(23): p. 14493-14586.

[54] Elvira, G.-B., et al., MgO-based adsorbents for CO2 adsorption: Influence of structural and textural properties on the CO2 adsorption performance. Journal of Environmental Sciences, 2017. 57: p. 418-428.

[55] Li, X., et al., Innovations in WO3 gas sensors: Nanostructure engineering, functionalization, and future perspectives. Heliyon, 2024. 10(6).

[56] Carlos, E., et al., Solution combustion synthesis: towards a sustainable approach for metal oxides. Chemistry–A European Journal, 2020. 26(42): p. 9099-9125.

[57] Bulemo, P.M., et al., Selectivity in chemiresistive gas sensors: strategies and challenges. Chemical reviews, 2025. 125(8): p. 4111-4183.

[58] Zang, Z., W. Cai, and Y. Zhou, Metal oxide semiconductors: synthesis, properties, and devices. 2023: John Wiley & Sons.

[59] Burman, D. and T. Thajudeen, Advances in nanostructured chemiresistive sensors for formaldehyde detection. Nanoscale, 2026. 18(9): p. 4622-4660.

[60] Ahemad, M.J., et al., Gas Adsorption-Driven Electronic Modulation in WO3@ Cu3 (HHTP) 2 Heterostructure: Mechanistic Origin of Selective Drift Resistance Room-Temperature Formaldehyde Sensing. Small, 2026: p. e74015.

[61] Sahu, S.R., et al., Pioneering p-and n-Type Chemiresistive Technologies: Broad-Spectrum Detection of Deleterious Airborne Pollutants. ACS Applied Electronic Materials, 2025. 7(22): p. 10028-10053.

[62] Wang, P., et al., Recent advances in resistive gas sensors: Fundamentals, material and device design, and intelligent applications. Chemosensors, 2025. 13(7): p. 224.

[63] Jose, A., et al. Porous inorganic nanomaterials: their evolution towards hierarchical porous nanostructures. in Micro. 2024. MDPI.

[64] Ciftyurek, E., Z. Li, and K. Schierbaum, Adsorbed oxygen ions and oxygen vacancies: their concentration and distribution in metal oxide chemical sensors and influencing role in sensitivity and sensing mechanisms. Sensors, 2022. 23(1): p. 29.

[65] Bärtsch, M. and M. Niederberger, The role of interfaces in heterostructures. ChemPlusChem, 2017. 82(1): p. 42-59.

[66] Liu, J., et al., Advancements and Strategies for Selectivity Enhancement in Chemiresistive Gas Sensors. Nanomaterials, 2025. 15(17): p. 1381.

[67] Yang, J., et al., Development of Long-Term Stable MXene-Based Gas Sensing Material. Molecules, 2025. 30(22): p. 4440.

[68] Hu, C., et al., Chemiresistive gas sensors for intelligent sensing: design strategies, emerging applications and future challenges. Chemical Society Reviews, 2025. 54(23): p. 11302-11367.

[69] Kim, S., et al., Aerosol-synthesized surfactant-free single-walled carbon nanotube-based NO2 sensors: unprecedentedly high sensitivity and fast recovery. Advanced Materials, 2024. 36(24): p. 2313830.

[70] Isaac, N.A., I. Pikaar, and G. Biskos, Metal oxide semiconducting nanomaterials for air quality gas sensors: operating principles, performance, and synthesis techniques. Microchimica Acta, 2022. 189(5): p. 196.

[71] Liu, M., et al., Recent advances in noble metal catalysts for hydrogen production from ammonia borane. Catalysts, 2020. 10(7): p. 788.

[72] Zhao, H., Y. Wang, and Y. Zhou, Accelerating the gas–solid interactions for conductometric gas sensors: impacting factors and improvement strategies. Materials, 2023. 16(8): p. 3249.

[73] Godja, N.-C. and F.-D. Munteanu, Hybrid nanomaterials: a brief overview of versatile solutions for sensor technology in healthcare and environmental applications. Biosensors, 2024. 14(2): p. 67.

