

Review

Recent Advances in Resistive Gas Sensors: Fundamentals, Material and Device Design, and Intelligent Applications

Peiqingfeng Wang ¹, Shusheng Xu ^{1,*}, Xuerong Shi ¹, Jiaqing Zhu ¹, Haichao Xiong ¹ and Huimin Wen ^{2,*}

¹ School of Materials Science and Engineering, Shanghai University of Engineering Science, Shanghai 201620, China; m350122107@sues.edu.cn (P.W.); shixuer05@mails.uca.ac.cn (X.S.); m350122110@sues.edu.cn (J.Z.); m350123101@sues.edu.cn (H.X.)

² Department of Micro/Nano Electronics, School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

* Correspondence: xushusheng@sues.edu.cn (S.X.); wenhuimin@sjtu.edu.cn (H.W.)

Abstract

Resistive gas sensors have attracted significant attention due to their simple architecture, low cost, and ease of integration, with widespread applications in environmental monitoring, industrial safety, and healthcare diagnostics. This review provides a comprehensive overview of recent advances in resistive gas sensors, focusing on their fundamental working mechanisms, sensing material design, device architecture optimization, and intelligent system integration. These sensors primarily operate based on changes in electrical resistance induced by interactions between gas molecules and sensing materials, including physical adsorption, charge transfer, and surface redox reactions. In terms of materials, metal oxide semiconductors, conductive polymers, carbon-based nanomaterials, and their composites have demonstrated enhanced sensitivity and selectivity through strategies such as doping, surface functionalization, and heterojunction engineering, while also enabling reduced operating temperatures. Device-level innovations—such as microheater integration, self-heated nanowires, and multi-sensor arrays—have further improved response speed and energy efficiency. Moreover, the incorporation of artificial intelligence (AI) and Internet of Things (IoT) technologies has significantly advanced signal processing, pattern recognition, and long-term operational stability. Machine learning (ML) algorithms have enabled intelligent design of novel sensing materials, optimized multi-gas identification, and enhanced data reliability in complex environments. These synergistic developments are driving resistive gas sensors toward low-power, highly integrated, and multifunctional platforms, particularly in emerging applications such as wearable electronics, breath diagnostics, and smart city infrastructure. This review concludes with a perspective on future research directions, emphasizing the importance of improving material stability, interference resistance, standardized fabrication, and intelligent system integration for large-scale practical deployment.

Keywords: resistive gas sensor; metal oxide; smart sensing; machine learning; material design; device optimization; environmental monitoring



Received: 16 May 2025
Revised: 16 June 2025
Accepted: 18 June 2025
Published: 21 June 2025

Citation: Wang, P.; Xu, S.; Shi, X.; Zhu, J.; Xiong, H.; Wen, H. Recent Advances in Resistive Gas Sensors: Fundamentals, Material and Device Design, and Intelligent Applications. *Chemosensors* **2025**, *13*, 224. <https://doi.org/10.3390/chemosensors13070224>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In recent years, environmental pollution has become increasingly severe, industrial safety accidents occur frequently, and public awareness of health monitoring continues to rise. These factors have created an urgent demand for gas-sensing technologies [1–5]. Gas sensors, capable of real-time monitoring of concentration changes in various target gases

in the air, are widely applied in fields such as air quality monitoring, industrial process safety control, and medical diagnosis [6–10]. Monitoring atmospheric pollutants—such as CO, NO_x, SO₂, and volatile organic compounds (VOCs)—through sensor networks is crucial for air pollution early warning, mitigation, and public health protection [11–13]. In industrial settings, early detection of flammable and toxic gas leaks helps prevent explosions, poisoning, and other accidents [14]. In healthcare, non-invasive disease screening and early diagnosis through the analysis of characteristic VOCs in human exhaled breath have emerged as a promising direction for sensing technologies, although widespread clinical implementation remains a future goal [15,16].

Currently, mainstream gas detection methods rely on high-precision analytical instruments, such as optical sensing, gas chromatography (GC), and mass spectrometry (MS) [17–20]. These technologies offer high sensitivity and selectivity and are widely used for precise gas composition analysis [21–24]. However, such equipment is typically bulky, expensive, and operationally complex, requiring professional maintenance [25,26]. These limitations hinder their suitability for real-time on-site monitoring and large-scale deployment, particularly in applications such as environmental field monitoring and portable safety warning systems.

In contrast to complex instruments, resistive gas sensors have emerged as an attractive alternative due to their low cost and simple structure. Resistive gas sensors operate on the principle that the electrical resistance of a sensing material undergoes significant changes upon exposure to target gases, converting gas concentration into easily measurable electrical signals [27]. Their device structure is typically straightforward: a sensing unit can be constructed by integrating electrodes onto an inert substrate and coating it with a thin film of sensing material, accompanied by relatively simple readout circuitry [28]. Compared with optical sensors requiring complex optical components and electrochemical sensors with liquid electrolyte handling constraints [29], this architecture enables miniaturization potential and scalable manufacturing. Owing to their highly simplified working principle and structure, resistive sensors offer numerous advantages, including low manufacturing cost, compact size, low power consumption, and ease of operation [5,30,31]. Additionally, they can be easily integrated with signal-processing circuits via microelectronic fabrication processes and mass-produced as multi-sensor arrays for simultaneous detection of multiple gases. Due to these advantages, resistive gas sensors have garnered significant attention in recent years and are regarded as a key technology for achieving low-cost and intelligent gas sensing in environmental monitoring and portable gas detection [32].

Despite their promise, resistive sensors exhibit fundamental limitations: baseline drift requires more frequent calibration than electrochemical sensors with solid-state references, while their selectivity underperforms surface-enhanced optical sensing methods [29]. Practical challenges include high power consumption, demanding temperature requirements for optimal performance, poor selectivity leading to cross-interference, signal drift requiring frequent calibration, as well as humidity interference, slow response times, and high detection limits [33–36]. Recent research has made significant progress in material, structural, and algorithmic optimizations. In terms of materials, nanostructured metal oxides (e.g., nanowires and porous particles), doped semiconductors, metal–organic frameworks (MOFs), and other novel sensing materials have improved sensitivity and selectivity while reducing operating temperatures [37,38]. In device design, core–shell heterostructures, MEMS microheaters, and other innovations have enhanced gas reaction efficiency and reduced power consumption. Furthermore, sensor arrays combined with machine learning (e.g., electronic nose technology) have improved gas recognition capabilities, while intelligent algorithms effectively compensate for signal drift and environmental interference. These synergistic advancements have significantly enhanced the overall performance of sen-

sors, making them viable for practical applications in environmental monitoring, industrial safety, and healthcare. Moving forward, further improvements in material stability, power consumption reduction, and anti-interference capabilities remain key research points.

Given these advancements and challenges, this review focuses on “resistive gas sensors”, systematically summarizing recent progress, existing issues, and future directions in the field. To ensure a focused and representative overview of recent advances, we primarily selected high-impact original research articles and authoritative reviews published within the last 7 years, emphasizing significant breakthroughs relevant to the key research areas covered in this review. The article highlights the current state of research on resistive gas sensors in terms of sensing material design, device structure optimization, signal processing, and integration with artificial intelligence, analyzing their respective advantages and limitations (Figure 1). The structure of this review is as follows: Section 2 introduces the composition and design strategies of sensing materials for resistive gas sensors; Section 3 discusses optimization methods for sensor device structures and novel sensing mechanisms; Section 4 summarizes advances in signal-processing techniques and artificial intelligence for gas sensing; and Section 5 provides an outlook on future trends and challenges for resistive gas sensors.

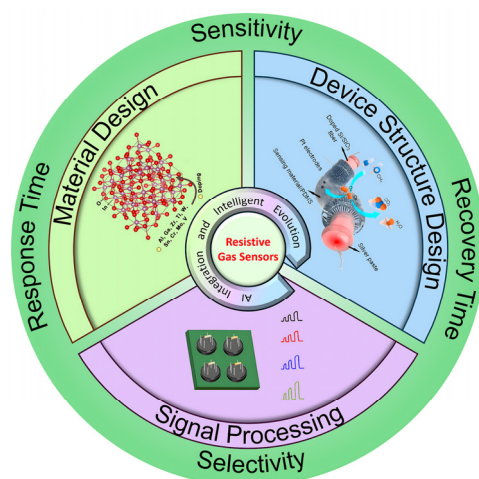


Figure 1. AI-driven resistive gas sensors: evolutionary pathways from materials to signal processing. Reprinted with permission from Ref. [39]. Copyright 2018, American Chemical Society. Reprinted with permission from Ref. [40]. Copyright 2023, Feng Niu et al. Reprinted with permission from Ref. [41]. Copyright 2022, the Authors.

