



Gas Sensors Based on SnO₂-WO₃-CuO Oxide Nanomaterials: A Review

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Abstract: This review paper presents a comprehensive analysis of the development and application of CO₂ gas sensors based on SnO₂-WO₃-CuO oxide nanomaterials. These composite nanomaterials have emerged as promising candidates for CO₂ detection due to their enhanced surface area, catalytic activity, and unique electronic properties. The paper explores various synthesis techniques, material characterization methods, and the synergistic effects of SnO₂, WO₃, and CuO in optimizing the sensing performance. The mechanisms of CO₂ adsorption and interaction at the surface of these oxide nanomaterials are examined, alongside their influence on the sensor's response, sensitivity, selectivity, and stability. Additionally, the review addresses key challenges, including the need for high selectivity towards CO₂ over other gases, low operating temperatures, and long-term sensor stability. Applications in environmental monitoring, industrial emission control, and indoor air quality are discussed, highlighting the potential of SnO₂-WO₃-CuO-based sensors for practical CO₂ detection. The review concludes with insights into future research directions aimed at further improving the performance and practical applicability of these sensors for CO₂ monitoring.

Keywords: Gas sensors; nanomaterials; copper oxide; cupric oxide; cuprous oxide; air quality monitoring.

1. Introduction

The rising concentration of carbon dioxide (CO₂) in the atmosphere, driven by industrial activities and fossil fuel combustion, poses serious environmental and health challenges. CO₂ is a primary greenhouse gas contributing to global warming, and its monitoring is essential across various domains, including environmental surveillance, indoor air quality management, industrial process control, and medical diagnostics (e.g., capnography). Traditional CO₂ detection technologies such as non-dispersive infrared (NDIR) sensors, although effective, are often bulky, expensive, and energy-intensive [1-3].

In recent years, metal oxide semiconductor (MOS)-based gas sensors have gained attention due to their low cost, compact size, and compatibility with microelectronic fabrication. However, many single-phase MOS sensors suffer from limited selectivity, reduced sensitivity at room temperature, and slow response/recovery behavior. To overcome these drawbacks, researchers have begun exploring nanostructured composite and heterostructure materials that exhibit enhanced surface reactivity, tailored band structures, and improved gas interaction mechanisms. Among the promising candidates, SnO₂, WO₃, and CuO are notable for their gas-sensing properties. Combining these in nanocrystalline form, supported on Al₂O₃ substrates, offers a promising route for achieving superior CO₂ sensing performance [3-4].

Despite advancements in gas sensor technology, the reliable detection of low concentration CO₂ remains a major technical challenge due to poor sensor selectivity, low sensitivity at ambient temperatures, and slow response dynamics. Current MOS-based sensors typically show suboptimal performance for CO₂ because of its weak interaction with the sensor surface compared to more reactive gases like NO₂ or NH₃. Furthermore, the absence of synergistic effects in single-component sensors limits their application in complex sensing environments.

This research addresses the critical need for advanced sensor materials by focusing on the design and development of nanocrystalline SnO₂-WO₃-CuO composites and binary layers on Al₂O₃ substrates. The core problem is to overcome the inherent limitations of existing materials and configurations by engineering heterostructures with enhanced surface area, defect chemistry, and interfacial charge transfer properties, all tailored for efficient, selective, and low-temperature CO₂ detection[5-8].

2. Nanomaterial, Device and Sensor System Design

The most significant factors influencing the characteristics of chemical sensor devices are depicted in the schematic diagram (Fig.1). These influencing elements must be taken into account while designing the nanomaterials, the device structure, and the entire sensor system in order to produce logically constructed gas sensors with optimized performance matched to the specific application [9-12].