[74] Na, H.-B., et al., Large-scale synthesis of hierarchically porous ZnO hollow tubule for fast response to ppb-level H2S gas. ACS Applied Materials & Interfaces, 2019. 11(12): p. 11627-11635.

[75] Zhao, S., et al., Complex-surfactant-assisted hydrothermal synthesis of one-dimensional ZnO nanorods for high-performance ethanol

gas sensor. Sensors and Actuators B: Chemical, 2019. 286: p. 501-511.

[76] Cui, J., et al., UV-light illumination room temperature HCHO gas-sensing mechanism of ZnO with different nanostructures. Sensors and Actuators B: Chemical, 2016. 227: p. 220-226.

[77] Yoo, R., et al., Highly selective detection of dimethyl methylphosphonate (DMMP) using CuO nanoparticles/ZnO flowers heterojunction. Sensors and Actuators B: Chemical, 2017. 240: p. 1099-1105.

[78] Liu, J., et al., Highly sensitive and low detection limit of ethanol gas sensor based on hollow ZnO/SnO2 spheres composite material. Sensors and Actuators B: Chemical, 2017. 245: p. 551-559.

[79] Zhang, J., et al., Reactive-template fabrication of porous SnO2 nanotubes and their remarkable gas-sensing performance. ACS applied materials & interfaces, 2013. 5(16): p. 7893-7898.

[80] Cao, S., et al., Hydrothermal synthesis, characterization and gas sensing properties of the WO3 nanofibers. Materials Letters, 2016. 169: p. 17-20.

[81] Cai, Z.-X., et al., NO sensing by single crystalline WO3 nanowires. Sensors and Actuators B: Chemical, 2015. 219: p. 346-353.

[82] Park, S., et al., Synthesis of nanograined ZnO nanowires and their enhanced gas sensing properties. ACS Applied Materials & Interfaces, 2012. 4(7): p. 3650-3656.

[83] Kwon, Y., et al., Enhanced ethanol sensing properties of TiO2 nanotube sensors. Sensors and Actuators B: Chemical, 2012. 173: p. 441-446.

[84] Shen, Y., et al., In-situ growth of mesoporous In2O3 nanorod arrays on a porous ceramic substrate for ppb-level NO2 detection at room temperature. Applied Surface Science, 2019. 498: p. 143873.

[85] Mandal, B., et al., Architecture tailoring of MoO3 nanostructures for superior ethanol sensing performance. Materials Research Bulletin, 2019. 109: p. 281-290.

[86] Li, Z., et al., Hydrothermally synthesized CeO2 nanowires for H2S sensing at room temperature. Journal of Alloys and Compounds, 2016. 682: p. 647-653.

[87] Leng, J.-y., et al., Synthesis and gas-sensing characteristics of WO3 nanofibers via electrospinning. Journal of colloid and interface science, 2011. 356(1): p. 54-57.

[88] Jin, W., et al., Enhancement of ethanol gas sensing response based on ordered V2O5 nanowire microyarns. Sensors and Actuators B: Chemical, 2015. 206: p. 284-290.

[89] Wang, J., et al., Preparation of high aspect ratio nickel oxide nanowires and their gas sensing devices with fast response and high sensitivity. Journal of materials chemistry, 2012. 22(17): p. 8327-8335.

[90] Yang, C., et al., Gas sensing properties of CuO nanorods synthesized by a microwave-assisted hydrothermal method. Sensors and Actuators B: Chemical, 2011. 158(1): p. 299-303.

[91] Li, X., et al., Highly sensitive H 2 S sensor based on template-synthesized CuO nanowires. Rsc Advances, 2012. 2(6): p. 2302-2307.

[92] Bai, S., et al., Ultrasonic synthesis of MoO3 nanorods and their gas sensing properties. Sensors and Actuators B: Chemical, 2012. 174: p. 51-58.

[93] Xu, L., et al., Electrospinning preparation and room temperature gas sensing properties of porous In2O3 nanotubes and nanowires. Sensors and Actuators B: Chemical, 2010. 147(2): p. 531-538.

[94] Park, J.-A., et al., Structure and CO gas sensing properties of electrospun TiO2 nanofibers. Materials Letters, 2010. 64(3): p. 255-257.