2. Fundamentals of Resistive Gas Sensors

2.1. Working Principle

Resistive gas sensors (also known as chemiresistive sensors) detect gases by measuring changes in electrical resistance caused by interactions between sensitive materials and gas molecules. When target gases diffuse into the sensing layer, gas molecules first adsorb onto the material surface and interact with active sites, altering the charge carrier concentration or mobility of the material and thereby inducing measurable changes in conductivity (or resistance). This resistance variation is processed by signal transduction circuits to achieve quantitative gas detection. In essence, the working principle relies on the reversible modulation of the electrical properties of sensitive materials, where gas concentration information is reflected through changes in electrical signals.

The interaction mechanisms between gas molecules and sensitive materials primarily include physical adsorption, surface redox reactions (chemical adsorption), and charge transfer effects. Physical adsorption relies on van der Waals' forces between gas molecules and the material surface, typically without a chemical bond formation, exhibiting reversible

characteristics. Such interactions have a minor influence on resistance, and their sensing mechanisms are often associated with physical deformation of the material, such as swelling in polymeric materials or changes in the dielectric properties of porous materials [42]. In contrast, chemical adsorption and surface redox reactions involve stronger chemical bonding or electron transfer processes. Taking metal oxide semiconductor (MOS) sensors as an example: in air, oxygen molecules (O_2) adsorbed onto the material surface capture conduction band electrons to form chemisorbed oxygen species (O_2^{2-} or O^-), creating an electron depletion layer on the surface [43]. In the presence of reducing gases (e.g., CO or H_2), these gases react with adsorbed oxygen and release trapped electrons back into the conduction band, leading to increased carrier concentration and decreased resistance in n-type MOS (e.g., SnO_2 , ZnO). For p-type MOS (e.g., NiO and CuO), reducing gases consume hole carriers, resulting in increased resistance. This surface oxygen adsorption–reaction mechanism constitutes the core working principle of traditional MOS gas sensors. The corresponding working principle is illustrated in Figure 2, where Figure 2a shows the electron depletion layer formation and modulation in n-type MOS, and Figure 2b depicts the hole accumulation layer behavior in p-type MOS during interaction with reducing gases [44].

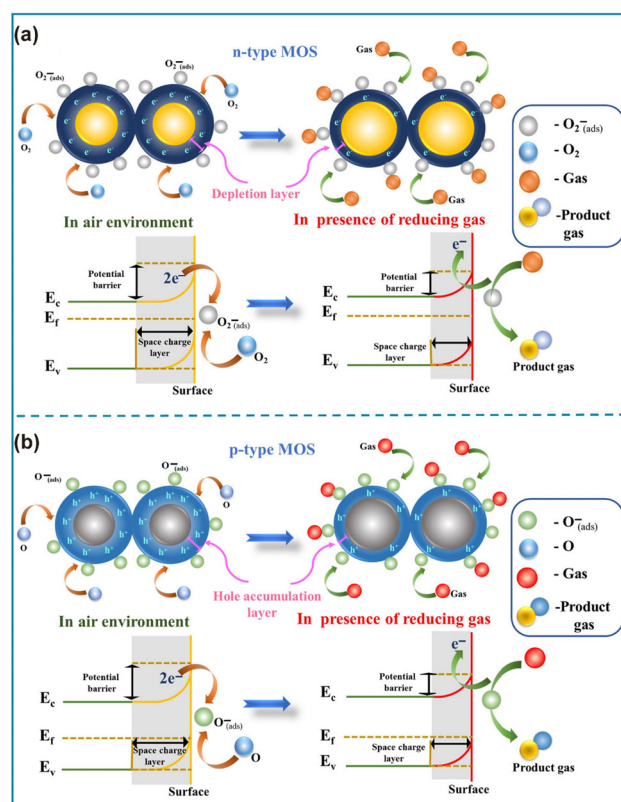


Figure 2. Schematic illustration of the working principle of oxide semiconductor gas sensors: (a) N-type semiconductors in air and reducing gas environments; (b) p-type semiconductors. Reprinted with permission from Ref. [44]. Copyright 2023, Elsevier.

In certain systems, gas molecules directly react with sensitive materials, causing abrupt resistance changes. For instance, H_2S reacts with ZnO at room temperature to form conductive ZnS , drastically reducing sensor resistance and enabling high sensitivity to H_2S [45]. Beyond adsorption and redox processes, charge transfer effects play a critical role in low-dimensional nanomaterials (e.g., graphene, carbon nanotubes, and transition metal dichalcogenides) and organic semiconductor sensors. In such mechanisms, gas molecules act as electron donors (e.g., NH_3) or acceptors (e.g., NO_2), exchanging electrons with the

material and producing a chemical doping-like effect [46]. For example, NO₂ adsorption withdraws electrons from graphene, reducing carrier concentration and increasing resistance, whereas NH₃ adsorption donates electrons, enhancing conductivity [47]. Additionally, in composite materials, gas adsorption may influence overall resistance by altering interparticle conductive pathways (e.g., contact resistance changes) [48]. Researchers summarize the most commonly cited mechanisms for sensor performance enhancement [49]. These diverse sensing mechanisms enable resistive gas sensors to achieve high selectivity and sensitivity for various gas detection applications.

2.2. Classification

Resistive gas sensors can be classified in various ways according to different dimensions. Common classification methods include categorization by sensitive material type, output signal form, and device structure form. Below is a brief introduction to each classification method and its characteristics.

2.2.1. Classification by Sensitive Material Type

The performance of resistive gas sensors highly depends on the physicochemical properties of sensitive materials. According to the type of sensitive material, resistive sensors can be divided into four major categories: semiconductor type, composite type, organic type, and carbon-based material type. These different material types exhibit significant differences in gas-sensing mechanisms and operational characteristics.

Semiconductor sensors can be further classified into n-type and p-type based on their carrier type; n-type semiconductors, such as SnO₂, ZnO, and Fe₂O₃, regulate resistance through electron depletion layers formed by surface oxygen adsorption. Reducing gases (e.g., H₂ and CH₄) decrease their resistance, while oxidizing gases (e.g., NO₂ and O₃) increase resistance. The response values for strong reducing gases can reach 10²–10⁴, while for gases like CO₂ the response values are only around 1–2. The specific response value is related to many factors, including gas type, concentration, and operating temperature. However, they require operation at 200–400 °C [50]. p-type semiconductors (e.g., NiO, Co₃O₄, and CuO) are dominated by hole conduction, showing opposite response patterns to n-type semiconductors and exhibiting higher selectivity for oxidizing gases. For example, NiO-based sensors can achieve a response value of 15.7 to 10 ppm NO₂ at 300 °C [51].

To optimize performance, researchers construct n–n, p–p, or n–p heterojunctions (e.g., SnO₂/Co₃O₄ or CuO/ZnO) to regulate band structures. The space charge regions formed at heterointerfaces can reduce activation energy (from 1.2 eV to 0.8 eV), improving response speed by 30–50% [49]. For instance, the MXene/TiO₂ composite system shows a response of 247% to 100 ppm NH₃, which is nearly 8 times higher than pure TiO₂ [52].

Additionally, organic materials such as polyaniline and polypyrrole achieve room-temperature detection by changing doping levels through redox reactions. PANI-based sensors show a response time of 12 s to 1 ppm NH₃, but their humidity sensitivity ($\Delta R/R_0 > 20\%$ at 70%RH) needs to be suppressed through PVDF composite modification [53]. Carbon-based materials like graphene and carbon nanotubes are also suitable for room-temperature detection due to their ultra-high carrier mobility (>10,000 cm²/V·s) and specific surface area (2630 m²/g) [54]. Functionalized CNTs show a response of 35% to 50 ppm NO₂ but require Au nanoparticle decoration to shorten recovery time. Recent studies show that graphene/cobalt phthalocyanine hybrid materials can significantly improve acetone selectivity, with a selectivity coefficient reaching 8.7, providing new ideas for designing high-performance gas sensors [55]. Table 1 provides a comparative overview of the gas-sensing performance of different material types under various conditions. It

highlights the diversity in sensing capabilities and the influence of material properties on sensor performance.