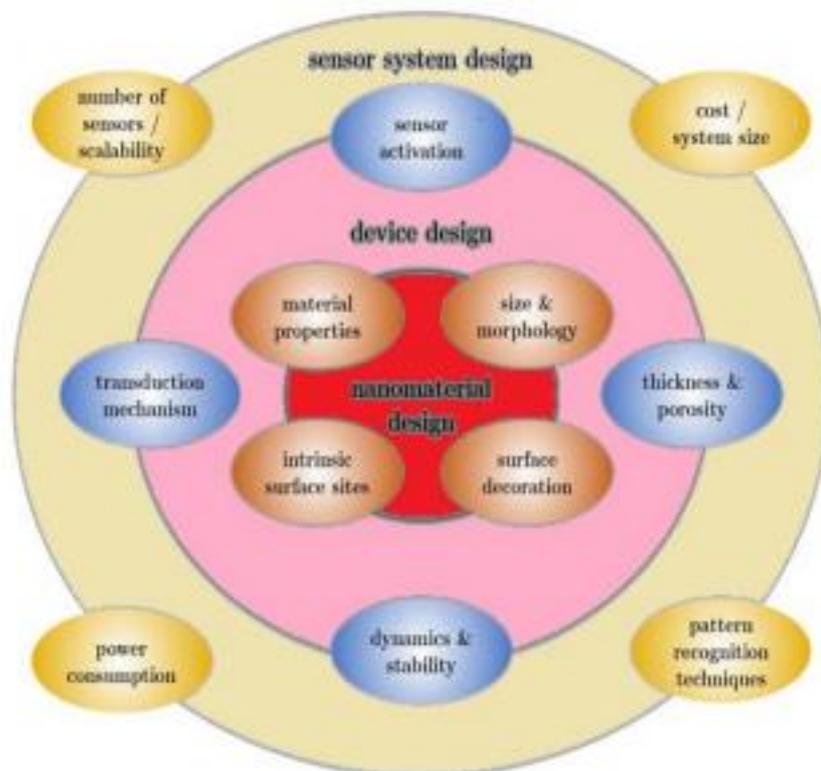


Fig. 1

Figure 1 shows a schematic representation of the general parameters affecting the properties of gas sensors that must be taken into consideration when designing nanomaterials, devices, and sensor systems. The purpose of this contribution is to review the relevant aspects of gas sensors that have been documented in the literature [13-16].

2.1. Influence of SnO₂-WO₃-CuO Phase

The incorporation of SnO₂, WO₃, and CuO into a composite oxide material has significantly enhanced the performance of gas sensors, with the specific phase interactions between these materials playing a crucial role in improving sensor sensitivity, selectivity, and overall stability. The combination of SnO₂-WO₃-CuO in nanostructured form brings about phase-dependent properties that contribute to more efficient gas sensing mechanisms. Each of these metal oxides SnO₂, WO₃, and CuO has unique characteristics in terms of its electronic structure, catalytic properties, and interaction with gases, and their integration into a composite phase introduces synergistic effects that cannot be realized by the individual components alone [17-20].

The SnO₂-WO₃-CuO phase interactions significantly influence the overall performance of gas sensors by enhancing the sensitivity, selectivity, and response time. The combination of SnO₂'s n-type conductivity with WO₃ and CuO's p-type properties leads to the formation of heterojunctions that promote efficient charge separation and faster electron transfer, which in turn improves the gas sensing mechanism. The catalytic properties of WO₃ and CuO further enhance the sensor's response to a broad range of gases, while the

morphology and crystallinity of the composite material play a crucial role in optimizing these properties. As such, the SnO₂-WO₃-CuO composite phase holds great promise for the development of advanced gas sensors capable of operating in complex and variable environments, with potential applications in environmental monitoring, industrial safety, and healthcare [21-23].

2.2. Influence of Nanomaterial and Sensor Morphology

The performance of gas sensors is critically influenced by the choice of materials and their morphology. In particular, the incorporation of composite metal oxide nanomaterials such as SnO₂-WO₃-CuO, combined with substrates like Al₂O₃ (alumina), offers enhanced gas sensing properties due to the synergistic effects between the nanomaterials and the structural support. The nanomaterial's intrinsic properties—such as surface area, electronic structure, and catalytic activity—play a fundamental role in determining the sensitivity, selectivity, and stability of the sensor. Additionally, the morphology of these nanomaterials, including their size, shape, and dispersion, influences their interaction with gases, which is key to optimizing sensor performance [24-26].

2.2.1 Nanomaterial Influence: SnO₂-WO₃-CuO/Al₂O₃ Composite for Gas Sensing

In composite materials, each constituent contributes unique properties that enhance the overall performance of gas sensors. SnO₂ (tin oxide), WO₃ (tungsten oxide), and CuO (copper oxide) are among the most commonly used metal oxides for gas sensing due to their high chemical reactivity, ability to undergo redox reactions, and ability to interact with a variety of gas molecules. When combined, SnO₂-WO₃-CuO composites exhibit remarkable synergistic effects, resulting in improved gas sensing capabilities [27-30].

