

A Review on Chemiresistive Gas Sensors: Basic Concepts, Evolution, and Perspective

Kaykhosrow Khojier¹ | Hadi Savaloni² | Saiedeh Goudarzi³ | Masoomeh Gholami⁴

1. Corresponding Author, Department of Physics, Cha.C, Islamic Azad University, Chalous, Iran. Email: k.khojier@iau.ac.ir
2. School of Physics, College of Science, University of Tehran, North-Kargar Street, Tehran, Iran
3. Department of Physics, Cha.C, Islamic Azad University, Chalous, Iran.
4. Department of Physics, Cha.C, Islamic Azad University, Chalous, Iran.

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ABSTRACT

With rapid advancements across industry, technology, and medicine, the demand for efficient gas and vapor detection has intensified. Among various sensing technologies, chemiresistor gas sensors have emerged as a leading choice due to their affordability, compactness, broad sensitivity range, and user-friendly operation. These sensors play a crucial role in applications spanning environmental monitoring, industrial safety, and healthcare. This review provides a comprehensive overview of chemiresistor gas sensors, beginning with their fundamental principles and operational mechanisms. Key performance factors, such as sensitivity, response time, selectivity, and stability, are examined, while the material innovations driving their progress are also considered. The evolution of these sensors is explored through recent research studies, shedding light on both breakthroughs and persistent challenges, including issues of selectivity and environmental interference. Finally, future perspectives are discussed, highlighting emerging technologies such as AI-assisted sensing, flexible electronics, and sustainable sensor materials that could shape the next generation of chemiresistor-based detection.

INTRODUCTION

Gas detection is crucial in ensuring safety, protecting lives, and preserving the environment. In industrial settings, residential areas, and public spaces, detecting harmful gases is essential to prevent hazardous incidents and maintain overall well-being. One of the most significant aspects of gas detection is its ability to safeguard human health and lives. Many gases, such as carbon monoxide, methane, and hydrogen sulfide, are colorless and odorless, making them undetectable to human senses. Prolonged exposure to these gases can lead to serious health problems or even fatalities. Gas detection systems provide an early warning, enabling timely evacuation or remediation to prevent harm. In industrial environments, gas detection is critical for avoiding accidents and explosions. Many industries, such as oil and gas, chemical manufacturing, and mining, handle flammable and toxic gases daily. A reliable gas detection system helps monitor gas concentrations and mitigate risks by alerting workers to potential dangers, ensuring safe operations. Additionally, gas detection contributes to environmental protection. Some gases, like methane, are potent greenhouse gases that contribute to climate change. Early detection and

control of gas leaks help minimize their environmental impact, supporting sustainability efforts and complying with environmental regulations. In residential settings, gas detection systems, such as smoke and carbon monoxide detectors, are indispensable for home safety. A schematic illustration of the application of gas detection in various fields is presented in Fig. 1.

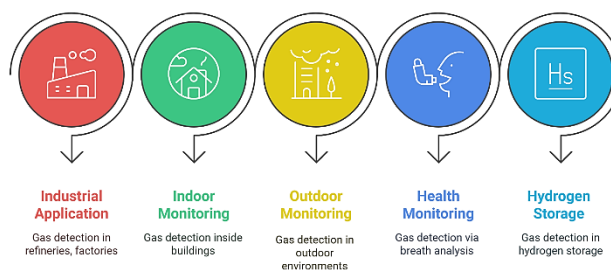


Fig. 1. A schematic illustration of the application of gas detection in various fields

Several types of sensors are used to detect gases, each with its working principles, advantages, and applications. Some of the most common types include electrochemical, infrared (IR), catalytic, photoionization, optical,

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thermopile, acoustic-based, and chemiresistive sensors, which are briefly explained below.

Electrochemical Sensors

Electrochemical sensors are commonly used to detect toxic gases such as carbon monoxide (CO), hydrogen sulfide (H₂S), and ammonia (NH₃) (which are not limited to these gases). They allow gas to flow through a porous membrane to an electrode where it is oxidized or reduced. The amount of current produced is proportional to gas concentration [1]. In other words, electrochemical sensors transform information from electrochemical reactions (interactions between an electrode and an analyte) into a useful qualitative or quantitative signal. [2].

Infrared (IR) Sensors

Infrared sensors are used to detect gases like methane (CH₄) and carbon dioxide (CO₂). They work by measuring the absorption of infrared light by the gas. The concentration of the gas is determined based on the amount of light absorbed [3].

Catalytic Sensors

Catalytic sensors are used to detect combustible gases. They consist of two platinum wire coils embedded in beads of alumina. One bead contains a catalyst that allows combustible compounds to oxidize, changing its electrical resistance. The resulting voltage difference between the active and passive beads is proportional to the concentration of combustible gases [4].

Photoionization (PID) Sensors

PID sensors detect volatile organic compounds (VOCs) and toxic gases. They work by exposing the gas to high-energy photons, usually in the UV range, which ionize the gas molecules. The ions generate an electric current that is proportional to the concentration of the gas [5].

Optical Sensors

Optical sensors use light to detect gases. They consist of an optical probe and a circuit board. The optical probe detects the concentration of gas by measuring the absorption or scattering of light, and the circuit board transmits these signals to a display [6].

Thermopile Sensors

Thermopile sensors detect gases by measuring the temperature difference created by the absorption of infrared radiation. They consist of a thermopile probe and a circuit board. The thermopile probe detects the concentration of gas, and the circuit board transmits these signals to a display [7,8].

Acoustic-based Sensor

An acoustic-based gas sensor is a device that uses sound waves to detect the presence and concentration of gases [9]. When sound waves travel through a gas, their speed is influenced by the gas's physical and chemical properties, such as density and composition. By measuring changes in the speed of sound, the sensor can identify the type and concentration of gases present.

Chemiresistor Sensors

These sensors are composed of chemiresistive materials such as metal oxides, conductive polymers, and carbon-based materials. Their performance operates on the principle that the electrical resistance of the sensor alters when it comes into contact with the target gas, as a result of the interaction between the sensor surface and the gas molecules. This interaction converts the gas concentration into detectable physical signals [9,10]. The advantages, weak points, and applications of the above-mentioned sensors are summarized in Table 1.

Table 1
Advantages, Weak points, and applications of different types of gas sensors [1-13].

Sensor Type	Good Points	Weak Points	Applications
Electrochemical	High sensitivity, low power consumption, specific to certain gases	Limited lifespan, cross-sensitivity, affected by temperature and humidity	Toxic gas detection (e.g., CO, H ₂ S), industrial safety, environmental monitoring
Infrared (IR)	High accuracy, non-contact measurement, unaffected by other gases	Expensive, affected by humidity, limited to gases with IR absorption	CO ₂ and CH ₄ detection, industrial process control, environmental monitoring
Catalytic	Reliable, long lifespan, cost-effective	Can be poisoned by certain chemicals, requires oxygen to function	Combustible gas detection (e.g., methane, propane), industrial safety
Photoionization	High sensitivity, fast response, portable	High cost, low specificity, requires maintenance	VOC detection, environmental monitoring, industrial hygiene, safety applications
Optical	High sensitivity, immune to electromagnetic interference, remote sensing	Susceptible to environmental interference, costly	Industrial automation, environmental monitoring, medical diagnostics
Thermopile	Non-contact measurement, suitable for moving objects, affordable	Sensitive to static, requires careful handling, affected by direct sunlight	Temperature measurement, medical thermometers, thermal imaging
Acoustic-based	Non-invasive, quick response time	Low accuracy, careful calibration requirement	Leak detection in petrochemicals, environmental monitoring
Chemiresistive	Low cost, simple design, high sensitivity	Affected by environmental conditions, non-linear response	Air quality monitoring, industrial safety, medical diagnostics, environmental monitoring

It is worth noting that the quest to detect and quantify gaseous species dates back centuries, from the use of canaries in coal mines as biological indicators of toxic gases to the development of early electrochemical and catalytic combustion sensors in the 20th century. These foundational technologies, although groundbreaking for their time, often faced limitations in terms of size, cost, power consumption, and integration potential. The paradigm shift began with the seminal work on metal oxide semiconductors as sensing materials in the 1960s, which laid the groundwork for the modern chemiresistive gas sensor. This field experienced a revolutionary acceleration with the advent of nanotechnology in the late 1990s and early 2000s. The ability to engineer materials, such as metal oxide nanoparticles, nanowires, two-dimensional materials like graphene, and conducting polymers, at the nanoscale unlocked unprecedented control over the sensing interface, leading to dramatic improvements in sensitivity, response speed, and operating temperatures.