Table 1. Gas-sensing performance of representative materials for resistive sensors.

Type	Materials	Analyte Gas/ Concentration (ppm)	T (°C)	Response	$\tau_{\text{res}}/\tau_{\text{rec}}$ (s)	Refs.
n-type	SnO ₂	CO ₂ /1000	400	1.14	-	[56]
	ZnO	CO ₂ /400	350	2.86	75/108	[57]
p-type	NiO	NO ₂ /10	300	15.7	-	[51]
	CuO	CO ₂ /100	RT	1.04	10/6	[58]
organic	PANI-based	NH ₃ /1	RT	-	12/-	[53]
carbon-based	graphene	CO ₂ /100	RT	1.26	8/10	[59]
	CNT	CO ₂ /500	RT	1.09	33/46	[54]

In summary, while semiconductor materials offer high sensitivity and well-established fabrication, they typically require elevated operating temperatures. Organic and carbon-based materials enable room-temperature operation but often face challenges with humidity interference and long-term stability. Composite materials, leveraging synergistic effects, show promise in addressing these limitations and enhancing overall performance. Future research should further explore material interface engineering and microstructure regulation to address key issues such as selectivity and stability.

2.2.2. Classification by Device Structure Form

As shown in Figure 3, resistive gas sensors can be divided into two typical technical forms according to hardware architecture [60]. Single-element sensors use a single sensitive component (e.g., metal oxide semiconductor) to construct an independent sensing unit, featuring compact structure and high sensitivity, but being susceptible to cross-sensitivity. Array sensor systems integrate 4–8 sensing elements with differentiated responses (e.g., SnO₂/ZnO heterojunctions or temperature gradient configurations), and combined with algorithms such as PCA or CNN, can achieve multi-component gas identification with accuracy reaching 94.7%. However, their performance depends on strict component calibration and periodic calibration [61].

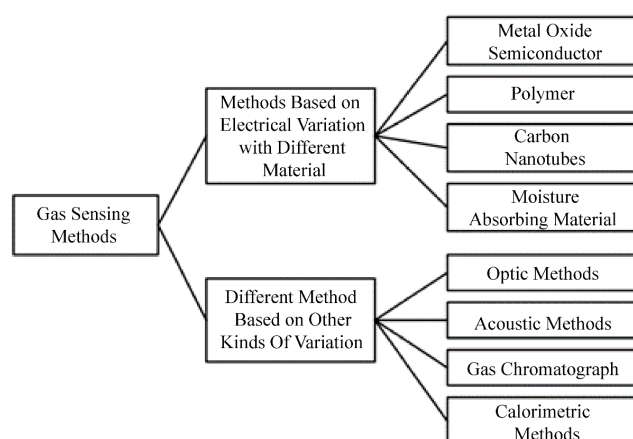


Figure 3. Classification of gas sensor architectures. Reprinted with permission from Ref. [60]. Copyright 2012, MDPI.

Multimodal smart sensors utilize MEMS technology to achieve three-dimensional integration of resistive sensing units with auxiliary modules such as temperature, humidity, and optical sensing, significantly enhancing detection performance [62]. For instance, breath

analysis systems integrating gas-sensitive arrays and humidity compensation modules reduce acetone detection error from 22.3% to 8.7% [51]. Intelligent microsystems employ multi-parameter fusion algorithms, such as the D-S evidence theory, improving formaldehyde recognition specificity to 89.2% [63]. However, such sensors still face challenges, including signal synchronization delays and the need for further power consumption optimization. Overall, single-element sensors provide simplicity and high sensitivity for single-target detection but suffer from cross-sensitivity. Array sensors, through diversified sensing elements and pattern recognition, enable multi-gas discrimination at the cost of increased complexity and calibration needs. Multimodal smart sensors represent the most advanced form, integrating complementary sensing modalities and intelligence for enhanced accuracy and functionality in complex environments, albeit with higher system complexity and power consumption.

Currently, gas sensors are evolving toward system-on-chip (SoC) integration, adaptive calibration (AIoT), and multi-physics coupling (e.g., resistive-photoelectric synergy). However, key technologies such as standardized manufacturing and edge computing algorithms still require breakthroughs [64]. The development of third-generation smart sensors will focus more on environmental adaptability, low-power design, and multimodal data fusion to meet the demand for high-precision gas detection in complex scenarios.

2.3. Performance Evaluation of Sensors

Comprehensive performance assessment of resistive gas sensors requires the establishment of a multi-dimensional indicator system, encompassing core parameters such as sensitivity, selectivity, dynamic response characteristics, long-term reliability, and detection capability. These indicators are interrelated yet mutually constraining, collectively determining the sensor's applicability in practical scenarios.

2.3.1. Sensitivity

Sensitivity typically describes the response intensity of a sensor to target gases, quantitatively defined as the change in output signal per unit gas concentration. For resistive sensors, sensitivity is experimentally expressed as the relative change in resistance between target gas exposure and clean reference gas conditions. Sensitivity reflects the sensor's "signal amplification" capability for given gas concentrations; higher sensitivity indicates significant resistance changes even at low gas concentrations. Multiple strategies in material science and device design are employed to achieve high sensitivity. For instance, nanostructured materials with high specific surface area provide more active sites for gas interaction, generating greater resistance changes. Incorporating catalysts such as noble metal nanoparticles can reduce activation energy for target gas reactions, thereby amplifying response signals [40]. Additionally, operating temperature selection affects sensitivity, where elevated temperatures generally enhance gas-surface reaction rates, but excessive temperatures may reduce surface adsorption, necessitating experimental optimization to identify the optimal value [25]. Sensitivity testing typically involves measuring response curves across a series of known gas concentrations, with quantification based on slope or response amplitude at specific concentrations. Notably, sensitivity often exhibits nonlinear attenuation with increasing concentration, thus requiring explicit specification of applicable concentration ranges during evaluation.

2.3.2. Selectivity

Selectivity refers to a gas sensor's ability to distinguish target gases while suppressing interference from other gases. Ideally, sensors should exhibit high sensitivity to target gases with minimal response to interfering species. Selectivity is evaluated by comparing response amplitudes across different gases, where higher ratios between target and interfer-

ing gas responses indicate better selectivity. Enhancing selectivity remains a key challenge in gas sensor research.

Current approaches include: (1) chemical modification and catalytic selection, incorporating catalysts or adsorption films that preferentially react with target gases [65]; (2) operational condition modulation, such as temperature cycling operation (TCO) that exploits differential gas responses across temperatures combined with pattern recognition algorithms [25]; and (3) signal pattern recognition using sensor arrays to obtain multi-dimensional response data analyzed through machine learning for gas mixture identification [66]. Practical testing validates selectivity by exposing sensors to various interfering gases and recording responses. High-performance gas sensors require both high sensitivity and selectivity to ensure that outputs exclusively reflect target gas concentrations without background interference.

Recent advances in gas sensor technology have introduced novel materials and structures to enhance selectivity. For example, Zhang et al. explored the use of metal oxide semiconductors with unique crystal structures and morphologies, such as SnO₂-based sensors doped with specific elements and structured into hierarchical nanostructures, which showed improved selectivity for CO₂ [67]. These structural modifications not only increase the surface area for gas adsorption but also create specific active sites that favor reactions with target gases.

Another promising approach is the development of core-shell nanostructures, as demonstrated by Xie et al., who synthesized In₂O₃@Co₃O₄ core-shell nanofibers via coaxial electrospinning. These nanofibers exhibited excellent selectivity for triethylamine (TEA) due to their unique core-shell architecture and p-n heterojunction, which provided additional active sites and facilitated electron transfer, enabling effective distinction of TEA from other similar gases [68].

Chojer et al. highlighted the potential of sensor arrays combined with pattern recognition algorithms in improving selectivity. By analyzing the multi-dimensional response data from an array of sensors with varying selectivities using machine learning techniques, it is possible to identify and quantify individual gases within complex mixtures, even in the presence of interfering species. This strategy moves beyond the limitations of single-sensor models and offers a more robust solution to the selectivity challenge [69].