2.2.2 Influence of Nanomaterial Morphology on Sensor Performance

The morphology of SnO₂-WO₃-CuO/Al₂O₃ composites has a significant influence on the performance of gas sensors. Morphological characteristics such as particle size, shape, surface area, and the distribution of the composite material on the alumina substrate can have a profound impact on the gas adsorption behavior, charge transfer, and overall sensing efficiency [31-32].

Surface Functionalization Surface modifications and functionalization of SnO₂-WO₃-CuO composites, including doping with other elements or coating with additional catalytic layers, can further enhance gas sensor performance. For example, doping SnO₂ with transition metals or other elements can create additional charge carriers or improve the catalytic activity of the composite, which can lead to increased sensitivity for specific gases [33-35].

2.2.3 Synergistic Effect between Nanomaterials and Alumina Substrate

The use of Al₂O₃ as a substrate or support for SnO₂-WO₃-CuO nanocomposites further enhances the sensor's performance. Al₂O₃ not only provides structural support but also plays a role in heat dissipation, ensuring that the sensor operates efficiently at higher temperatures, which is often required for gas sensing applications. The thermal stability of Al₂O₃ ensures that the composite material remains stable even under high operational temperatures, which is essential for sensors used in industrial and environmental monitoring [36-37].

Moreover, Al₂O₃ contributes to enhancing the mechanical robustness of the gas sensor. The alumina support prevents the nanomaterial from being degraded or damaged due to mechanical stresses, vibrations, or temperature fluctuations, leading to improved durability and longevity of the sensor.

2.2.4 Performance Evaluation and Challenges

The overall performance of SnO₂-WO₃-CuO/Al₂O₃ composite gas sensors can be evaluated based on key parameters such as sensitivity, selectivity, response time, stability, and reproducibility. These sensors exhibit significantly higher sensitivity and selectivity compared to single-component metal oxide sensors. The SnO₂-WO₃-CuO composite shows enhanced performance due to the synergistic interaction between the three metal oxides, each contributing different characteristics to the sensor. In addition, the control of morphology, particle size, and dispersion on the Al₂O₃ substrate allows for further tuning of the sensor's response characteristics [38-

40].

The integration of SnO₂-WO₃-CuO nanocomposites with Al₂O₃ substrates offers a promising approach to developing high-performance gas sensors. The influence of nanomaterial composition and sensor morphology, including particle size, shape, and dispersion, plays a critical role in determining the sensor's gas sensing properties. The synergy between SnO₂, WO₃, and CuO, coupled with the structural support and stability provided by Al₂O₃, results in enhanced sensitivity, selectivity, and stability, making these composite sensors highly effective for detecting a wide range of gases. Future research should focus on further optimizing the synthesis methods, improving the control over nanomaterial morphology, and exploring innovative ways to enhance sensor selectivity and durability for real-world applications in environmental monitoring, industrial safety, and healthcare [41-42].

2.3. Impurity Doping and Nanoparticle Decoration

Impurity doping and nanoparticle decoration are key techniques for enhancing the performance of SnO₂-WO₃-CuO nanocomposites in gas sensing, including the detection of CO₂. Impurity doping involves introducing foreign elements, such as transition metals (Cu, Ni, Fe) or rare earth elements (Ce, La), into the metal oxide structure to modify its electronic properties, increase oxygen vacancy concentrations, and improve catalytic activity. For instance, doping SnO₂ with Cu enhances its interaction with CO₂, promoting more efficient CO₂ adsorption and accelerating the gas-surface reaction. WO₃, when doped with metals like Pt or Pd, also improves its sensitivity to CO₂ by enhancing its redox properties and facilitating charge transfer during gas adsorption. Similarly, doping CuO with elements like Fe or Zn can further improve its ability to detect CO₂, as these dopants promote charge carrier mobility and oxygen vacancy formation, both critical for enhancing the sensor's response. Nanoparticle decoration, particularly with noble metals such as Pt, Pd, and Au, further improves the performance of SnO₂-WO₃-CuO composites by enhancing their catalytic properties [43-46]. The noble metal nanoparticles serve as electron sinks, boosting the overall charge transfer and promoting faster detection of CO₂. The combination of doping and decoration not only increases the sensitivity and selectivity of SnO₂-WO₃-CuO nanomaterials for CO₂ detection but also improves their stability and response time, making them more effective for environmental monitoring and industrial applications.

