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Toxic gas sensors: sensing principles, materials, technologies, and challenges for environmental and industrial safety

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ABSTRACT

Toxic gases released by industrial processes, transportation, mining, and accidental chemical events create acute risks to human health and the environment. Reliable gas sensing is therefore essential for early warning, exposure control, and process safety, yet practical detectors must balance sensitivity, selectivity, response time, stability, power consumption, and cost. This review examines established toxic-gas sensing technologies reported up to 2016, with emphasis on semiconducting metal-oxide chemiresistors, electrochemical sensors, and optical approaches. The discussion considers how surface chemistry, morphology, catalytic additives, operating temperature, and humidity influence sensor performance. Representative applications for hydrogen sulfide (H_2S), ammonia (NH_3), chlorine (Cl_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and hazardous volatile compounds are used to illustrate both progress and persistent limitations. The literature indicates that metal-oxide devices offer low-cost fabrication and broad gas responsiveness, whereas electrochemical and optical systems can provide improved selectivity or operation at lower power, depending on their design. However, cross-sensitivity, environmental drift, calibration requirements, and the gap between laboratory testing and real-world exposure remain major barriers. The review concludes that practical toxic-gas monitoring requires application-specific sensor selection, robust calibration, multisensor validation, and integration with dependable alarm systems.

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1. INTRODUCTION

Toxic gases are significant hazards in industrial facilities, laboratories, mines, wastewater treatment plants, and densely populated urban environments. Substances such as hydrogen sulfide (H_2S), ammonia (NH_3), chlorine (Cl_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) can cause serious health effects even when exposure occurs over relatively short periods. Some gases are difficult to identify without instruments because they are colorless, may have unreliable warning odors, or can impair the human sense of smell. Consequently, reliable gas sensors are essential for detecting hazardous concentrations before they develop into emergencies.

The development of toxic-gas sensors involves several interconnected engineering problems. A detector must identify a target gas at a sufficiently low concentration while minimizing responses to other substances present in the same environment. It should also provide a rapid response, maintain stable performance under changing temperature and humidity, and operate reliably over an extended service period. These requirements are challenging because sensor materials interact with gases through surface reactions that may be affected by environmental conditions and material degradation [1], [2].

This review examines the principal sensing technologies and material approaches reported up to 2016. It focuses on metal-oxide semiconductor sensors, electrochemical detection, and optical techniques, while considering their relevance to selected toxic gases and hazardous vapors. The review also evaluates the factors that influence practical sensor performance, including selectivity, response time, stability, and

calibration. The central objective is to connect the limitations of conventional detection methods with material and system-level strategies that can improve toxic-gas monitoring.

2. TOXIC-GAS SENSOR TECHNOLOGIES

2.1. Metal-oxide semiconductor sensors

Metal-oxide semiconductor (MOS) sensors are among the most widely investigated solid-state gas detection technologies. Common sensing materials include tin dioxide (SnO_2), zinc oxide (ZnO), tungsten trioxide (WO_3), and titanium dioxide (TiO_2). Their operation generally depends on changes in electrical resistance when gas molecules interact with oxygen species or other adsorbed compounds on the sensing surface. These interactions modify the concentration and mobility of charge carriers, producing an electrical signal that can be measured by an external circuit [1], [3].

The performance of MOS sensors is strongly influenced by material composition and surface structure. Grain size, porosity, film thickness, crystallographic orientation, and surface defects determine how effectively target molecules reach and react with active sensing sites. Nanostructured materials, including nanoparticles, nanowires, nanorods, and nanotubes, can provide a larger accessible surface area than conventional bulk materials. However, a larger surface area does not automatically guarantee improved selectivity because different gases may interact with similar surface sites [3]–[5].

Operating temperature is another important factor in MOS-based detection. Heating can accelerate surface reactions and improve response and recovery, but it increases power consumption and may complicate the use of portable battery-powered devices. Humidity can also influence sensor resistance by competing with target molecules for adsorption sites or changing surface reaction pathways. Wang *et al.* [4] identified chemical composition, surface modification, microstructure, temperature, and humidity as important factors affecting the sensitivity of metal-oxide sensors.

2.2. Electrochemical gas sensors

Electrochemical sensors detect gases through chemical reactions occurring at electrodes in contact with an electrolyte. In many designs, the target gas diffuses through a porous membrane and undergoes oxidation or reduction at the working electrode. The resulting current or potential change is related to the concentration of the gas under defined operating conditions. This approach is particularly useful for portable detectors because electrochemical devices can operate at relatively low power and provide quantitative measurements.