Environmental factors, such as humidity and temperature, can significantly impact sensor selectivity. Zhang et al. noted that high humidity could lead to false responses in some metal oxide gas sensors due to water molecule adsorption on the sensor surface. To address this, researchers have investigated surface modification and the use of hydrophobic materials to reduce humidity interference and enhance selectivity [67].

In summary, while significant progress has been made in improving the selectivity of resistive gas sensors, ongoing research is necessary to explore innovative material designs, optimize sensor array configurations, and advance data analysis techniques. These efforts aim to achieve higher levels of selectivity in gas-sensing applications, ensuring that sensor outputs accurately reflect target gas concentrations without interference from background gases.

2.3.3. Response and Recovery Time

Response time is defined as the duration required for sensor resistance to reach 90% of its final change upon target gas exposure, while recovery time represents the period needed for resistance to return to 90% of its initial state after gas removal. Response time reflects detection speed, whereas recovery time indicates signal clearance capability. Rapid response and recovery are critical for real-time monitoring applications, such as safety alerts where fast response enables early leak detection and quick recovery prepares

sensors for subsequent measurements. Four primary factors influence response/recovery kinetics according to the gas diffusion and reaction kinetics theory: (1) pore structure and specific surface area of sensing materials determine gas molecule transport rates to active sites, with nanoporous structures typically accelerating response [70]; (2) reaction activation energy, where catalysts or elevated temperatures enhance surface reaction rates to shorten response times [71]; (3) gas concentration effects, where higher concentrations may accelerate response times but cause strong adsorption that delays recovery [72]; and (4) temperature and humidity impacts molecular motion and reaction rates, though excessive temperatures may reduce material activity.

Standard testing employs gas switching experiments: sudden gas introduction records resistance changes to calculate 90% stabilization time as response time, while subsequent air switching measures 90% resistance recovery as recovery time. High-performance sensors typically exhibit response/recovery times ranging from seconds to tens of seconds, depending on materials and gas species.

3. Key Technological Advancements

3.1. Material Design

In material design, representative modification strategies for enhancing gas-sensing performance include doping, surface functionalization, composite material design, and heterojunction construction. Doping involves introducing trace impurity elements or compounds into sensitive materials to modulate their band structure and surface chemical properties [73]. For example, incorporating noble metal catalysts (e.g., Pt, Pd, and Au) into n-type metal oxides can promote oxygen molecule adsorption and dissociation. Liu et al. demonstrated the preparation of Au-decorated SnO₂ nanobelts with different wt% Co doping via chemical vapor deposition (CVD). The study showed that the 1.5 wt% Co-doped Au-Co-SnO₂ sensor exhibited optimal gas-sensing performance for 1-butanol, with the highest response increasing from 41 to 793, which is nearly a 20-fold enhancement. The optimal operating temperature was reduced from 340 °C to 280 °C. This performance enhancement is primarily attributed to the increased surface-active sites caused by oxygen vacancies formed by doping, which promotes additional oxygen adsorption and dissociation, thus improving the overall sensitivity of the sensor [74]. Additionally, doping-induced Fermi level shifts or Schottky barrier effects amplify resistance changes triggered by gas adsorption [43]. As shown in Figure 4a, Zou et al. demonstrated that doping Al, Ga, or Zr into In₂O₃ shifts the Fermi level upward, enhancing electron donation and formaldehyde response, while doping Ti, Mo, Sn, or V lowers the Fermi level and deteriorates sensing performance [39].

Surface functionalization enhances gas molecule recognition by chemically modifying the sensitive material surface with specific functional groups or promoters.

A compelling example is the work by Wang et al. [75], who synthesized hollow MoS₂/C nanomaterials and decorated them with Au nanoparticles (NPs). Their Au@MoS₂/C sensor demonstrated a significantly enhanced response of 240.5 to 50 ppm triethylamine (TEA) at 160 °C compared with MoS₂/C alone, along with accelerated response and recovery times (reduced from 80 s/500 s to 13 s/198 s).

To elucidate the underlying mechanisms responsible for this performance enhancement, Wang et al. proposed the following dual role for the Au NPs (as depicted in Figure 4b,c [75]):

- (i) Au NPs increased the thickness of the electron depletion layer on the MoS₂/C surface (Figure 4b), thereby enhancing the adsorption capacity for oxygen molecules and providing more active sites for the TEA sensing reaction. This mechanism is crucial for achieving a high response magnitude.

- (ii) Concurrently, the Au NPs formed Schottky contacts with MoS₂ (Figure 4c), facilitating an efficient electron transfer at the interface. This accelerated charge transfer kinetics directly contributes to the observed reduction in response and recovery times [75].

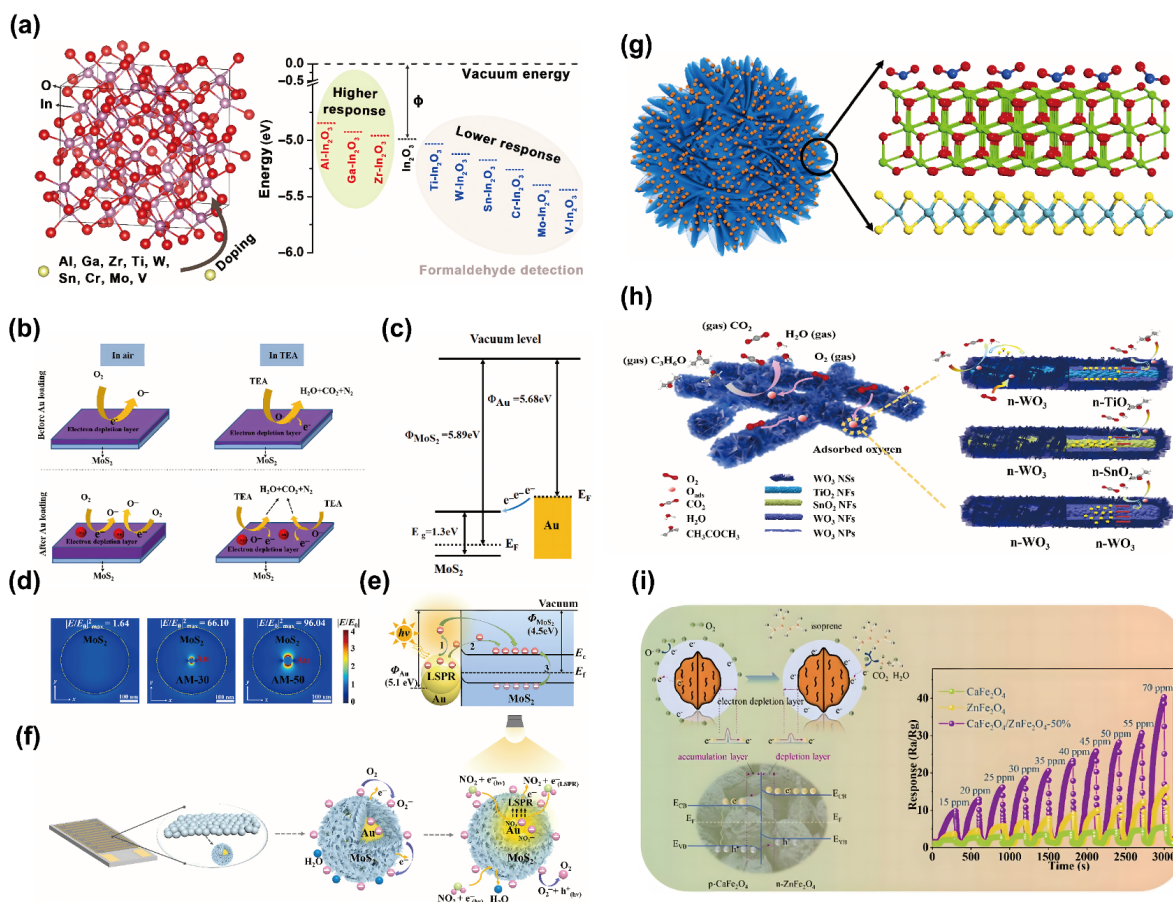


Figure 4. Material design strategies for resistive gas sensors: (a) Schematic diagram of metal heteroatom-doped In₂O₃ and the corresponding Fermi level. Reprinted with permission from Ref. [39]. Copyright 2018, American Chemical Society. (b) Electron depletion layer in air and TEA before and after Au loading and (c) the energy band structures of Au and MoS₂. Reprinted with permission from Ref. [75]. Copyright 2024, Elsevier. (d) Normalized electric field maps on MoS₂, AM-30, and AM-50; (e) schematic diagram of electron transfer paths of AM-50 under light excitation; (f) schematic illustration of the NO₂-sensing mechanism of the white-light-assisted AM-50 gas sensor. Reprinted with permission from Ref. [76]. Copyright 2023, Elsevier. (g) Schematic illustration of the sensing mechanism of the CeO₂/MoS₂ composite. Reprinted with permission from Ref. [77]. Copyright 2024, Elsevier. (h) Schematic illustration of the gas-sensing mechanism for the nanocomposite. Reprinted with permission from Ref. [78]. Copyright 2024, Elsevier. (i) Gas-sensing mechanism and energy band structure of the CaFe₂O₄/ZnFe₂O₄ composite. Reprinted with permission from Ref. [79]. Copyright 2021, Elsevier.