The significance of this work lies in its comprehensive approach. By integrating knowledge across various material systems and application fields, we offer a foundational resource for both newcomers and experienced researchers, helping them understand the connections between material properties, sensing mechanisms, and device performance. This review provides a unique perspective by comparing and contrasting the fundamental limitations and strengths of different material classes within a common theoretical framework, emphasizing future directions for convergence or hybrid strategies. This thorough, perspective-driven analysis will serve as a valuable reference and inspire the next wave of innovations in chemiresistive gas sensing.

DETECTION MECHANISM OF CHEMIRERESISTIVE GAS SENSOR

Chemiresistive gas sensors are a widely used class of gas detection devices that leverage changes in electrical resistance upon exposure to specific target gas molecules. These sensors play a critical role in various applications, including environmental monitoring, industrial safety, and air quality control.

Chemiresistive gas sensors consist of a sensing (chemiresistor) material, such as metal oxides, conductive polymers, and carbon-based materials, whose electrical resistance changes when exposed to specific gas molecules [9,14]. The modulation of the electrical resistance or conductance in a target gas environment is known to be the basic gas sensing mechanism of the chemiresistive sensor [13,15,16].

In an atmospheric environment, oxygen molecules are adsorbed on the surface of the sensing materials by taking electrons from the conduction band of the sample. The adsorption process of oxygen is strongly dependent on the operating temperature of the sensing material. So, oxygen is physically adsorbed in its molecular form (O_2) at temperatures below 100 °C and chemically adsorbed in ionic forms (O^{2-} , O^-) at temperatures greater than 100 °C (Eqs. 1-3). This results in the formation of a depletion layer on the surface of n-type sensing materials and a hole

accumulation layer on the surface of p-type sensing materials [13,17,18].



At this stage, target gases are classified as oxidizing and reducing gases based on their tendency to gain or lose electrons during chemical reactions.

Once an n-type sensing material (like ZnO or TiO₂) is exposed to a reducing gas (like H₂), the gas molecules bond with the adsorbed and ionized oxygens on the surface, forming H₂O molecules and electrons. These electrons move back to the conduction band of the sensing material and cause a decrease in the width of the depletion layer. Therefore, the concentration of carriers (electrons) increases, and the electrical resistance decreases [17,19,20]. This process, step-by-step, is illustrated in Fig. 2.

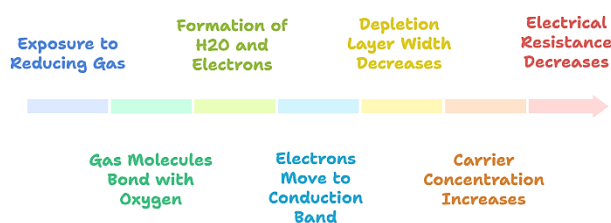


Fig. 2. The step-by-step illustration of the interaction reducing gas with n-type sensing material

Conversely, exposure to an oxidizing gas (like NO₂) causes electrons to move from the conduction band of the sensing material, increasing the width of the depletion layer and electrical resistance.

A similar process occurred for P-type materials. Adsorption of a reducing gas (like CO) on the surface of a p-type sensing material (like CuO or NiO) returns the electrons and causes the reduction of the hole's concentration. Hence, the electrical resistance increases [18]. Conversely, exposure to an oxidizing gas (like NO₂) increases hole accumulation and decreases the electrical resistance.

The electrical resistance behavior based on sensing material type and target gas classification is summarized in Table 2 [21].

Table 2

The electrical resistance behavior of the sensing material versus different target gases

Sensing material ↓/ Target gas →	Reducing	Oxidizing
n-type	Electrical resistance decrease	Electrical resistance increase
p-type	Electrical resistance increase	Electrical resistance decrease

It is worth mentioning that n-type and p-type metal oxide-based chemiresistive gas sensors have advantages and disadvantages over each other. The n-type devices

usually show high sensitivity to oxidizing gases like NO₂, faster response time due to the abundance of free electrons, and cost-effective [22]. On the other hand, they are susceptible to environmental factors like humidity and often require functionalization or doping [23]. But, the other one (p-type devices) exhibit a higher catalytic effect, better selectivity for reducing gases like CO and H₂, low humidity dependence, and improved recovery speed [18]. It should also be noted that the n-type materials are well-researched due to accessible materials like SnO₂ and ZnO [22].

Sensing characteristics of chemiresistive gas sensors

Some parameters describe the static and dynamic features of the chemiresistive materials as a gas sensor. The main characteristics used to evaluate the chemiresistive gas sensor performance are explained as follows:

Response

The Response is one of the essential parameters to evaluate the performance of a chemiresistive device, defined as the ratio of changes in electrical resistance (or current) in the presence and absence of the target gas [24].

Operating temperature

It is well known that the activation energy between the sensing material and target gas differs for various materials and gases; hence, the maximum reaction can occur for different substances and gases at different temperatures. The operating temperature is the temperature that corresponds to the maximum sensitivity [24].

Detection limit

The lowest concentration value of the target gas which can be detected by the sensor at definite conditions is defined as the detection limit [25].

Selectivity

This parameter assesses the ability of the sensors to selectively respond to a specific group of gas targets or even a single gas, especially when other gases are also present in the measurement environment [25]. The selectivity of a sensor is characterized by the ratio of its response to a specific target compared to its response to other targets, expressed mathematically as follows:

$$K = R_A/R_B \quad (4)$$

Where, R_A and R_B are the responses of a sensor to a target gas (gas A) and an interfering gas (gas B), respectively [26].

Response and Recovery Times

The response time refers to how long it takes for a sensor to reach 90% of its ultimate response value, and recovery time is the duration needed for the sensor to return to 90% of its original baseline value. [25].

Reproducibility

The reproducibility of a sensor is assessed by observing changes in its sensing performance after repeatedly alternating between the 'ON' and 'OFF' states [26].

Stability

Stability is a parameter to evaluate the feature of a sensor to maintain its properties when it is continuously employed in hostile environments for a long time [26].

Reproducibility and stability are two key characteristics that confirm the reliability of the sensing device.

When a chemiresistive material is designed and prepared as a gas sensing device, the above-mentioned characteristics are evaluated and reported. These parameters will be the criteria for determining the performance and reliability of the devices.