Electrochemical sensing is relevant to gases such as CO, H_2S, NH_3, and NO_2, although the electrode chemistry and electrolyte must be selected according to the target analyte. The detection performance depends on electrode materials, catalyst activity, electrolyte composition, gas diffusion, and the stability of the electrochemical reaction. Xu *et al.* [6] reviewed electrochemical approaches to H_2S measurement and discussed their importance in detecting sulfide in biological and analytical applications. Nevertheless, electrolyte degradation, sensor aging, cross-interference, and the need for periodic calibration can limit long-term reliability.

2.3. Optical gas sensors

Optical gas sensors identify gases through their interaction with light. Depending on the design, detection may rely on absorption at characteristic wavelengths, changes in optical transmission, fluorescence, or refractive-index variation. Infrared absorption and laser-based techniques are particularly useful because many gas molecules exhibit characteristic spectral absorption features. These properties can support selective detection when the optical system is properly configured.

Optical methods offer several advantages for hazardous environments. Because the sensing signal can be transmitted through optical fibers, the measurement point may be separated from electrical equipment or locations where sparks could create additional risks. Optical systems can also support remote monitoring and measurements over extended distances. However, their cost, optical alignment requirements, signal-processing complexity, and sensitivity to contamination may restrict their use in low-cost distributed detectors [2], [7].

3. MATERIALS AND DETECTION OF REPRESENTATIVE TOXIC GASES

3.1. Hydrogen sulfide

H_2S is a highly toxic gas associated with petroleum processing, wastewater treatment, agricultural facilities, and certain industrial operations. Its detection is challenging because exposure at high concentrations can rapidly become life-threatening, while odor is not a dependable warning mechanism.

MOS sensors based on SnO_2 have been investigated for H_2S detection, particularly when modified with catalytic materials. Chowdhuri *et al.* [8] demonstrated that incorporating CuO nanoparticles onto SnO_2 thin films could improve the response speed for trace-level H_2S detection.

The improved response is associated with interactions between CuO and H_2S that influence the surface oxygen species and electrical properties of the sensing layer. This illustrates the importance of combining a semiconductor with a suitable catalytic additive rather than relying exclusively on the properties of the base oxide. Electrochemical detection provides another approach, especially where low-power operation and quantitative measurement are required. However, sensor selection must consider the expected concentration range, humidity, response and recovery time, and the consequences of sensor failure [6], [8].

3.2. Ammonia

NH_3 is widely used in fertilizer production, refrigeration systems, chemical manufacturing, and agricultural processes. Although it has a recognizable odor, odor perception is not an adequate substitute for instrument-based monitoring because exposure conditions and individual sensitivity vary. ZnO-based thick-film sensors have been investigated for NH_3 detection, including devices modified with ruthenium-containing compounds. Wagh *et al.* [9] reported that modified ZnO thick films exhibited useful sensitivity toward NH_3, demonstrating the potential of surface modification for improving gas response.

The detection of NH_3 remains difficult when other reducing gases are present. A sensor that responds strongly to NH_3 may also exhibit a measurable response to alcohols, hydrogen, or other compounds, depending on its operating conditions. Material modification and temperature control can improve discrimination, but these strategies must be validated under realistic mixtures rather than isolated laboratory gas exposure. Therefore, NH_3 monitoring systems should combine appropriate sensing materials with calibration procedures and, where necessary, complementary detection channels [4], [9].

3.3. Chlorine and other reactive gases

Cl_2 is a corrosive and toxic gas used in water treatment, chemical production, and disinfection processes. Accidental releases can cause severe respiratory irritation and require rapid detection in industrial environments. Metal-oxide materials are promising candidates because their surface chemistry can be modified to interact with reactive gases. Tong *et al.* [10] reported a WO_3-based sensor using self-assembled nanorod structures for detecting low concentrations of Cl_2, illustrating the potential of nanostructured sensing layers.

The detection of Cl_2 requires particular attention to material durability and chemical compatibility. Strongly reactive gases may alter sensing surfaces over time, potentially changing the baseline resistance and reducing repeatability. Sensor packaging and protective structures must therefore allow gas diffusion while limiting damage from corrosive environments. These requirements demonstrate why sensitivity alone is insufficient for evaluating a toxic-gas detector intended for industrial deployment [3], [10].