Beyond this specific case, surface functionalization strategies include plasma oxidation of graphene to introduce polar groups for adsorbing polar gases [80], grafting specific molecules onto carbon nanotubes for selective recognition [81], and loading ultrathin catalyst layers as molecular sieves to block interferences while targeting specific gases.

Heterojunction construction is one of the cutting-edge strategies for enhancing semiconductor gas-sensing performance. Heterojunctions typically involve the intimate contact of two semiconductor materials with different band structures, including n–n, p–p, and p–n types. At the heterojunction interface, the difference in Fermi levels between the two materials generates a space charge region. Target gas adsorption modulates this

interfacial potential, superimposing an additional response beyond that of individual components and often producing more pronounced resistance changes than single materials. Combining p-type and n-type semiconductor oxides not only complements their gas recognition advantages but also stabilizes conductivity through the interfacial charge redistribution [72]. Consequently, composite sensing materials with heterojunctions typically exhibit higher sensitivity. Moreover, the unique interfacial interaction mechanisms can improve selectivity toward specific gases. For instance, $\text{CaFe}_2\text{O}_4/\text{ZnFe}_2\text{O}_4$ p–n heterojunction composites with a porous walnut-like structure have demonstrated excellent sensing performance for toxic isoprene gas, achieving a high response ($S = 19.50$ to 30 ppm), low operating temperature (200°C), rapid response–recovery times (~ 72 – 35 s), and an ultra-low detection limit of 0.12 ppb. These superior properties are attributed to enhanced electron–hole separation, reduced charge transfer resistance, high oxygen vacancy content, large BET surface area, narrowed band gap, and effective heterojunction formation, highlighting the significant advantages of heterostructure engineering in gas sensor design [79]. Synergistic effects at the interface may also lower the operating temperature and accelerate response/recovery kinetics due to faster charge transfer across the heterojunction. Hu et al. constructed an Au@MoS_2 core–shell nanostructure as an example of the heterojunction strategy [76]. This structure utilizes the localized surface plasmon resonance (LSPR) effect of gold nanoparticles to significantly enhance the light absorption efficiency of MoS_2 under visible light assistance. As shown in Figure 4d–f, the Au@MoS_2 core–shell structure forms unique electron transfer pathways at the heterojunction interface, including plasmon-induced hot electron transfer, plasmon-mediated interfacial charge transfer transitions, and plasmon-activated carrier generation. These mechanisms not only increase the number of photo-generated carriers but also promote the adsorption and reaction of NO_2 molecules on the surface of MoS_2 . Consequently, this heterojunction gas sensor demonstrates exceptional overall performance in detecting NO_2 under indoor white light illumination, including a ppb-level detection limit (25 ppb), significantly enhanced sensitivity (response increased more than 8 times), full recoverability (with recovery rates reaching 98%), excellent selectivity, and robust stability, which fully embodies the advantages of the heterojunction strategy in enhancing gas sensitivity. The edge-enriched $\text{CeO}_2/\text{MoS}_2$ heterostructure (Figure 4g) developed by Zhang et al. [77], significantly enhances NO_2 sensing. The sensing response to 5 ppm NO_2 is 1033% and 450% higher than that of pure CeO_2 and MoS_2 , respectively. It also achieves a low detection limit of 1 ppm, a high recovery rate of over 90%, and excellent long-term stability and selectivity at room temperature. These improvements are mainly due to the synergistic effects of the heterojunction, including strong adsorption, abundant adsorption sites, and a coupled interface. First-principle calculations show that CeO_2 has a more negative binding energy for NO_2 than MoS_2 , indicating CeO_2 acts as the main adsorption center while MoS_2 provides the conductive path. As MoS_2 's Fermi level is closer to the vacuum level, electrons transfer from MoS_2 to CeO_2 at the interface. This forms an electron accumulation layer on CeO_2 , promoting electron exchange between NO_2 and the sensor and enhancing the NO_2 sensing response.

Composite material design combines materials with different properties (via physical mixing or in situ growth) to form novel sensing media with synergistic enhancement effects. For example, composites of metal oxide nanoparticles with graphene or carbon nanotubes leverage the high conductivity of carbon materials and the abundant active sites of metal oxides [82]. Organic–inorganic composites, such as conductive polymers mixed with metal oxides or nanocarbon materials, improve mechanical strength, conductivity, and gas diffusion properties [53]. Liao et al. developed 1D hierarchical core–shell MOS@WO_3 nanocomposites where TiO_2/WO_3 sensors demonstrated a response value of 23.6 to acetone, a detection limit of 10 ppb, and rapid response–recovery times of 12.0 s and 35.5 s

(Figure 4h) [78]. This performance enhancement is attributed to TiO_2 's high specific surface area and active sites, combined with WO_3 's high catalytic activity and stability, optimizing gas adsorption and charge transfer. Guo et al. fabricated $\text{CaFe}_2\text{O}_4/\text{ZnFe}_2\text{O}_4$ composites, achieving a high isoprene response (19.50), and a $6.3\times$ and $2.9\times$ improvement over pure CaFe_2O_4 and ZnFe_2O_4 , with a detection limit of 0.12 ppb (Figure 4i) [79]. This strategy combines p-type CaFe_2O_4 and n-type ZnFe_2O_4 , leveraging their different conductivity types for efficient charge transfer and enhanced sensor response and stability. These examples demonstrate that combining different materials can enhance gas sensor performance through complementary properties.

In summary, the flexible application of these material modification strategies can significantly enhance sensor sensitivity, selectivity, and stability. Researchers can select or combine these methods based on application requirements to develop high-performance resistive gas sensors.

3.2. Device Structure Design

In addition to the material itself, the structural parameters of gas-sensitive devices also have a significant impact on performance. By optimizing the geometric structure and integration methods of sensors, key metrics such as gas diffusion conditions, response speed, and device power consumption can be improved.

3.2.1. Thickness Control of Sensitive Films

The thickness of the sensitive film directly affects the diffusion depth of gas molecules and the reactive volume within the material. Thinner films facilitate gas interaction throughout the entire material, allowing more charge carriers to participate in surface reactions, thereby enhancing sensitivity. In semiconductor metal oxide sensors, when the film thickness is comparable to the Debye length, the space-charge region formed by gas adsorption nearly penetrates the entire film, resulting in significant resistance changes and maximum sensitivity enhancement. Recent studies on the WS_2 -ZnO p-n heterojunction nanosheet-based gas sensors demonstrate this principle: by depositing ZnO layers of different thicknesses (10–50 nm) on WS_2 nanosheets using atomic layer deposition (ALD), researchers found that sensors with 10 nm ZnO layers exhibited optimal responses to reducing gases (e.g., NH_3) at 150 °C, where WS_2 dominated the gas-sensing process through an enhanced interfacial charge transfer (Figure 5a). Conversely, at 300 °C, sensors with 30 nm ZnO layers showed superior performance, indicating the predominant role of ZnO in high-temperature sensing environments [83]. Conversely, excessively thick films hinder gas penetration into deeper layers, limiting reactions to the surface and leaving internal sensitive material underutilized. This not only fails to improve sensitivity but also significantly delays the response time due to prolonged diffusion paths. Studies indicate that nanoscale thin-film sensing materials exhibit an optimal thickness that balances sensitivity and response time, beyond which device performance degrades [84]. These findings demonstrate that the optimal thickness of sensitive films requires co-optimization with operating temperature and material properties. Additionally, film thickness influences sensor noise levels and stability, necessitating precise deposition techniques such as spraying, spin-coating, sputtering, or atomic layer deposition to ensure consistency and reliability across devices.