EFFECTIVE PARAMETERS ON THE PERFORMANCE OF CHEMIREISISTIVE GAS SENSORS

Chemiresistive sensors are fascinating devices that detect different gases and vapors by measuring changes in electrical resistance due to a reaction between the sensing material surface and the target gas. Their performance can be affected by several parameters. Some of the most important are considered as follows:

Crystallinity and crystal planes

The crystallinity of materials used in chemiresistive gas sensors plays a significant role in their sensitivity. High-crystallinity materials often exhibit superior electrical conductivity and stability, as their ordered atomic structure minimizes defects that could scatter charge carriers. This can enhance the response of the sensor to target gases. Conversely, materials with low crystallinity, which are more amorphous, may have increased defect sites or a larger surface area. These properties can promote gas adsorption, thereby boosting sensitivity, but at the cost of slower response and recovery times. On the other hand, polycrystalline materials have grain boundaries where different crystallites meet. These boundaries can trap charge carriers and alter gas-sensing performance. A higher density of boundaries might increase sensitivity but can sometimes compromise stability.

In summary, achieving an optimal balance between crystallinity and other parameters is key to maximizing sensitivity without sacrificing response time or stability. Many researchers work with nanostructured materials to harness the advantages of both high and low crystallinity [27-29]. For example, Katoch et al. [30] studied the effect of grain size and crystallinity on the gas-sensing performance of ZnO nanofibers. They suggested that the simultaneous optimization of the grain size and crystallinity is essential to maximize the sensing abilities of oxide nanofibers.

In addition to crystallinity, the crystal plane can also play an important role in the sensing performance of chemiresistive gas sensors. Different crystal planes have varying atomic arrangements, surface energies, and defect

densities, which affect gas adsorption, reaction kinetics, and charge transport. For instance, in SnO₂, the (110) plane often shows higher sensitivity due to its favorable surface energy and active sites. A study on SnO₂ nanowires demonstrated that the (110) plane exhibited superior sensitivity to NO₂ compared to other planes due to its high density of oxygen vacancies [31].

Li et al. [32] using density functional theory (DFT) calculations, showed that the (110) face of SnO₂ is more sensitive to water molecules than others.

Teimoori et al. [26] also investigated the sensitivity and selectivity of ZnO thin films to volatile organic compounds (VOC) and reported that the best sensitivity of the sample was related to acetone vapor. This result was due to the larger dipole moment of acetone, compared to other VOCs, facilitated adsorption and reaction processes with polar (002) facets at lower temperatures.

As another example, ε-WO₃ phase exhibits selectivity towards trace acetone vapor, whereas γ-WO₃ is selective towards NO [33]. Righettoni et al. [34] demonstrated that Si-doped ε-WO₃ could selectively detect trace amounts of acetone vapor as low as 20 ppb, even under conditions of 90% relative humidity (RH). Similarly, Wang et al. [35] reported the rapid, sensitive, and selective detection of acetone vapor in the range of 0.2–1 ppm using 10% Cr-doped ε-WO₃. Gouma et al. [36] discovered that γ-WO₃ efficiently detected trace levels of NO, down to 300 ppb. Morito et al. [37] also confirmed that γ-WO₃ was effective in selectively sensing both NO and NO₂. Furthermore, hydrothermally synthesized α-MoO₃ nanoribbons demonstrated the ability to detect trace ammonia vapor as low as 280 ppt [38].

Surface morphology, grain size, and porosity

Surface morphology is an effective parameter on the sensing performance of the chemiresistive gas sensors. The surface morphology determines the effective surface area that reacts with the target gas. Hence, a larger surface area, often achieved through porous structures or nanostructures like nanorods, nanowires, and nanolayers, enhances gas adsorption. This leads to improved sensitivity as more gas molecules interact with the surface of the sensor. Specific features such as particle/grain size, physical surface roughness, and porosity can also be placed in this section. Smaller particle/grain size, more surface roughness, and more porosity provide a higher surface-to-volume ratio, which is beneficial for detecting low concentrations of gases. In addition, a decrease in particle/grain size increases surface energy, resulting in enhanced sensitivity along with quicker response and recovery times.

Khojier et al. [39] studied the influence of the temperature gradient of the annealing process on nanostructure, porosity, and the sensitivity of sputtered WO₃ thin films to NO₂ gas and relative humidity. Their results showed that the gradually annealed sample had smaller grains, more surface roughness, and more porosity, resulting in more effective surface area and enhanced sensitivity to NO₂ gas and relative humidity. Teimoori et al. [40] examined the influence of the deposition method on the structural, electrical, and methane gas-sensing

properties of ZnO thin films. They demonstrated that the deposited film by the e-beam evaporation method, due to its different surface morphology, which provided a larger ratio of surface-to-bulk area, showed the highest sensitivity. Li et al. [41] studied the effect of SnO₂ particle size on gas-sensing performance for ppb-level NO₂ at room temperature under UV light. They showed that the particle sizes of sensitive material have a significant effect on the gas properties. A comparative study on the NO₂ gas sensing properties of ZnO thin films, nanowires, and nanorods was also carried out by Ozturk et al. [42]. Their results revealed that the sensor response was related to the shape and size of ZnO nanostructures, electrode configurations, and types.

The morphology also affects electron transport within the sensor material. For example, well-aligned nanostructures can facilitate efficient charge transfer, improving the sensor's response time and recovery. Zhang et al. [43] fabricated Indium tin oxide (ITO) materials with different morphologies via sputtering technology by adjusting the oxygen flow rate and RF power. Their results showed that the nanowires had a larger specific surface area, more oxygen vacancies, and an oriented electron transport channel, which enhanced sensing performance.

Moreover, tailoring the surface morphology may enhance selectivity for specific gases and improve stability under varying environmental conditions. For instance, research on cerium dioxide (CeO₂) nanomaterials has shown that tailoring their morphology, such as creating nanoplates, nanocubes, or porous structures, can significantly influence their chemical and physical properties [44]. These changes can enhance their selectivity and stability for specific applications, such as chemical reactions.

Thickness of sensing materials

The chemiresistive materials as a gas sensing device can be designed with different thicknesses. It is necessary to remember that the thick films often follow the bulk's principles. But in thin films, the structure and, subsequently, the properties are affected by the thickness. The Parameters such as grain size, porosity, and concentration of carriers are strongly affected by the film thickness, which can change the sensing properties. Generally, the conductance of an n-type thin film is given by [45]:

$$G = n_0 e \mu \pi R^2 L \quad (5)$$

where n_0 is the surface carrier concentration, e is the electronic charge, μ is the mobility of electrons, and R and L are the width and length of the films, respectively.

During gas sensing, upon introduction to a reactant gas, a change in conductance in the thin films will result from the change in surface carrier concentration Δn_s , according to:

$$\Delta G = \Delta n_s e \mu \pi R^2 L \quad (6)$$

Dividing equation (6) to equation (5) results in the sensitivity, namely variation of conductance as:

$$\frac{\Delta G}{G} = \frac{\Delta n_s}{n_0} \quad (7)$$

According to this equation, the sensitivity of the chemiresistive sensor can be enhanced by lowering the concentration of surface carriers (n_0). In other words, when the carrier concentrations are low, minor variations become more pronounced. Thus, because the concentration of carriers is strongly influenced by thickness, it significantly affects the sensitivity (response value, response time, and recovery time) of chemiresistive thin films.

Kannan et al. deposited ZnO thin films on glass substrates using a DC reactive magnetron sputtering technique and optimized the sensing performance to the film thickness [46]. Based on their results, the sample with lower thickness showed a higher value of response and lower response and recovery times. Geng et al. [47] synthesized mesoporous CuO materials and showed that the gas-sensing performance of the samples followed the film thickness. Hosein-Babaei and Orvatinia used a mathematical model for simulation of the effect of film thickness on the sensitivity of the resistive gas sensors. Their model revealed that in micro-cracked or porous films, the relationship between sensitivity and thickness significantly depended on the nature of the target gas [48].