2.4. Advances in Scalable Device Integration: From Microhotplates to Flexible Substrates

Advances in scalable device integration for gas sensors using SnO₂, WO₃, and CuO nanomaterials have led to significant improvements in sensor performance and application versatility, particularly through the development of microhotplates and flexible substrates. Microhotplates enable miniaturized, low-power, and highly sensitive gas sensors by incorporating integrated heating elements that allow for fast and uniform temperature control, essential for the optimal operation of metal oxide semiconductors. This integration improves the sensor's response time and energy efficiency. Meanwhile, the use of flexible substrates, such as polymers and textiles, facilitates the creation of lightweight, bendable, and portable gas sensors, ideal for wearable devices, environmental monitoring, and healthcare applications. Advanced deposition techniques, like spray pyrolysis and chemical vapor deposition, have made it possible to apply SnO₂, WO₃, and CuO onto these flexible surfaces while maintaining high sensor performance [47-50]. These innovations enable the development of scalable, cost-effective, and highly adaptable gas sensors, paving the way for their integration into smart systems, such as real-time air quality monitors and health tracking devices.

3. Mechanisms for Sensing and Transduction Mechanisms

3.1. Surface Reactions and Transduction Mechanisms

The surface reactions and transduction mechanisms of SnO₂, WO₃, and CuO nanomaterials are fundamental to their performance as gas sensors, including for the detection of CO₂. When exposed to gases, these metal oxides undergo surface reactions that induce changes in their electrical properties, which are then used for sensing. In SnO₂, the sensing mechanism primarily involves the chemisorption of oxygen species (O₂⁻, O₂²⁻) on the surface, which interact with target gases like CO₂. The reaction with CO₂ leads to the formation of surface carbonates, which changes the carrier concentration and consequently the material's conductivity. WO₃ operates by creating oxygen vacancies upon exposure to reducing gases, such as CO or CO₂, which results in a decrease in

conductivity. The presence of CO_2 can facilitate the reduction of WO_3 , further enhancing its response to CO_2 . CuO exhibits a similar mechanism, where CO_2 interacts with the surface to form carbonates, altering its electrical resistance. The transduction mechanisms in all three materials are primarily based on the change in resistance or conductivity upon gas adsorption, which can be measured as a change in the sensor's output signal [51-53]. The high surface area and nanoscale morphology of these materials enhance gas adsorption, making them highly sensitive to low concentrations of gases like CO_2 . Factors such as surface morphology, doping, and nanostructure also play a significant role in improving sensitivity and selectivity, enabling SnO_2 , WO_3 , and CuO -based sensors to detect CO_2 with high accuracy.

3.2. Humidity Interference Effects

The humidity interference effects on SnO_2 , WO_3 , and CuO gas sensors are an important factor to consider, as the presence of water vapor can significantly impact their performance. In metal oxide semiconductors like SnO_2 , WO_3 , and CuO , humidity can alter the surface chemistry by influencing the adsorption and desorption of oxygen species, which are crucial for the gas-sensing mechanism. For instance, SnO_2 sensors can show reduced sensitivity to target gases like CO and NO_2 in high humidity conditions because water molecules can compete with gas molecules for adsorption sites, thus hindering the surface reactions that lead to conductivity changes. Similarly, WO_3 is sensitive to humidity, as water vapor can affect the formation of oxygen vacancies, which are important for its response to gases like CO_2 or H_2S . CuO sensors also suffer from humidity interference, as water vapor can alter the oxidation state of copper and interact with surface oxygen species, leading to variations in sensor signal. These humidity effects can cause false positives or false negatives and lead to unstable sensor responses [54-56]. To mitigate this, strategies such as humidity compensation algorithms, coatings, or material doping are often employed to enhance the sensor's stability and reduce humidity-related interference, ensuring reliable gas detection in varying environmental conditions.