3.2.2. Electrode Spacing Design

Recent studies further demonstrate the synergistic effects of electrode spacing and interdigitated electrodes optimization. An In_2O_3 -based resistive gas sensor achieved ultrasensitive H_2S detection by tuning interdigitated electrode spacing (Sf) and finger number (Nf) [85]. When Sf decreased from 100 μm to 2 μm (corresponding to Nf increasing from 2 to 30), the detection limit improved dramatically from 8380 ppb to 6.42 ppb. This

enhancement stems from two mechanisms: (1) smaller S_f shortens carrier transport paths in the sensing layer, increasing the contribution of contact resistance (RC) to gas response from 17% to 68% and (2) the parallel electric field distribution in interdigitated structures suppresses current crowding effects, reducing normalized low-frequency noise (LFN) by two orders of magnitude compared to conventional parallel electrodes. The optimized sensor exhibits a 300-fold improvement in the signal-to-noise ratio (SNR) while maintaining sub-milliwatt power consumption, highlighting the capability of electrode geometry to co-regulate sensitivity, noise, and energy efficiency.

Another representative case involves an ammonia gas sensor based on a cross-linked ZnO nanorod (NR) configuration [86]. The study systematically investigated the impact of interdigitated electrode spacing (d) on NH_3 sensing performance (Figure 5b). As the electrode spacing (d) decreased from 50 μm to 2 μm , a remarkable transition in ZnO NR growth patterns was observed; at larger spacing (50 μm), the nanorods exhibited highly ordered alignment (well-aligned ZnO NRs), with their regular architecture clearly visible in the foreground region of Figure 5b. When the spacing was reduced to 2 μm , spatial confinement during growth induced the formation of densely cross-linked networks, as demonstrated in the background region of Figure 5b. This electrode spacing-driven structural evolution directly enhanced the ammonia response (S)—sensors with 2 μm spacing achieved a maximum response value of 81.6 upon exposure to 1000 ppm NH_3 /air at 573 K, coupled with a detection limit as low as 10 ppm. The performance enhancement primarily stems from the multiplicative effect of potential barrier contact points (point-to-point) in cross-linked architectures, while the comparative analysis in Figure 5b explicitly reveals the governing role of electrode spacing in modulating the microstructural morphology of sensing materials. It was demonstrated that reducing electrode spacing not only optimizes charge transport pathways through geometric confinement but also intensifies surface interactions between gas molecules and active materials, thereby improving synergistically both sensitivity and response kinetics.

The geometric arrangement of sensor electrodes significantly impacts sensing performance by influencing the electric field distribution and conductive pathways in sensitive material. In the interdigitated electrode structure commonly used in resistive gas sensors, the electrode spacing determines the distance the sensitive film must bridge. Excessive spacing requires thicker, more uniform films or long one-dimensional nanostructures to establish conductive pathways between electrodes, increasing fabrication complexity and baseline resistance. Smaller electrode spacing, however, enables conduction with less material, effectively reducing baseline resistance [87]. In single-nanowire/nanotube-based gas sensors, electrode spacing directly determines nanowire length and resistance. Larger spacing increases nanowire length, allowing self-heating under bias to reach reaction temperatures without external heating, significantly reducing power consumption. Studies show that increasing electrode spacing to tens of micrometers enables self-heated In_2O_3 nanowire sensors to achieve milliwatt-level power consumption while maintaining sensitive detection of target gases [88]. Thus, electrode design must balance sensitive material coverage and power consumption, optimizing spacing to maximize sensor performance.

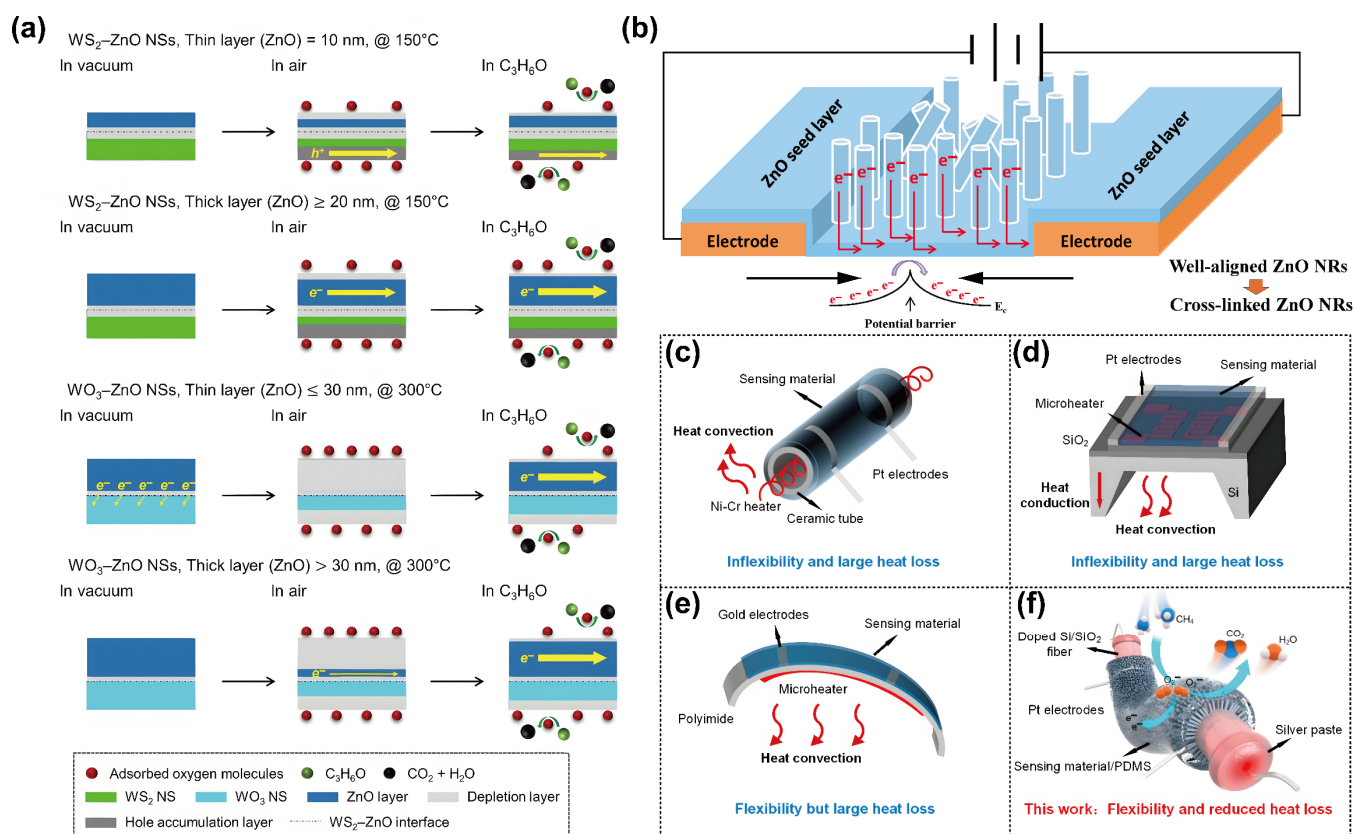


Figure 5. Device structure design strategies for resistive gas sensors. **(a)** Schematically illustrates the thickness-dependent sensing mechanisms of WS₂-ZnO heterojunctions, where the charge transfer processes between WS₂ nanosheets and ZnO layers (10 nm vs. >10 nm) dictate their acetone detection performance under different operating conditions. Reprinted with permission from Ref. [83]. Copyright 2024, Elsevier. **(b)** Structural transition of ZnO nanorod assemblies and current pathway modulation driven by reduced interdigitated electrode spacing. Adapted with permission from Ref. [86]. Copyright 2015, Elsevier. **(c–f)** Integrated microheater designs on different substrates. Reprinted with permission from Ref. [40]. Copyright 2023, Feng Niu et al.