[95] Chen, Y., et al., ZnO-nanowire size effect induced ultra-high sensing response to ppb-level H2S. Sensors and Actuators B: Chemical, 2017. 240: p. 264-272.

[96] Hosseini, Z. and A. Mortezaali, Room temperature H2S gas sensor based on rather aligned ZnO nanorods with flower-like

structures. Sensors and Actuators B: Chemical, 2015. 207: p. 865-871.

[97] Wang, L., et al., ZnO nanorod gas sensor for ethanol detection. Sensors and Actuators B: Chemical, 2012. 162(1): p. 237-243.

[98] Sinha, M., et al., Ultrafast and reversible gas-sensing properties of ZnO nanowire arrays grown by hydrothermal technique. The Journal of Physical Chemistry C, 2016. 120(5): p. 3019-3025.

[99] Tonezzer, M. and N. Hieu, Size-dependent response of single-nanowire gas sensors. Sensors and Actuators B: Chemical, 2012. 163(1): p. 146-152.

[100] Qin, Y., M. Hu, and J. Zhang, Microstructure characterization and NO2-sensing properties of tungsten oxide nanostructures. Sensors and Actuators B: Chemical, 2010. 150(1): p. 339-345.

[101] Lee, C.-Y., et al., Glucose-mediated hydrothermal synthesis and gas sensing characteristics of WO3 hollow microspheres. Sensors and actuators B: chemical, 2009. 142(1): p. 236-242.

[102] An, S., et al., Enhanced ethanol sensing properties of multiple networked Au-doped In2O3 nanotube sensors. Journal of Physics and Chemistry of Solids, 2013. 74(7): p. 979-984.

[103] Jaroenapibal, P., et al., Improved NO2 sensing performance of electrospun WO3 nanofibers with silver doping. Sensors and Actuators B: Chemical, 2018. 255: p. 1831-1840.

[104] Guo, L., et al., Ultra-sensitive sensing platform based on Pt-ZnO-In2O3 nanofibers for detection of acetone. Sensors and Actuators B: Chemical, 2018. 272: p. 185-194.

[105] Safe, A.M., A. Nikfarjam, and H. Hajghassem, UV enhanced ammonia gas sensing properties of PANI/TiO2 core-shell nanofibers. Sensors and Actuators B: Chemical, 2019. 298: p. 126906.

[106] Wang, D., et al., Enhanced formaldehyde sensing properties of hollow SnO2 nanofibers by graphene oxide. Sensors and Actuators B: Chemical, 2017. 250: p. 533-542.

[107] Li, C., et al., Electrospun nanofibers of p-type NiO/n-type ZnO heterojunction with different NiO content and its influence on trimethylamine sensing properties. Sensors and Actuators B: Chemical, 2015. 207: p. 90-96.

[108] Lee, J.-H., et al., Co3O4-loaded ZnO nanofibers for excellent hydrogen sensing. International Journal of Hydrogen Energy, 2019. 44(50): p. 27499-27510.

[109] Li, R., et al., SnO 2/SnS 2 nanotubes for flexible room-temperature NH 3 gas sensors. RSC Advances, 2017. 7(83): p. 52503-52509.

[110] Shao, S., et al., Ultrasensitive and highly selective detection of acetone based on Au@ WO3-SnO2 corrugated nanofibers. Applied Surface Science, 2019. 473: p. 902-911.

[111] Fan, J., et al., Carbon nanotubes-CuO/SnO2 based gas sensor for detecting H2S in low concentration. Nanotechnology, 2019. 30(47): p. 475501.

[112] Abideen, Z.U., et al., Sensing behavior to ppm-level gases and synergistic sensing mechanism in metal-functionalized rGO-loaded ZnO nanofibers. Sensors and Actuators B: Chemical, 2018. 255: p. 1884-1896.

[113] Yang, X., et al., Fabrication of highly sensitive gas sensor based on Au functionalized WO3 composite nanofibers by electrospinning. Sensors and Actuators B: Chemical, 2015. 220: p. 1112-1119.