4. Highly Sensitive Detection of Gaseous Molecules

4.1. Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) are omnipresent in our daily environment, originating from a wide range of anthropogenic sources such as paints, solvents, fuels, and industrial emissions. Many VOCs are known to be toxic and carcinogenic, posing significant health risks even at sub-ppb-level exposure. Therefore, their detection is critical not only for industrial process control but also for maintaining indoor air quality, which demands cost effective, real-time sensor solutions with high sensitivity and selectivity. Metal oxide semiconductor (MOS) materials have emerged as promising candidates for VOC detection due to their simple design, stability, and tunable sensing properties. Among them, copper oxide (CuO), tin oxide (SnO_2), and tungsten trioxide (WO_3) nanomaterials have been extensively studied for VOC sensing applications [57-60].

CuO , a p-type semiconductor, detects VOCs primarily through surface reactions between chemisorbed oxygen species and reducing gas molecules, which modulate the space charge region and alter electrical conductivity. Similarly, SnO_2 , an n-type semiconductor, is one of the most widely used materials for gas sensing owing to its high electron mobility, chemical stability, and strong response to reducing gases such as ethanol, acetone, and formaldehyde. The adsorption of oxygen on SnO_2 extracts electrons from the conduction band, forming an electron depletion layer; exposure to VOCs reduces this layer, decreasing resistance and allowing quantitative gas detection. WO_3 , another n-type semiconductor, offers excellent sensitivity, selectivity, and stability toward various VOCs due to its high surface area, tunable morphology, and rich surface oxygen vacancies that enhance gas adsorption and reaction kinetics [60-63]. Overall, CuO , SnO_2 , and WO_3 nanomaterials exhibit complementary properties and have been widely explored for developing efficient, reliable,

4.2. Hydrogen Sulfide (H_2S)

The occurrence of hydrogen sulfide (H_2S) results from the bacterial decomposition of organic matter in anaerobic environments or from various industrial processes. This corrosive and toxic gas, recognized by its characteristic —rotten egg— odor at very low concentrations (in the ppb range), can paralyze the olfactory nerves at higher levels, making exposure particularly dangerous. Short-term exposure to H_2S can cause headaches, nausea, unconsciousness, and even suffocation, while long-term exposure at ppb levels has been linked to central nervous

and respiratory symptoms. Because safe exposure limits lie in the low ppm range, highly sensitive detection is required. Metal oxide semiconductors (MOS) such as CuO, SnO₂, and WO₃ have been extensively explored for this purpose. Among them, copper oxide nanomaterials exhibit excellent sensitivity and selectivity to H₂S, with detection limits down to 1 ppb. The detection mechanism varies with temperature: at elevated temperatures, H₂S reacts with chemisorbed oxygen forming SO₂ and H₂O, while at lower temperatures; CuO is converted to CuS, leading to significant conductivity changes due to low-resistance percolation pathways. This CuS formation can be exploited for dosimeter-type sensors that measure cumulative exposure [64-67]. Similarly, SnO₂ and WO₃-based nanomaterials have also shown high performance toward H₂S detection. In SnO₂ sensors, H₂S reacts with adsorbed oxygen species, leading to a reduction in resistance through the formation of SnS or SnS₂, whereas in WO₃-based sensors, H₂S reduces the oxide surface and can form tungsten sulfide (WS₂) phases, enhancing conductivity. Both SnO₂ and WO₃ systems offer fast response and recovery characteristics, good stability, and potential for room-temperature operation when modified with catalytic additives or nanostructuring. Combining these metal oxides provides promising pathways for developing next-generation H₂S sensors with improved selectivity, sensitivity, and operational stability.

4.3. Carbon Monoxide (CO)

Carbon monoxide (CO) is a major environmental pollutant produced by incomplete combustion of carbon-based fuels in industrial processes, vehicle exhaust, and fuel-burning household appliances. Being odorless, colorless, and highly toxic, CO readily binds to hemoglobin, forming carboxyhemoglobin and impairing oxygen transport in the bloodstream. Exposure to concentrations as low as 10 ppm is considered acceptable for up to 8 hours, but higher levels can cause headaches, dizziness, confusion, unconsciousness, or even death, with CO poisoning remaining a global health concern. To address this, extensive research has focused on developing sensitive and reliable CO sensors, particularly using metal oxide semiconductors (MOS) such as CuO, SnO₂, and WO₃, which operate via changes in electrical resistance upon gas exposure [68-69].