The effect of film thickness on the gas-sensing properties of ultra-thin TiO₂ films was also investigated by Wilson et al. [49]. They employed that atomic layer deposition (ALD) to prepare the samples and proved that the film thickness played a dominant role within the sensing process. Aiempnanakit et al., in a research study, highlighted the importance of thickness optimization to balance sensitivity and response. They developed SnO₂-based gas sensors integrated with low-temperature co-fired ceramic (LTCC) micro hotplate for ethanol detection [50].

Srivastava et al. [51] explored the role of film thickness and oxygen vacancies on the H₂S gas-sensing performance of RF magnetron-sputtered NiO thin films. Their investigations revealed that the crystallinity, defect content, stoichiometry, and subsequently sensing performance were affected by film thickness.

Doping and decorating

Doping can significantly enhance the performance of chemiresistive gas sensors by modifying their electrical, structural, and surface properties. It can be effective in different forms as follows:

i) Doping introduces additional charge carriers (electrons or holes) into the sensing material, which increases its conductivity and responsiveness to target gases. For instance, doping metal oxides like ZnO or SnO₂ with noble metals (e.g., Ag, Pt) enhances their sensitivity by creating active sites for gas adsorption [52,53]. Khojier et al. [17] studied the chemiresistive behavior of spray-deposited Cu-doped TiO₂ thin films for application in hydrogen sensing devices. Their results showed that Cu-doping significantly affected the hydrogen sensing performance of the TiO₂ thin films due to the increase of oxygen adsorption sites (active sites). When transition metals from the 3d group, such as Cu, are introduced into TiO₂ as dopants, Ti⁴⁺ ions are replaced, leading to alterations in the charge center of the crystal structure. These structural modifications generate localized electric

fields and create additional oxygen defects, which enhance hydrogen decomposition. As a result, oxygen adsorption sites near these metals increase, significantly boosting the likelihood of reactions between hydrogen and oxygen. (Fig. 3) [17,20].

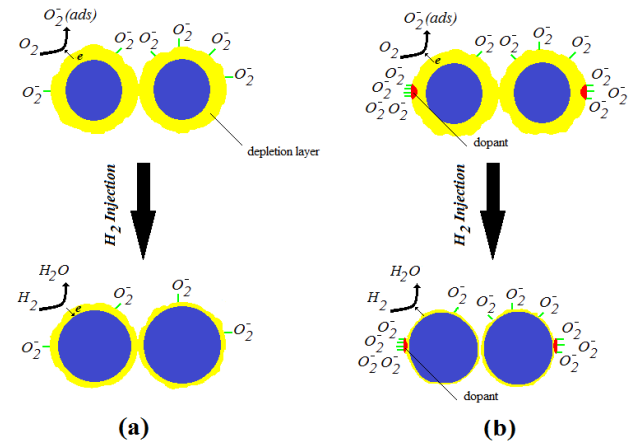


Fig. 3. Hydrogen sensing mechanism of a) pure TiO₂, and b) Cu-doped TiO₂ thin films. (The effect of dopant on sensing mechanism based on the ref. [17])

ii) Specific dopants can make the sensor more selective to certain gases. It can improve/facilitate the adsorption of the target gas on the sensing material surface and reduce interference from other gases.

[54]. Goudarzi and Khojier [55] investigated the role of substrate temperature on the ammonia gas sensing performance of Mg-doped ZnO thin films for application in breath analysis devices. Their research revealed that magnesium doping makes the ZnO thin films selective toward ammonia gas. Consistent with this report, other literature confirms the selectivity of Mg-doped ZnO thin films to ammonia gas at room temperature [56].

iii) Different reports discuss the doping process's reduction of the activation energy required for gas sensing reactions, enabling effective operation at lower temperatures. This is particularly beneficial for energy efficiency and sensor longevity [53]. An investigation of the literature [56-61] confirms the effect of different dopants, including Cu, Cd, Ni, Mg, and Na, on the operating temperature of ZnO thin film as an NH₃ sensing device.

iv) Doping often alters the nanostructure of the sensing material, such as creating porous structures or increasing surface area. These changes improve gas diffusion and interaction with the sensor surface, resulting in a decrease in response time and an increase in response value [52,62].

v) Combining multiple dopants or bimetallic modifications can result in synergistic effects, further boosting the sensor's performance. For example, bimetallic-doped materials often exhibit superior sensitivity and selectivity compared to single-metal-doped counterparts [52,53,63]. A research study by Li et al. [64] demonstrated that how single-atom gold and cerium dopants on mesoporous SnO₂ nanospheres improved sensitivity to volatile sulfur compounds.

As explained above, doping primarily modifies the bulk properties of the material. But decorating refers to the addition of nanoparticles or thin layers of materials (often noble metals like Pt, Pd, or Au) onto the surface of the sensing material. The decorated nanoparticles act as catalytic sites and promote the adsorption and reaction of gas molecules on the sensor's surface. This enhances the surface properties of the sensor. In other words, doping modifies the internal properties of the sensing material, while decorating focuses on enhancing surface interactions. However, methods can be used independently or in combination to optimize the performance of chemiresistive gas sensors for specific applications.

Amani et al. [65] tried to improve the H₂ gas sensitivity of WO₃ thin films by changing the deposition angle and thickness of different promoter layers (Pt and Au). Their results demonstrated that the H₂ gas sensitivity of the samples was improved by an increase in the Pt layer thickness and oblique deposition of the Au layer. Furthermore, the WO₃ thin films activated with Pt layer showed more reliability than the sample activated with Au layer. Penza et al. [66] used different activator layers (Pt, Pd and Au) with various thicknesses (ranging from 10 to 60 nm) on RF sputtered-WO₃ thin film. They studied the sensing performance of activated films toward various gases. Their results proved that the sensitivity and selectivity of the samples were affected by the kind and thickness of activator layer. Imawan et al. [67] used a Ti overlayer for modifying of MoO₃ thin films. Their results revealed that this modification enhanced the sensitivity to ammonia vapor while reducing cross-sensitivity towards H₂, CO, and SO₂. Wu et al. [68] reported the enhanced H₂ sensing performance of Pd-decorated MoS₂. They considered the experimental and DFT insights.

Huang et al. [69] employed the solvothermal method and subsequent Ag-loading treatments to synthesize hierarchical flower-like Cu-doped SnO₂/Ag₂S heterojunctions decorated with Ag (CSAA). The optimal CSAA composite exhibited the highest response of 1136 and the shortest response time of 6 s to 50 ppm n-butanol at 80°C, accompanied by superior selectivity, repeatability, humidity, and long-term stability.

Environmental Factors

Humidity and temperature variations, as primary air environmental factors, can influence sensor performance. As mentioned earlier, chemiresistive gas sensors detect changes in electrical resistance when exposed to target gases. Hence, their performance is strongly modulated by external environmental parameters, especially humidity and temperature [70]. A detailed explanation of how each factor can affect the chemiresistive sensor performance can be found in the following [70-72]:

Humidity Effect

For elevated humidity, water vapor can adsorb onto the sensor's active surface. In metal oxide sensors (e.g., SnO₂ or ZnO), the adsorbed water molecules frequently form hydroxyl groups that modify the surface chemistry. These groups can compete with target gas molecules for active sites, leading to reduced sensitivity (fewer available sites

for the target gas means a smaller change in resistance), and baseline drift (continuous or fluctuating water adsorption alters the sensor's baseline resistance, causing signal instability and potentially false readings). Water molecules may also interfere with redox reactions on the sensor surface. They can change the population of chemisorbed oxygen species, which are critical for the oxidation (or reduction) of the target gas. As a result, the sensor's response (both in detection and recovery phases) is affected.