3.2.3. Sensor Array Integration

To expand the detection range and reliability, multi-element sensor arrays are often employed to construct gas detection systems. Multiple sensing units with different sensitive materials or operating parameters can be integrated on a single substrate to form a matrix array, enabling simultaneous detection of multiple gases. Such arrays provide composite response signals for complex gas mixtures, improving identification accuracy through combined analysis [89]. Array design must consider unit layout and spacing to ensure full exposure to the test atmosphere without cross-interference. Highly integrated electronic nose systems may incorporate dozens of gas sensors on a single chip, achieving miniaturization and high-throughput detection via microfabrication. Integration also requires careful connection and packaging design to minimize parasitic effects and external interference on channel consistency. Additionally, arrays often include reference elements or auxiliary sensors for calibration and compensation, enhancing overall system accuracy and stability.

3.2.4. Integrated Microheater Design

For gas-sensitive materials requiring high-temperature operation, integrated microheaters are essential. Optimized microheaters provide uniform, controllable heating with minimal power consumption. Suspended membrane structures with low thermal capacity

and excellent thermal isolation enable rapid heating to target temperatures, significantly accelerating sensor startup and recovery. Well-designed heater resistor shapes ensure uniform heating of sensitive films, avoiding localized hot or cold spots to improve signal stability and repeatability. Integrated microheaters also enable flexible operation at varying temperatures, such as programmed heating or cyclic temperature modulation, to obtain characteristic responses for different gases [90]. In recent years, the synergistic design of flexible substrates and low-power microheaters has further propelled the development of wearable gas sensors. As illustrated in Figure 5c–e, contrary to conventional rigid architectures (e.g., ceramic tubes or MEMS substrates) that suffer from high thermal inertia (>15 mW) and fracture risks under bending, the p-Si/SiO₂ fiber-based platform developed by Niu et al. achieves sub-5 mW operation through integrated Joule heating and PDMS-encapsulated Co-ZnO nanorod arrays (Figure 5f), demonstrating a 16% response to 1000 ppm CH₄ with 10,000-cycle bend durability [40]. The PDMS encapsulation synergizes with the microheater to enhance thermal isolation, reducing power consumption while protecting the sensing material (Co-ZnO nanorod arrays) from mechanical and environmental degradation. Experimental results show a 16% response to 1000 ppm CH₄ at 50 °C operating temperature, with a power consumption of 3.2 mW/mm and response/recovery times of 350 s and 106 s, respectively. Remarkably, the sensor maintains stable performance under 10,000 bending cycles and high humidity ($>85\%$ RH), validating its suitability for practical wearable scenarios. This case study highlights that integrating microheater substrate materials (e.g., flexible fibers) with low-heat-capacity composite structures can significantly improve thermal management efficiency while balancing mechanical flexibility and environmental robustness. Overall, advanced integrated microheater designs are driving gas sensors toward low power consumption, rapid response, and high integration. Innovations in materials (e.g., low-heat-capacity suspended membranes) and fabrication techniques (e.g., flexible substrate compatibility) enable efficient thermal management at reduced energy budgets, alongside accelerated response times and enhanced device compactness. These advancements lay the technical foundation for practical applications of portable and wearable gas sensors, particularly in environmental monitoring, medical diagnostics, and industrial safety.

3.3. Signal Processing

High-performance gas sensors rely not only on improvements in materials and structures but also require effective signal-processing and self-calibration technologies to maintain reliable and stable outputs in complex environments. Resistive gas-sensing elements often encounter issues such as baseline drift, sensitivity attenuation, and interference from temperature and humidity fluctuations during prolonged operation. To address these challenges, a series of signal-processing methods have been developed to enhance sensor reliability, stability, and repeatability.

3.3.1. Multivariate Response Pattern Decoding

The composite signals generated by sensor arrays (Section 3.2.3) require advanced decoding algorithms to extract gas-specific features. By combining responses from multiple sensors into patterns, the type and concentration of gases can be identified through analysis. For example, the spatial distribution of sensing units in the array can be mapped to the dimensionality of response patterns, enabling PCA to separate overlapping gas signatures [41]. This multivariate pattern decoding improves the selectivity and reliability of gas detection, enabling accurate identification of target gases even in the presence of interference based on comprehensive response profiles.

3.3.2. Response Drift Compensation

Gas sensors often exhibit baseline and sensitivity drift over prolonged operation. To ensure accurate readings, drift compensation is necessary. Common methods include periodic recalibration of the zero point in clean air and real-time algorithmic subtraction of drift components [91]. For example, a reference sensor unaffected by the target gas can be used, or drift models based on historical data can be established to correct current signals. These measures ensure that the sensor output remains consistent with the initial calibration state even after long-term operation, significantly improving long-term stability and result comparability.

3.3.3. Baseline Normalization and Dynamic Calibration

Baseline normalization standardizes sensor responses relative to their zero-point reference, eliminating baseline variations between different sensors or measurement cycles and reducing errors caused by baseline drift. Dynamic calibration involves periodic adjustment of sensor outputs during operation to maintain alignment with standard values. Common practices include periodic recalibration using standard gases of known concentrations or resetting the zero point using purified air [92]. Through baseline normalization and dynamic calibration, even during prolonged continuous operation and under varying environmental conditions, sensor outputs can be corrected to accurate and trustworthy levels, greatly enhancing measurement reliability and traceability.

In conclusion, significant progress has been made in resistive gas sensors through innovations in material design (e.g., catalytic functionalization and heterojunction engineering), device structure optimization (e.g., thin films and electrode spacing), and intelligent signal processing, these advancements inherently involve trade-offs between key performance metrics. The pursuit of high sensitivity often adversely affects selectivity. Achieving both high sensitivity and selectivity typically requires elevated operating temperatures, presenting a fundamental conflict with the critical need for low power consumption. Furthermore, structural designs aimed at accelerating response may compromise long-term stability. Addressing these fundamental constraints requires future research focused on the strategic co-design of materials, device architectures, and algorithms. This integrated approach is essential to effectively balance the competing demands of sensitivity, selectivity, response kinetics, stability, and power efficiency for diverse application scenarios.

4. AI Integration and Intelligent Evolution

With the continuous development and iteration of the Internet of Things (IoT), smart appliances, and machine learning software, resistive gas sensors have gradually become crucial electronic components, integrating communication technologies and artificial intelligence to serve people's work and daily lives [1]. Over the past two decades, machine learning has provided robust support for developing novel materials for resistive gas sensors, with numerous advanced materials being designed through both supervised and unsupervised learning paradigms [93]. Intelligent resistive gas sensors have increasingly emerged as efficient tools in fields such as healthcare, precision analysis, and safety monitoring [94]. In the healthcare sector, smart resistive gas sensors have achieved flexibility, functioning as wearable devices for personal health monitoring and activity tracking. Furthermore, they are progressively being integrated into telemedicine through IoT-enabled medical equipment. In precision analysis, gas sensors are not only utilized in pharmaceutical research but also in clinical applications such as dental care. In the field of safety monitoring, resistive gas sensors are employed in remote gas leakage early-warning systems [95] and industrial safety alarms [96], providing reliable safeguards for industrial production.

4.1. Machine Learning-Assisted Design of Novel Material Compositions

The foundation of intelligent gas sensors lies in advanced material design. Machine learning has revolutionized this process by enabling predictive modeling and high-throughput screening of sensing materials, which in turn enhances the performance of downstream AI-driven systems. This subsection focuses on material-level selectivity enhancements achieved through machine learning-assisted material design (e.g., surface modification and heterojunction engineering). Machine learning (ML) primarily serves to analyze and extract patterns from vast datasets, enabling accurate predictions and judgments for subsequent interactions. It consists of five key components: data acquisition, data preprocessing, feature engineering, model training/algorithm selection, and model evaluation/interpretation. Figure 6 illustrates the operational framework of ML [97]. In the development of resistive gas sensor materials, ML has been employed not only to predict critical gas-sensitive mechanistic parameters, such as adsorption energy, bandgap, dielectric constant, and thermal conductivity [98–100], but also to accelerate the discovery and structural design of novel sensing materials [101].