Among these, CuO nanomaterials exhibit notable selectivity toward CO, where the sensing mechanism involves the surface reaction of CO with chemisorbed oxygen species to produce CO₂, thereby modulating the surface charge layer and electrical conductivity. SnO₂-based sensors are among the most established for CO detection, offering high sensitivity and rapid response due to the reaction of CO with surface-adsorbed oxygen ions (O⁻ or O₂⁻), which releases electrons back into the conduction band and reduces resistance. Their performance can be further enhanced through nanostructuring and doping with catalytic metals such as Pt or Pd, enabling lower operating temperatures and improved selectivity. Similarly, WO₃ nanomaterials have demonstrated excellent CO sensing performance, particularly at low operating temperatures, owing to their high surface reactivity and ability to form oxygen vacancies that facilitate gas adsorption [70-71]. In WO₃ sensors, CO acts as a reducing gas, consuming surface oxygen and leading to a significant increase in conductivity. The combination of these oxides, through nanocomposites or heterojunctions (e.g., CuO–SnO₂ or WO₃–SnO₂), further enhances sensitivity, selectivity, and stability, making them promising candidates for next-generation CO detection technologies in environmental monitoring and safety applications.

4.4. Carbon Dioxide (CO₂)

Despite active research efforts for several decades, the realization of miniaturized sensor solutions for detecting carbon dioxide (CO₂) using solid-state materials has remained challenging. Conventional CO₂ sensors predominantly rely on optical sensing principles, which, while accurate, are often limited by high cost, power consumption, and large device size. To overcome these drawbacks, solid-state electrochemical sensors, particularly resistive sensors based on metal oxide semiconductors (MOS), have been explored as promising low cost and scalable alternatives [72-74].

Among various MOS materials, copper oxide (CuO) nanomaterials have shown excellent potential for CO₂ sensing. CuO-based sensors, including Ag-doped CuO/BaTiO₃ perovskite heterostructures, CuO/CuFe₂O₄ nanocomposites, and CuO nanoparticles with work-function-based readouts, have demonstrated effective CO₂ detection in humid atmospheres at low operating temperatures (down to room temperature) and in the practical concentration range of 400–4000 ppm. Furthermore, ZnO₂-added CuO nanoparticles and Au decorated CuO thin films have exhibited enhanced sensing responses and stability, highlighting the suitability of

CuO-based materials for developing miniaturized, low-cost CO₂ sensors[75-76].

Similarly, tin oxide (SnO₂) and tungsten trioxide (WO₃) have emerged as promising candidates for CO₂ detection due to their excellent chemical stability, tunable electronic properties, and high surface reactivity. In SnO₂-based sensors, CO₂ molecules interact with adsorbed oxygen species on the oxide surface, altering the surface charge and electrical resistance. The incorporation of catalytic dopants such as Pd, Ag, or Cu has been shown to enhance sensitivity and lower the operating temperature by facilitating gas adsorption and charge transfer processes. WO₃ nanomaterials, on the other hand, offer strong oxygen vacancy formation and high surface activity, enabling efficient CO₂ adsorption and electron exchange, particularly under humid or low-temperature conditions [77-80]. Their performance can be further improved through morphological control (e.g., nanorods, nanoplates) and composite formation with other oxides like CuO or SnO₂ to create synergistic effects.

Overall, the combination of CuO, SnO₂, and WO₃ nanostructures offers a promising pathway toward the development of next-generation, miniaturized, low-cost solid-state CO₂ sensors suitable for widespread applications. These include greenhouse gas monitoring, industrial emission tracking, smart home and IoT-based indoor air quality management, and portable sensors for agricultural and food safety monitoring, where real-time CO₂ detection is essential for environmental and health-related advancements [81-83].

4.5. Hydrogen (H₂)

With the growth of the hydrogen economy and the increasing use of hydrogen (H₂) as a sustainable fuel and energy carrier, the reliable detection of H₂ gas has become critically important due to its high flammability and wide explosive concentration range. Metal oxide semiconductors (MOS) have been extensively explored for chemoresistive H₂ sensors, offering sensitive and rapid detection capabilities. Among these, copper oxide (CuO) nanomaterials have been widely studied, where resistance changes upon H₂ exposure are primarily due to reactions with chemisorbed oxygen, forming H₂O and modulating the charge carrier density at the surface [84-87]. Advanced transduction approaches have also been proposed, including metallic percolation pathways in CuO nanowires and thermal-property based detection using microhotplate devices, which offer potential improvements in selectivity and sensitivity.