While this fundamental mechanism is well-understood in laboratory settings, its implications for real-world deployment are profound and represent a major bottleneck for the commercialization of reliable chemiresistive sensors. The primary practical challenge is the dynamic nature of ambient environments. Unlike controlled lab experiments with constant humidity, field deployments, from environmental monitoring stations to wearable health devices, experience significant diurnal and seasonal fluctuations in relative humidity. This leads to two critical problems: first, a drifting baseline resistance that makes it difficult to define a stable "zero" for gas concentration measurement, and second, a variable sensitivity that can cause the same gas concentration to produce different signal magnitudes depending on the background humidity level. This effectively masks the target signal, leading to inaccurate readings and false alarms.

Temperature Effect

Temperature directly influences the kinetics of gas-surface interactions. At low temperatures, reduced thermal energy leads to stronger adsorption of gas molecules, but sometimes too slow. In addition, sensor response may be sluggish, and incomplete desorption can lead to prolonged recovery times.

At high temperatures, thermal energy boosts the reaction kinetics, speeding up both adsorption and desorption. However, excessively high temperatures can impede the adsorption process by causing too rapid desorption, which in turn reduces the sensor's effective sensitivity. Generally, there is typically an optimal temperature range where the sensor exhibits maximum sensitivity and fast response/recovery times.

Humidity and temperature not only influence the sensor's sensitivity and response dynamics but also dictate the design of compensation strategies (such as humidity-insensitive coatings or integrated temperature control circuits). Future sensor designs increasingly incorporate adaptive algorithms and materials engineering (e.g., hydrophobic surface treatments) to mitigate these influences and ensure robust performance across a wide range of environmental conditions.

Heterojunction, Homo Junction, and Complex Oxides

Chemiresistive gas sensors rely on changes in the electrical resistance of a semiconducting material upon gas adsorption. The performance of these sensors can be dramatically tuned by engineering the sensor material's internal junctions and composition. In this context,

heterojunctions, homojunctions, and complex oxides play distinct roles.

Heterojunction Effect

A heterojunction forms when two dissimilar semiconducting materials are interfaced. This can be an n-n, p-p, or p-n junction. The different energy band structures of the two materials cause a band offset at the interface. This generates depletion (or accumulation) layers where charge carriers are either depleted or enriched. When gas molecules interact at the interface, they perturb this delicate balance, leading to an amplified modulation of the potential barrier and, hence, a larger resistance change [72-74].

The built-in electric field at the heterojunction interface enables the effective separation of charge carriers. For instance, in an n-type/p-type (p-n) heterojunction (e.g., ZnO/CuO), gas-induced changes can lead to dramatic shifts in barrier height, enhancing sensitivity and lowering the detection limit. This interface can also serve as a selective barrier, favoring interactions with specific gas species [73,74]. Some literature that explains the sensing mechanism of chemiresistive gas sensors, according to the heterojunction, can be found in the earlier reports [75,76].

Homojunction Effect

A homojunction is formed within a single semiconducting material, typically by creating regions with different carrier concentrations (e.g., through differential doping) or by exploiting intrinsic variations such as oxygen vacancy gradients.

In metal oxides, variations in oxygen vacancies or dopant concentrations can naturally create regions of differing conductivity. The interface between these regions forms a homojunction that possesses its depletion region. When a target gas is adsorbed, it can change the local carrier density, which, in turn, modulates the built-in potential of the homojunction. Although the resistance change may not be as dramatic as in heterojunctions, even subtle modulation can be exploited to improve sensitivity and baseline stability. Some literature that explains the sensing mechanism of chemiresistive gas sensors, based on the homojunction, can be found in the earlier reports [77,78].

Complex Oxides

Complex oxides generally refer to multi-cation oxides, often with perovskite or spinel structures, and inherently possess rich defect chemistry and multiple crystalline phases. Because they typically contain more than one type of metal cation or exhibit mixed valence states, complex oxides can naturally form various internal junctions. These include both homojunction-like domains (due to local stoichiometric differences) and heterojunction-like interfaces between different crystalline phases.

The complex chemistry allows for a wide range of active sites for gas adsorption. Catalytic reactions on these surfaces can be more efficient, and the synergistic effect of multiple conduction pathways, both electronic and ionic, can lead to enhanced sensor responses and even faster

recovery times. Various research works have reported and discussed this phenomenon [79-84].

DEVICE STRUCTURE OF CHEMIREISTIVE GAS SENSORS

Device structure, including the arrangement of materials, electrodes, packaging, and other elements, is pivotal in translating gas-material interactions into a measurable electrical signal. Although it might seem like just another technical detail, it plays an important role in defining the sensor's core performance characteristics. The configuration and geometry of the electrode are central elements of this section. Various configurations and geometries of electrodes can be found elsewhere [62]. Each of these configurations has its characteristics and is suitable for specific applications. One of the best-known and most used is the finger pattern or teeth-like configuration. The teeth-like interlocking design significantly increases the active contact area between the electrodes and the sensing film. It also generates a more homogeneous field across the film, ensuring that gas-induced changes in conductivity are represented consistently across the sensor. Both of the factors cause a positive effect on the performance of the device. In this configuration, decreasing the gap between the electrodes enhances the sensitivity by shortening the conduction path; however, overly narrow gaps might lead to increased leakage currents or heightened susceptibility to noise [85,86].

Furthermore, electrodes interface with the sensing film can create regions of enhanced or inhibited charge transfer. For example, in some sensors, the electrode/sensing film interface may form a Schottky barrier that is sensitive to changes in the environment and affects the sensing performance.

The type of electrode material is a parameter that must be considered. Electrode materials such as gold (Au), platinum (Pt), or palladium (Pd) not only serve as conductive contacts but can also have intrinsic catalytic properties that affect local gas adsorption.

Alharbi et al. [87] produced LaFeO₃ (LFO) thick film on alumina substrates and used different noble metals (platinum and gold) as electrodes. They investigated the acetylene and ethylene sensing properties of the samples and reported that the electrode material is a crucial factor in the sensing performance of the samples. Stanoiu et al. studied the CO₂ interaction mechanism of SnO₂-based sensors with respect to the Pt interdigital electrodes gap and highlighted the importance of Pt interdigital electrodes on sensing performance [86].

It should be noted that chemiresistive sensors often operate at elevated temperatures to improve sensor kinetics. Hence, a well-designed device structure should ensure two things. First, uniform heating, which refers to avoiding thermal gradients across the sensor area, could lead to non-uniform responses. Second, isolation, which indicates preventing heat loss to the substrate, thus ensuring that the active area remains at an optimal temperature.

It is also worth mentioning that packaging strategies must allow the target gases to reach the sensing film while protecting the device from contaminants and moisture. This is crucial in applications where long-term stability and reliability are paramount.

DIFFERENT TYPES OF CHEMIRESENSITIVE GAS SENSORS

Chemiresistive gas sensors, as a class of chemical sensors, are categorized based on the materials used for their sensing layers. Conductive polymers, carbon-based materials, and metal oxides exhibit chemiresistive properties and serve as sensing materials in these sensors. Herein, an overview of the three types is discussed.

Conductive Polymer Gas Sensors

The conductive polymer is a polymer with a backbone of π -conjugated electrons. These polymers, unlike conventional polymers, possess some metal characteristics, such as magnetic, electrical, and optical properties, but also exhibit conventional polymer characteristics, including processability and mechanical properties [88,89].