3.4. Nitrogen dioxide, carbon monoxide, and hazardous vapors

NO_2 and CO are important air pollutants associated with combustion, traffic emissions, and industrial activities. NO_2 is an oxidizing gas that can modify the electrical conductivity of semiconductor sensing layers through surface charge-transfer processes. CO is generally detected through its reaction with adsorbed oxygen species on suitable metal-oxide materials. The resulting sensor response depends on the oxide composition, operating temperature, surface morphology, and the presence of interfering gases [1], [4].

Hazardous volatile organic compounds also require attention because several compounds are toxic or harmful after prolonged exposure. Mirzaei *et al.* [7] reviewed metal-oxide nanostructures for detecting hazardous volatile organic compounds, including formaldehyde and benzene-related compounds. Their review highlights the importance of nanostructured sensing materials and the relationship between surface characteristics and gas response. Although these compounds differ chemically from inorganic toxic gases, their detection presents similar engineering challenges involving selectivity, detection limits, environmental interference, and long-term stability.

4. FACTORS AFFECTING SENSOR PERFORMANCE

Sensitivity is an important measure of a sensor's ability to respond to changes in gas concentration, but it cannot independently establish whether a device is suitable for safety monitoring. Selectivity is equally important because industrial atmospheres often contain mixtures of gases, vapors, moisture, and airborne contaminants. A sensor with high sensitivity but poor selectivity may generate false alarms or fail to distinguish a dangerous target gas from a harmless interferent. Material selection, catalytic additives, operating temperature, and signal-processing methods must therefore be considered together [2], [4].

Response and recovery times determine how quickly a sensor can detect a hazardous release and return to its baseline condition. Slow response may delay warnings, whereas incomplete recovery can cause

baseline drift and inaccurate measurements during repeated exposure. Morphology and microstructure influence gas diffusion and surface reaction kinetics, while grain boundaries and catalytic interfaces can affect charge transport. These relationships explain why sensor development requires both material characterization and testing under representative operating conditions [3], [5].

Long-term stability is another critical requirement for practical toxic-gas monitoring. Sensor properties may change because of contamination, corrosion, thermal cycling, aging, or irreversible reactions with target gases. Calibration is consequently necessary to maintain measurement accuracy, particularly in environments where temperature and humidity fluctuate. Moos *et al.* [11] emphasized the importance of realistic testing and application-oriented development in solid-state gas sensor research.

5. CHALLENGES AND FUTURE DEVELOPMENT

Despite substantial progress in gas-sensitive materials, several barriers remain between laboratory demonstrations and reliable field deployment. One major challenge is cross-sensitivity, particularly for MOS devices that respond to multiple reducing or oxidizing gases. Another is the influence of environmental conditions, especially humidity and temperature, which can alter adsorption and reaction processes. Future development should therefore prioritize selective surface functionalization, stable sensing interfaces, and compensation methods that account for environmental variation [2], [4], [5].

Miniaturization and low-power operation are also important for portable and distributed monitoring systems. Microfabricated sensing platforms can reduce device size and support integration with wireless communication and alarm circuits. However, reducing power consumption must not compromise response time, detection limits, or long-term stability. The integration of multiple sensing elements may provide improved gas discrimination, especially when combined with pattern-recognition methods and carefully designed calibration procedures [2], [11].

A further priority is the adoption of standardized evaluation procedures. Sensor performance should be tested across realistic concentration ranges, gas mixtures, humidity levels, and operating temperatures. Reports should clearly distinguish laboratory detection limits from demonstrated performance in actual industrial or environmental settings. Such practices would make comparisons more meaningful and help engineers select sensors according to the specific risks and operational requirements of each application [1], [7], [12].

6. CONCLUSION

Toxic-gas sensors are essential instruments for protecting workers, communities, and industrial infrastructure from hazardous chemical exposure. Metal-oxide semiconductor sensors offer attractive advantages in cost, fabrication flexibility, and sensitivity, while electrochemical and optical technologies provide alternative approaches with distinct strengths. Research reported up to 2016 demonstrates that material composition, surface modification, nanostructure, and operating conditions strongly influence detection performance. Applications involving H_2S, NH_3, Cl_2, NO_2, CO, and hazardous volatile compounds also show that no single sensing technology is optimal for every gas or environment. The principal research challenge is to achieve reliable selectivity and long-term stability without sacrificing affordability, response speed, or low-power operation. Progress will depend on application-specific material design, realistic performance evaluation, effective calibration, and integration with dependable monitoring and alarm systems. Multisensor configurations may further improve reliability when individual sensor responses are interpreted collectively. Ultimately, the practical value of a toxic-gas sensor should be judged not only by its laboratory sensitivity but also by its ability to provide accurate and timely warnings under real operating conditions.

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