Similarly, tin oxide (SnO₂) and tungsten trioxide (WO₃) nanomaterials have demonstrated excellent performance for H₂ sensing. In SnO₂ sensors, H₂ acts as a reducing gas that reacts with oxygen adsorbed on the surface, releasing electrons back into the conduction band and decreasing the sensor resistance. Sensitivity and operating temperature can be further optimized by doping with noble metals (e.g., Pd, Pt) or creating nanostructured morphologies. WO₃-based sensors also respond effectively to H₂, benefiting from high surface reactivity, oxygen vacancy sites, and structural tunability, which enhance gas adsorption and electron exchange [88-89]. The combination of these MOS materials, including heterostructures or composites like CuO–SnO₂ or WO₃–SnO₂, can synergistically improve sensitivity, selectivity, and stability, enabling the development of next-generation H₂ sensors suitable for industrial safety, energy applications, and hydrogen infrastructure monitoring.

4.6. Nitrogen Dioxide (NO₂)

In addition to copper oxide (CuO), other metal oxide semiconductors such as tin dioxide (SnO₂) and tungsten trioxide (WO₃) have also been extensively explored for NO₂ sensing applications due to their unique properties and performance characteristics.

SnO₂ is one of the most widely studied metal oxides for gas sensing due to its high stability, low cost, and ease of fabrication. It exhibits excellent sensitivity to a wide range of gases, including NO₂, particularly at elevated temperatures. SnO₂ operates on the principle of adsorption and desorption of gas molecules on its surface, which modulates its electrical conductivity [90-91]. In the presence of NO₂, which is an electron acceptor, SnO₂ experiences a decrease in conductivity, making it easier to detect even low concentrations of NO₂. However, high-temperature operation is typically required to achieve optimal sensitivity, which can lead to higher energy consumption. Nonetheless, SnO₂-based sensors are often used in industrial and automotive applications, where high sensitivity and robust performance are crucial.

WO₃ is another promising material for NO₂ detection, offering high chemical stability and a wide operating temperature range. Similar to SnO₂, WO₃ exhibits sensitivity to NO₂ due to its electronic structure, which undergoes changes upon gas adsorption. WO₃ sensors typically operate by detecting changes in the electrical properties (conductivity or resistance) upon NO₂ adsorption. One of the advantages of WO₃ is its ability to function well at moderate to high temperatures, which can enhance its performance in environments with fluctuating temperatures [92-93]. Additionally, WO₃ has shown potential for selective NO₂ sensing even in the presence of other gases, making it a valuable material for real-time air quality monitoring and environmental sensing.

In summary, while copper oxide (CuO) is known for its excellent sensitivity to low concentrations of NO₂ at room temperature, materials like tin dioxide (SnO₂) and tungsten trioxide (WO₃) also offer significant advantages in specific applications. SnO₂ is favored for its cost-effectiveness and stability in industrial and automotive settings, while WO₃ stands out for its high-temperature operation and gas selectivity. These metal oxide materials, each with their own strengths, play an important role in the development of highly efficient and reliable NO₂ sensor technologies.

4.7 Other Target Molecules

Copper oxide (CuO)-based devices, other metal oxide materials like tin dioxide (SnO₂) and tungsten trioxide (WO₃) have also shown promising results in detecting various gases, including ozone (O₃), sulfur dioxide (SO₂), ammonia (NH₃), and methane (CH₄).

SnO₂ is widely used for detecting ozone (O₃), sulfur dioxide (SO₂), and ammonia (NH₃) due to its high stability and excellent electron transfer properties. SnO₂ thin films, particularly those synthesized via techniques like reactive sputtering or sol-gel processes, have been employed in ozone detection in concentrations ranging from 50 to 300 ppb in dry air. Similar to CuO, SnO₂-based sensors also function through the adsorption and desorption of gas molecules on their surfaces, which modulates their electrical conductivity. SnO₂ nanostructures, such as nanowires or nanoparticles, have been utilized to enhance sensitivity and selectivity. For SO₂ detection, SnO₂ sensors have demonstrated a range of detection from 1–10 ppm, while ammonia sensing has been reported at concentrations ranging from 1–10 ppm. Doping SnO₂ with metals such as palladium or platinum has been found to improve sensor performance and lower the detection limits, making it suitable for real-time monitoring in industrial and environmental applications [94-95].