The chemiresistive gas sensors based on conductive polymers predominantly use organic conductive polymers, including polypyrrole (PPy), polyaniline (PANI), polythiophene (PTh), poly(3,4- ethylenedioxythiophene)

(PEDOT), and polyacetylene (PA) and their derivatives as the active transducer materials [90]. These sensors offer several outstanding features such as low-cost production, rapid detection, the ability to detect multiple gases simultaneously (as in array gas sensors), and suitability for portable devices [90,91]. They are also favorable because of their room-temperature operation. On the other hand, they suffer from limited long-term stability and susceptibility to environmental factors such as humidity [90,92]. Various materials (conductive or insulating) can serve as substrates for polymerization in conductive polymer-based gas sensors. Factors such as surface modifications and adding the metal oxides (composites) can enhance the performance of this type of sensor [91]. They have a variety of uses in detecting volatile organic vapors (VOCs), hydrogen, and pollutant gases [90-96].

According to the literature, the sensing characteristics of various conductive polymer sensors are summarized in Table 3, which provides appropriate information for a deeper understanding of these sensors [97-119]. Based on this data, the conductive polymers show more sensitivity and selectivity toward NH_3 , NO_2 , and CO compared to other gases and vapors. This result can also be supported by earlier reports that confirm the strong selectivity of PANI to ammonia [120,121,122], nitrogen dioxide [123], and carbon monoxide [124].

Table 3

The sensing characteristics of various conductive polymer sensors toward different gases and vapors

Material	Target gas	Response*	T _{ope.} (°C)	Gas Con. (ppm)	T _{res./T_{rec.}} (s)	Ref.
PANI (thin film)	NH_3	1.65	RT	50	10/70	[97]
Fe-Al doped PANI	CO	800	RT	150	5/10	[98]
PANI (thin film)	NO_2	206.19	RT	20	-/-	[99]
Gold nanoparticles functionalized PANI (nanowire)	H_2S	2.2	RT	1000	<120/<300	[100]
0.4 wt% Pd-doped electrospun PANI (nanofiber)	H_2	1.17	RT	20000	90/140	[101]
PANI (thin film)	Ethanol	1.64	RT	32	10/-	[102]
PANI (nanofiber)	Triethylamine	1.11	RT	18000	13.7/-	[103]
PANI (nanofiber)	Xylenes	1.23	RT	1000	-/-	[104]
PPy (thin film)	NH_3	1.14	RT	20	20/900	[105]
PPy functionalized with FeTPPCL	CO	1.12	RT	300	169/-	[106]
PPy (thin film)	NO_2	1.36	RT	100	126/2170	[107]
PPy (nanowire)	H_2	1.01	RT	12000	692-1396	[108]
PPy (thin film)	Acetone	1.12	RT	700	-/-	[109]
PPy (nanosheets)	HCL	24	RT	100	13/-	[110]
Iodine doped PTh (film)	NH_3	1.95	RT	1850	78/346	[111]
PTh (thin film)	NO_2	1.33	RT	100	220/1603	[112]
PTh (film)	H_2S	1.40	70	200	-/-	[113]
PTh (film)	Acetone	1.15	100	150	-/-	[114]
PEDOT (PSS film)	NH_3	1.28	RT	100	10/70	[115]
PEDOT (nanotubes)	NO_2	1.55	RT	63	-/-	[116]
PEDOT (nanowire)	NO	6.67	80	100	330/204	[117]
PEDOT (PSS thin film)	Ethanol	1.15	RT	2625	~0.6/-	[118]
PEDOT (nanotubes)	Methanol	1.06	RT	1000	~4/25	[119]

*: Depending on the type of majority carrier and gas/vapor (reducing or oxidizing), the response was determined as $R_{\text{gas}}/R_{\text{air}}$ or $R_{\text{air}}/R_{\text{gas}}$.

Literature review also shows that adding metal oxide semiconductors such as SnO_2 , TiO_2 , In_2O_3 , and ZnO to PANI improves its gas-sensing characteristics while pure PANI sensors frequently exhibit poor sensitivity or a high

detection limit [125-127]. Huyen et al. prepared PANI/ TiO_2 nanocomposites by in-situ chemical polymerization using aniline monomer and TiCl_4 as precursors [128]. They synthesized the samples with

different TiO₂ contents and showed that the electrical resistance of the samples is susceptible to oxygen and ammonia gas. Pawar et al. used chemical oxidative polymerization and sol-gel technique to synthesize PANI and TiO₂, respectively. To obtain the PANI-TiO₂ nanocomposite, they mixed PANI and TiO₂ by mechanical mixing and reported a response value of 50 % toward 100 ppm NH₃ [129]. Nasirain and Milani Moghadam also studied the hydrogen sensing performance of PANI-TiO₂ nanocomposites as a function of different parameters [130-132]. They demonstrated that PANI-TiO₂ nanocomposite can be considered a potential for producing H₂ sensing devices. Zhu et al. [125] used the hydrothermal process to make the PANI/TiO₂ nanocomposites with various TiO₂ contents. They showed that the samples were selective to ammonia compared to other vapors such as ethanol, acetone, acetylene, and ethylbenzene.

Metal Oxide Gas Sensors

In this class of chemiresistive gas sensors, metal oxide semiconductors (MOSs) serve as the sensing materials. They are a cornerstone of modern gas detection technology due to their simplicity, cost-effectiveness, and high sensitivity. One could argue that they are the most widely used type of chemiresistive gas sensors. The versatility of MOS chemiresistive sensors has led to their extensive

application in various fields, including environmental monitoring, industrial safety, automotive emissions control, medical diagnostics, smart homes, indoor air quality, and energy efficiency [10,13,25].

The MOS gas sensors are instrumental in detecting pollutants such as carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and volatile organic compounds (VOCs) for urban air quality assessment [25,39,133]. Zolghadr et al. [133] reported a detailed study on the sensitivity and selectivity of α -Fe₂O₃ thin films toward various toxic gases, including CO, H₂S, NH₃, and NO₂, as well as different alcohols such as C₃H₇OH, CH₃OH, and C₂H₅OH. Based on their results, α -Fe₂O₃ thin films (post-annealed at 800 °C) were selective to NO₂ gas and showed good stability and reproducibility at the operating temperature of 200 °C. Khojier et al. [39] studied the effect of the temperature gradient of the annealing process on nanostructure, porosity, and the sensitivity of sputtered WO₃ thin films toward NO₂ gas and relative humidity. The results confirmed that gradually annealed sample had the best sensitivity to NO₂ gas and the relative humidity due to the most effective surface area.

The results of the previous reports that focus on MOS gas sensors' toxic gas sensing performance are also summarized in Table 4 [40,133-138]. This data confirms the ability of MOS gas sensors as toxic gas sensors.