[114] Guo, J., et al., High-performance gas sensor based on ZnO nanowires functionalized by Au nanoparticles. Sensors and Actuators B: Chemical, 2014. 199: p. 339-345.

[115] Wang, L., et al., A Au-functionalized ZnO nanowire gas sensor for detection of benzene and toluene. Physical Chemistry Chemical Physics, 2013. 15(40): p. 17179-17186.

[116] Liu, W., et al., Rationally designed mesoporous In2O3 nanofibers functionalized Pt catalysts for high-performance acetone gas sensors. Sensors and Actuators B: Chemical, 2019. 298: p. 126871.

[117] Lin, Y., et al., Preparation of Pd nanoparticle-decorated hollow SnO2 nanofibers and their

enhanced formaldehyde sensing properties. Journal of Alloys and Compounds, 2015. 651: p. 690-698.

[118] Kim, N.-H., et al., Highly sensitive and selective hydrogen sulfide and toluene sensors using Pd functionalized WO3 nanofibers for potential diagnosis of halitosis and lung cancer. Sensors and Actuators B: Chemical, 2014. 193: p. 574-581.

[119] Sharma, H.J., N.D. Sonwane, and S.B. Kondawar, Electrospun SnO 2/Polyaniline composite nanofibers based low temperature hydrogen gas sensor. Fibers and Polymers, 2015. 16: p. 1527-1532.

[120] Zhang, J., et al., Fabrication of conductive graphene oxide-WO3 composite nanofibers by electrospinning and their enhanced acetone gas sensing properties. Sensors and Actuators B: Chemical, 2018. 264: p. 128-138.

[121] Feng, Q., et al., Reduced graphene oxide (rGO) encapsulated Co3O4 composite nanofibers for highly selective ammonia sensors. Sensors and Actuators B: Chemical, 2016. 222: p. 864-870.

[122] Guo, L., et al., Reduced graphene oxide/α-Fe2O3 composite nanofibers for application in gas sensors. Sensors and Actuators B: Chemical, 2017. 244: p. 233-242.

[123] Zhang, J., et al., Porous NiO–WO 3 heterojunction nanofibers fabricated by electrospinning with enhanced gas sensing properties. RSC Advances, 2017. 7(64): p. 40499-40509.

[124] Alali, K.T., et al., Electrospun np WO3/CuO heterostructure nanofibers as an efficient sarin nerve agent sensing material at room temperature. Journal of Alloys and Compounds, 2019. 793: p. 31-41.

[125] Huang, B., et al., Enhanced gas-sensing performance of ZnO@ In2O3 core@ shell nanofibers prepared by coaxial electrospinning. Sensors and Actuators B: Chemical, 2018. 255: p. 2248-2257.

[126] Wang, Y., H. Zhang, and X. Sun, Electrospun nanowebs of NiO/SnO2 pn heterojunctions for enhanced gas sensing. Applied Surface Science, 2016. 389: p. 514-520.

[127] Zhao, Y., et al., Porous CuO/SnO2 composite nanofibers fabricated by electrospinning and their H2S sensing properties. Sensors and Actuators B: Chemical, 2012. 165(1): p. 82-87.

[128] Yan, S., J. Xue, and Q. Wu, Synchronous synthesis and sensing performance of α-Fe2O3/SnO2 nanofiber heterostructures for conductometric C2H5OH detection. Sensors and Actuators B: Chemical, 2018. 275: p. 322-331.

[129] Wang, F., et al., Hierarchical composites of MoS2 nanoflower anchored on SnO2 nanofiber for methane sensing. Ceramics International, 2019. 45(17): p. 22981-22986.

[130] Zhao, S., et al., Vertically aligned MoS2/ZnO nanowires nanostructures with highly enhanced NO2 sensing activities. Applied Surface Science, 2018. 456: p. 808-816.

[131] Qiao, X.-Q., et al., Tunable MoS2/SnO2 P–N heterojunctions for an efficient trimethylamine gas sensor and 4-nitrophenol reduction catalyst. ACS sustainable chemistry & engineering, 2018. 6(9): p. 12375-12384.