WO₃ is another effective material for gas sensing, especially for detecting ozone, ammonia, and methane. WO₃ sensors are particularly valued for their high thermal stability and ability to operate over a broad temperature range, which is beneficial in real-world environmental conditions. WO₃ has been used in ozone sensors to detect concentrations between 50 and 300 ppb, similar to CuO and SnO₂. For sulfur dioxide (SO₂), WO₃-based devices have been able to detect concentrations in the range of 1–10 ppm. WO₃'s high surface area and strong interaction with gases like ozone make it an excellent candidate for sensitive detection. Additionally, doping WO₃ with elements like gold or platinum can enhance its catalytic properties, improving both its response time and selectivity. When it comes to methane (CH₄) detection, WO₃ is often used in the form of thin films or nanostructures, with detection limits in the range of 0.3–2.5%, similar to Cu₂O-based sensors.

While CuO nanomaterials have shown strong performance across a range of gases, SnO₂ and WO₃ also play key roles in environmental monitoring and industrial applications. SnO₂ offers high sensitivity to ozone, sulfur dioxide, and ammonia, while WO₃ is particularly useful for sensing ozone, methane, and sulfur dioxide, benefiting from its stability and tunable properties through doping [96-97]. The versatility of these materials, combined with various doping and nanostructuring techniques, enables the development of highly sensitive and selective gas sensors for a wide range of pollutants.

5. Conclusions

In summary, copper oxide (CuO) nanomaterials have demonstrated significant potential in the development of high-performance gas sensors for detecting common hazardous gases and environmental pollutants, with detection limits reaching down to ppb level concentrations or even lower. Despite these promising results, the gas selectivity of CuO-based sensors remains a challenge, limiting their practical application in real-world

environments. Although advancements in doping and nanoparticle decoration have shown some improvements, achieving highly selective sensors for diverse gases is still a hurdle. One possible solution is the integration of smart sensor systems, which utilize a large number of sensors coupled with pattern recognition techniques, such as machine learning, neural networks, and artificial intelligence for effective gas and odor classification [98-99]. For instance, principal component analysis has been successfully employed to distinguish different volatile organic compounds (VOCs) like ethanol, methanol, acetone, and 2-propanol using CuO thin films. Other strategies to improve selectivity include the use of gas-selective pre-filters to mitigate the effects of gases like H₂S or SO₂.

In addition to technological advancements, several fundamental scientific questions must be addressed, particularly regarding the mechanisms behind humidity and target gas interactions with copper oxide surfaces, as well as the role of additives for sensor functionalization. Experimental techniques such as infrared spectroscopy in operando, in situ transmission electron microscopy, and X-ray absorption spectroscopy are essential for studying sensor materials under real-world conditions, providing insights into the changes in morphology, chemical composition, and oxidation states of nanostructured materials when exposed to reactive gas species [100].

Tin dioxide (SnO₂) and tungsten trioxide (WO₃), in addition to CuO, have also emerged as highly promising materials for gas sensing applications. SnO₂ is widely recognized for its high sensitivity and stability, especially for detecting gases such as ozone, sulfur dioxide, and ammonia. SnO₂-based sensors benefit from the enhancement in sensitivity through doping with metals like platinum and palladium. Similarly, WO₃ offers excellent performance in detecting ozone and sulfur dioxide, with the advantage of operating effectively at elevated temperatures. Like CuO and SnO₂, WO₃'s performance can be tailored by doping with noble metals to improve its sensitivity and selectivity for specific gases. Both SnO₂ and WO₃, when combined with advanced sensor techniques and machine learning, hold the potential to enhance gas detection in complex environments.

To conclude, while copper oxide-based sensors have shown great promise in detecting hazardous gases at low concentrations, challenges related to gas selectivity still limit their real-world application. The development of smart sensor systems using advanced pattern recognition and AI technologies, alongside fundamental research into the interaction mechanisms of target gases and surface characteristics, will likely overcome these challenges. SnO₂ and WO₃ offer complementary advantages and should be explored in parallel, providing a broader range of materials for the next generation of highly sensitive, selective, and reliable gas sensors [101-102]. Future technological and scientific advancements will drive the rational design of nanomaterials for chemoresistive sensors with improved performance and wider applicability in environmental monitoring and industrial safety.

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