Table 4
The sensing characteristics of various MOS sensors toward toxic gases

Material	Target gas	Response	T _{Op.} (°C)	Gas Con. (ppm)	T _{res./T_{rec.}} (s)	Ref.
α -Fe ₂ O ₃ (thin films)	NO ₂	53 ^a	200	200	33/48	[133]
	H ₂ S	42 ^a	250	200	-/-	
	CO	10 ^a	200	200	-/-	
WO ₃ (nanofiber)	NO ₂	12.52 ^b	200	1	12/26	[134]
In ₂ O ₃ (belt-like)	CH ₄	1.1 ^b	100	90	36/44	[135]
ZnO	CH ₄	32 ^a	350	500	70/75	[40]
SnO ₂ (nanofiber)	H ₂ S	15.2 ^b	350	0.1	15/230	[136]
SnO ₂ (nanotube)	NO	33.3 ^b	160	0.5	214/115	[137]
Co ₃ O ₄ (nanosheets)	CO	2.4 ^b	100	5	14/36	[138]

$$^a: R_{\text{gas}}/R_{\text{air}} \text{ or } R_{\text{air}}/R_{\text{gas}}, \quad ^b: (R_{\text{gas}}-R_{\text{air}}/R_{\text{gas}}) \times 100 \text{ or } (R_{\text{air}}-R_{\text{gas}}/R_{\text{air}}) \times 100$$

Many reports can also be found on the detection of VOCs by metal oxide-based chemiresistive gas sensors. Volatile organic compounds (VOCs) are a group of chemical substances that can easily evaporate into the air at room temperature, and their presence plays a significant role in environmental, industrial, and health-related contexts. Effective sensing of VOCs is crucial for monitoring air quality, as these compounds contribute to pollution and can have harmful effects on human health, such as respiratory issues and long-term exposure risks. VOC sensors are also indispensable in industrial settings,

where detecting leaks or emissions ensures safety and compliance with regulations. Moreover, VOC sensing has applications in fields like food storage (where the detection of specific compounds can indicate spoilage), and medical diagnostics (where VOC profiles in human breath can serve as biomarkers for diseases). Accurately detecting and measuring VOCs enhances environmental safety, public health, and operational efficiency across diverse sectors. Table 5 presents the results of different research studies that focus on detecting VOCs by MOS sensors [139-152].

Table 5
The sensing characteristics of various MOS sensors toward VOCs

Material	Target gas	Response*	T _{Op.} (°C)	Gas Con. (ppm)	T _{res./T_{rec.}} (s)	Ref.
In ₂ O ₃ (nanowires)	ethanol	2	370	100	10/20	[139]
SnO ₂ (core-shell)	ethanol	60	260	50	9/20	[140]
ZnO (nanoroads)	acetone	30	300	100	5/-	[141]
α -Fe ₂ O ₃	acetone	10	300	100	34/44	[142]
NiO	formaldehyde	1.5	300	10	13.2/-	[143]

NiO	formaldehyde	4.3	340	20	420/-	[144]
PdO decorated-ZnO	toluene	10.9	240	100	1/9	[145]
TiO ₂ (nanotubular)	toluene	53	500	500	110/800	[146]
SnO ₂ (thin film)	methanol	21	250	10000	-/-	[147]
Hollow α -Fe ₂ O ₃ spheres	methanol	25	280	10	8/9	[148]
Pt loaded-ZnO	acetylene	836	300	10000	6/60	[149]
5% Ni-doped ZnO	acetylene	17	250	2000	5/10	[150]
Cu ₂ O (octahedral)	benzene	9.7	230	50	3/4	[151]
SnO ₂ (flower shape)	benzene	3.25	240	150	-/-	[152]

*: $R_{\text{gas}}/R_{\text{air}}$ or $R_{\text{air}}/R_{\text{gas}}$

As can be deduced from the data presented in Tables 4 and 5, although MOS-based gas sensors are the most commonly used due to their numerous advantages compared to other types of gas sensors, their requirement for high operating temperatures leads to significant energy consumption. This high energy demand restricts their use, particularly in mobile and portable devices. To overcome these limitations, several approaches have been proposed in recent years, including self-heating techniques, the use of MEMS technology, and the development of special morphologies that facilitate room-temperature operation [13].

Carbon-based Material Gas Sensors

Carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene (G), have emerged as promising candidates for chemiresistive gas sensing applications. Their inherent properties (high specific surface area, excellent electrical conductivity, and versatile chemical functionality) make these materials especially sensitive to adsorbed gas molecules. When a gas molecule interacts with the surface of a carbon nanomaterial, it can donate or withdraw electrons, resulting in a measurable change in electrical resistance. This principle underpins the operation of chemiresistive gas sensors that leverage

carbon-based materials, offering the potential for rapid, room-temperature detection of a wide range of gases [153-154].

One significant advantage of using carbon-based materials is their ability to operate at or near room temperature, thereby reducing energy consumption compared to traditional metal oxide sensors that typically require high working temperatures. Enhanced sensitivity arises from the nanostructured morphology of these carbon materials, which allows for extensive modifications such as doping or functionalization with selective receptors. These modifications tailor the sensor's selectivity and response speed by promoting specific interactions with target analytes. The research studies have demonstrated that integrating carbon nanomaterials with various functional groups or composite materials not only bolsters sensitivity but also improves the long-term stability and reproducibility of the sensor response [153,155]. Table 6 summarizes the results of several research reports employing carbon-based nanomaterials as chemiresistive gas sensors [156-169]. The carbon-based nanomaterials can serve in different forms, such as CNTs, metal-doped CNTs, metal oxide-doped CNTs, polymer-doped CNTs, graphene, metal-doped graphene, and reduced graphene as chemiresistive sensing materials.

Table 6

The sensing characteristics of carbon-based nanomaterials as chemiresistive gas sensors, according to earlier reports

Material	Target gas	Response	T _{Op.} (°C)	Gas Con. (ppm)	T _{res./T_{rec.}} (s)	Ref.
Multi-walled CNTs	methane	20%	RT	160	10/60	[156]
Multi-walled CNTs	ethanol	1.67%	RT	800	-/-	[157]
Multi-walled CNTs	H ₂	13%	RT	180000	20/-	[158]
Multi-walled CNTs	Cl ₂	15%	RT	2	900/-	[159]
Pt doped CNTs	H ₂	20.5%	RT	33	10/20	[160]
Au doped CNTs	CO ₂	3.4%	RT	800	-/-	[161]
Co doped multi-walled CNTs	NH ₃	1.5%	RT	14	30/200	[162]
ZnO doped Multi-walled CNTs	methane	12.1%	RT	10	-/-	[163]
SnO ₂ doped Multi-walled CNTs	H ₂	2.8%	RT	500	-/-	[164]
PANi doped Multi-walled CNTs	NH ₃	32%	RT	10	24/62	[165]
PANI doped CNTs	NO ₂	19.1%	RT	50	5.2/3.2	[166]
Graphene	NO ₂	6.66	RT	1	134/388	[167]
Pd doped graphene	H ₂	72%	RT	2000	3/7	[168]
Pt doped graphene	formaldehyde	36.4%	RT	400	720/50	[169]

Despite these advances, challenges remain in optimizing the performance of carbon-based gas sensors. Issues such as selectivity in complex gas mixtures, the influence of environmental factors like humidity and temperature, and reproducibility across production batches require further research. Future directions include the

development of nanocomposites that combine carbon materials with metal nanoparticles or conductive polymers, which may provide synergistic effects to overcome current limitations. Additionally, detailed investigations into the sensing mechanisms at the molecular level could lead to better-controlled fabrication

processes and more reliable sensor performance, broadening the scope of practical applications.

A Summary and Comparison of Different Types of Chemiresistive Gas Sensors

Each sensing material (conductive polymers, carbon-based materials, and metal oxides) offers unique advantages depending on the target gas and application requirements. Conductive polymers offer the advantages of operating at room temperature, high flexibility, and tunable sensitivity through chemical modifications. They sometimes suffer from limited long-term stability and sensitivity to humidity. In contrast, carbon-based materials such as

graphene and carbon nanotubes provide a high surface area for improved gas adsorption along with rapid response times and robust conductivity, though they too may face challenges in environmental stability and often require functionalization to enhance selectivity. Metal oxides remain dominant in industrial gas sensing and present higher sensitivity and selectivity, typically at elevated operating temperatures (often above 200°C), a factor that can limit their use in low-power or portable devices but generally ensures more stable performance over time. Table 7 presents a summary of various features of these sensing materials.

Table 7
A summary of various features of chemiresistive gas sensor sensing materials

Material	Operating Temp.	Sensitivity	Selectivity	Stability	Flexibility
Conductive Polymers	Room temperature	Moderate	Tunable	Limited	High
Carbon-Based	Room temperature	High	Moderate	Moderate	High
Metal Oxides	Elevated (>200°C)	Very High	High	High	Low

It is worth mentioning that, while traditional metal oxides, polymers, and carbon allotropes form the bedrock of chemiresistive sensing, recent years have witnessed the rapid emergence of novel material classes that offer unique mechanisms and properties, pushing the boundaries of performance. Among these, Metal-Organic Frameworks (MOFs) and MXenes stand out as particularly promising [170,171].

THE EVOLUTION OF CHEMIRERESISTIVE GAS SENSORS

Chemiresistive gas sensors have become a cornerstone in environmental monitoring, industrial safety, and healthcare diagnostics. These devices operate by detecting changes in the electrical resistance of a material upon exposure to target gases, a principle that has driven their widespread adoption. Over the decades, continuous advancements in material science, device architecture, and integration techniques have transformed these sensors from early prototypes with limited specificity and high operating temperatures into highly sensitive, low-power devices suited for modern, complex applications.

The roots of chemiresistive gas sensors trace back to the mid-20th century. Early incarnations predominantly employed bulk semiconducting metal oxides, such as SnO₂ and ZnO, which exhibited measurable changes in conductivity when exposed to reactive gases. Despite their groundbreaking nature, these early sensors required elevated operating temperatures to achieve adequate sensitivity and often suffered from poor selectivity and long recovery times. Nonetheless, the fundamental discoveries regarding gas-solid interactions during this period established the scientific foundation for subsequent innovations.

The transition to nanoscale materials marked a pivotal shift in sensor evolution. Advances in nanotechnology introduced nanowires, nanorods, and nanoparticles, vastly increasing the surface-to-volume ratio and, consequently, the sensitivity of the devices. Alongside these

morphological changes, material modifications through doping and surface decoration emerged as critical strategies. The incorporation of catalytic noble metals (such as palladium, platinum, and gold) has enhanced sensor performance by promoting selective catalytic reactions, reducing the required operating temperature, and speeding up both response and recovery times. These innovations have significantly expanded the practical applicability of chemiresistive sensors, enabling detection of trace gas concentrations in increasingly diverse environments.

Parallel to material enhancements, sensor design has evolved dramatically. Early sensor configurations have been largely supplanted by more sophisticated devices featuring interdigitated electrodes and micro-electromechanical systems (MEMS)-based platforms. These advances allow for precise control over electric field distributions and greater integration density, which are essential for miniaturization and robust performance. The development of sensor arrays (comprising multiple sensor elements) has further improved selectivity and reliability, as data fusion from diverse sensing elements can compensate for cross-sensitivities and environmental interferences.

Modern chemiresistive gas sensors are increasingly designed to perform reliably under real-world conditions, where variables such as humidity, temperature fluctuations, and interfering gases can compromise sensor accuracy. Recent strategies incorporate adaptive calibration algorithms, temperature stabilizers, and selective coatings that mitigate these environmental influences. By addressing these challenges, contemporary sensors achieve not only improved detection capabilities but also enhanced stability and lower false-positive rates, a necessity for their integration into dynamic systems like the Internet of Things and smart monitoring networks.

BRIDGING THE GAP: FROM LABORATORY PERFORMANCE TO COMMERCIAL VIABILITY

A critical analysis of the chemiresistive sensor field reveals a significant disparity between the number of high-performing materials reported in academic literature and the relatively few that successfully transition to commercial products. This gap often stems from a focus on optimizing a single parameter (typically sensitivity) under idealized laboratory conditions, while overlooking the complex matrix of requirements for real-world deployment. Addressing these overlooked factors is crucial for setting realistic expectations for new researchers and guiding the field toward more practical and impactful research directions. The journey from a promising lab-scale material to a reliable commercial sensor is fraught with challenges that are seldom the focus of fundamental research:

Long-term Stability

A sensor may show excellent sensitivity for weeks in a controlled environment, but a commercial product is expected to operate reliably for years with minimal calibration. Factors such as material aging, sintering of nanostructures at operating temperature, and poisoning by sensor contaminants are critical failure modes that must be addressed through durable material design and protective coatings.

Selectivity in Complex Matrices

Laboratory demonstrations often involve single-target gases in synthetic air. In contrast, real-world environments, such as urban air, industrial exhaust, or human breath, contain complex and dynamic mixtures of interferences. A sensor's response to a target gas must be decipherable amidst this background noise, a challenge that often necessitates the use of sensor arrays and advanced data analytics rather than relying on a single, perfectly selective material.

Power Consumption and Form Factor

The drive toward portable and Internet of Things (IoT) applications demands sensors with low power consumption. While many metal oxides require high operating temperatures (200-400 °C), the associated power draw for a micro-heater can be a major limitation for battery-operated devices. This has accelerated research into room-temperature materials (e.g., certain 2D materials and conducting polymers) and low-power heating strategies.

Environmental Robustness

As discussed previously, performance must be stable across a wide range of ambient temperature and humidity fluctuations. A sensor that functions perfectly at 25°C and 50% RH will be useless if it fails in a freezing winter or a humid summer without complex and costly compensation systems.

Therefore, while reporting high sensitivity remains important, the future of the field should increasingly

prioritize research that also quantifies these practical metrics. Evaluating new materials against benchmarks of long-term stability, cross-sensitivity, and environmental robustness under application-relevant conditions will provide a more meaningful assessment of their potential. By consciously designing research projects with these commercialization hurdles in mind, the academic community can play a more direct role in developing the next generation of gas sensors that are not only sensitive but also practical, durable, and ready for the market.

FUTURE DIRECTION OF CHEMIRERESISTIVE GAS SENSORS

Today's research is pushing the boundaries of chemiresistive sensor technology by integrating advanced computational methods and multifunctional materials. Key areas of ongoing development include hybrid sensor platforms that combine multiple detection principles and the use of machine learning techniques for real-time data analysis. Such approaches promise considerable improvements in selectivity, sensitivity, and energy efficiency, thereby expanding the application domains of these sensors. The next generation of chemiresistive gas sensors is poised to play a crucial role in addressing emerging challenges in environmental and public health monitoring, industrial process control, and beyond.

Researchers are exploring flexible and transparent electrodes (such as graphene-based structures) that can further enhance sensitivity and facilitate integration into wearable or flexible devices. Innovations in 3D printing and nano-fabrication allow for more complex electrode geometries, potentially opening up new avenues for multi-gas sensing arrays and hybrid sensor systems.

Coupling experimental approaches with computational simulations (e.g., finite element analysis) can predict electric field distributions and optimize the sensor's performance before fabrication, reducing costs and accelerating innovation.

CONCLUSION

This review has documented the development of chemiresistive gas sensors, showing that their impressive progress results from combined advances in materials science, device design, and data analysis. It begins with the sensing mechanism of chemiresistive gas sensors. Then, it discusses the sensing properties and the main factors influencing performance. The review also explores device structures and different types of chemiresistive sensors, ending with an outlook on future prospects. It analyzes 171 references and highlights key challenges like selectivity, stability, and humidity interference, which still pose significant hurdles. Additionally, the review offers a roadmap for future research, including integrating machine learning for data processing and creating multimodal sensing arrays. We believe this thorough, forward-looking analysis will be a valuable resource and motivate future innovations in chemiresistive gas sensing.

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DATA AVAILABILITY

All data is available in the main text.

AUTHOR CONTRIBUTIONS

K. Khojier: Supervision, Conceptualization, Writing, Editing.

H. Savaloni: Writing and Editing.

S. Goudarzi: Literature review, Software.

M. Golami: Literature review, Software.

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