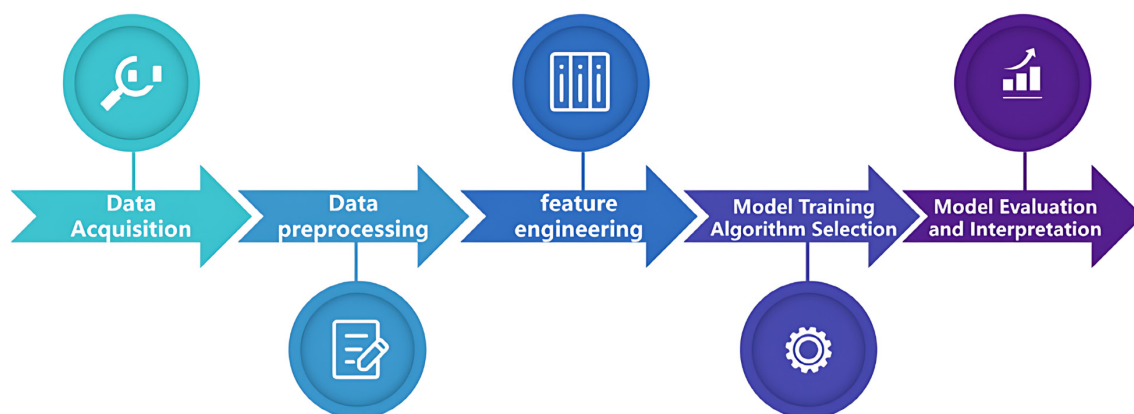


Figure 6. Workflow of the machine learning process. Reprinted with permission from Ref. [97]. Copyright 2024, Wiley-VCH GmbH.

Machine learning enables researchers to predict the parameters of gas-sensitive materials more rapidly and at a lower cost, thereby reducing excessive research expenditures and shortening development cycles. Zhang et al. developed a machine learning framework to systematically investigate the adsorption properties of boron-doped graphene [98], with a focus on the distribution and concentration of dopants and their effects on CO adsorption. Using random forest, gradient boosting regression tree, and neural network models, the study achieved rapid prediction of CO adsorption energies for various boron-doped graphene structures, elucidating structure–property relationships. This approach significantly enhanced the R&D efficiency of two-dimensional gas-sensitive nanomaterials while circumventing the high computational costs associated with traditional DFT calculations. Wang et al. employed feature selection methods to train three machine learning models to predict the bandgaps of solid-state gas-sensitive materials [99]. Cross-validation demonstrated a prediction accuracy of 96%, with a root-mean-square error (RMSE) of only 0.28 eV, highlighting the model’s exceptional bandgap prediction capability. Machine learning has also been successfully applied to predict the properties of various polymer systems, including high-throughput prediction of single-chain polymer conductivity [83] and precise evaluation of the macroscopic thermal conductivity of carbon nanotube-reinforced polymer composites (CNT-PCs) [73].

Machine learning further facilitates the efficient screening of novel materials and prediction of unknown structures, providing robust support for chemiresistive gas sensor

development. Wang et al. utilized four tree-based machine learning models to screen over 8000 materials, identifying 13 novel NO_2 -sensitive electrode candidates [102]. These materials exhibited response signals exceeding 50 mV to 100 ppm NO_2 , with selectivity coefficients below 40%. This work broke the conventional requirement that $\text{A}_x\text{B}_y\text{O}_z$ -type sensing electrodes must contain metal elements, pioneering the development of a nonmetallic BPO_4 -based NO_2 -sensitive material. The high-throughput screening method yielded sensors with excellent response–recovery characteristics, where the response magnitude followed a logarithmic linear relationship with gas concentration as shown in Figure 7. The optimized materials from ML-assisted design provide enhanced sensing properties (e.g., selectivity and sensitivity), which necessitate intelligent algorithms to decode complex response patterns in real-world applications.

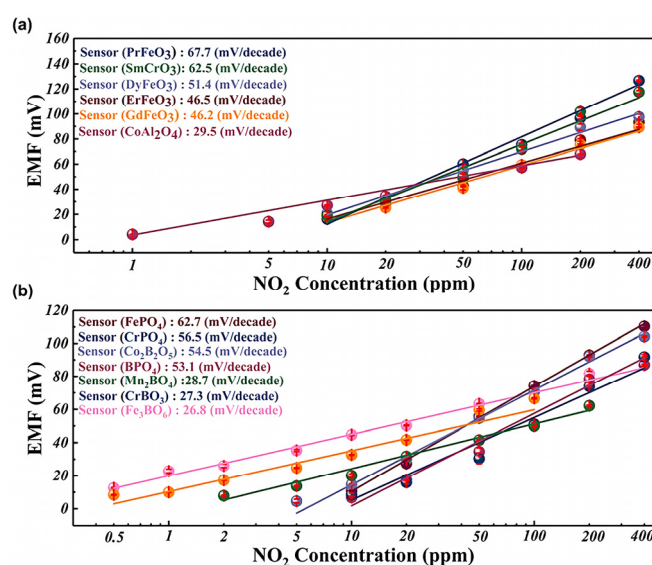


Figure 7. Comparative sensitivity analysis of gas sensors. (a) ABM-type and (b) BNUM-type sensors. Reprinted with permission from Ref. [103]. Copyright 2021, American Chemical Society.

However, the enhanced sensitivity of nanostructured materials also amplifies their susceptibility to environmental fluctuations (e.g., humidity and temperature) and non-ideal response nonlinearities. To reliably decode such complex sensing signals and achieve robust gas identification under real-world conditions, intelligent signal-processing algorithms become indispensable.

4.2. Intelligent Recognition and Signal Processing

This subsection addresses selectivity improvements at the algorithmic recognition level via intelligent signal-processing techniques. Machine learning has been extensively applied to optimize the performance parameters of resistive gas sensors, including selectivity, response/recovery time, stability, sensitivity, and accuracy. In environments with mixed gas compositions, improving identification accuracy while reducing false alarm rates remains a significant challenge. Kurtishaj Hamzaj et al. [80] developed a multi-gas detection system using a single ZnO gas sensor integrated with machine learning algorithms (Naive Bayes (NB), Logistic Regression (LR), Support Vector Machine (SVM), and Random Forest (RF)). This system achieved selective detection of NH_3 , CO_2 , and H_2S gases at operating temperatures of 250–350 °C with an impressive identification accuracy of 99.8%. Further advancing this field, Krivetskiy’s research [103] demonstrated that combining B-spline curves with Artificial Neural Networks (ANN) significantly enhances the selectivity of thermally modulated MOS gas sensors. The team also established an open dataset and achieved precise detection of CO in the 2.2–20 ppm range by integrating machine learning

with Singular Spectrum Analysis (SSA) preprocessing [103]. These studies collectively highlight the substantial potential of machine learning in improving the selectivity of metal oxide gas sensors. Stability and operational lifespan during prolonged use are also critical factors influencing the practical application of these sensors. In environments containing hazardous gases, sensor sensitivity becomes particularly crucial. Machine learning has proven effective in enhancing the detection sensitivity of chemiresistive gas sensors for trace gas concentrations. Iwata et al. optimized a TiO₂ nanotube (NT) gas sensor using a neural network regression model [104], improving the detection precision for CO and O₂ concentrations from 0.02% to 0.001%, thereby enabling highly sensitive detection of trace gases.

4.3. Intelligent Sensor System

As a bridge integrating material optimization and signal recognition, this subsection explores system-level solutions for multi-gas detection. Environmental gas monitoring is crucial for human health and safety. However, traditional chemiresistive gas sensors face limitations in practical applications due to their single-gas selectivity. Currently, researchers primarily employ multi-sensor arrays to achieve mixed gas detection. However, simply increasing the number and types of sensors leads to higher system costs, greater data processing complexity, and reduced reliability. To address these challenges, machine learning-based optimization methods for gas sensor arrays have emerged. These methods utilize intelligent algorithms to select the optimal sensor combination [105], significantly improving gas identification and detection performance while reducing hardware requirements.

Currently, intelligent resistive gas sensor arrays integrated with artificial intelligence systems have achieved significant breakthroughs in olfactory systems, biomedical applications, and other fields. The Fan team recently developed a bionic olfactory chip (BOC) system [106], whose core is a high-density monolithic 3D PdO/SnO₂ sensor array with 100–10,000 sensors integrated on a single chip, enabling odor recognition by simulating the pixel diversity of biological olfactory receptors. The system is equipped with peripheral signal readout circuits to precisely detect resistance changes in each pixel. Experimental results demonstrated that the CNN-based model achieved 99.04% accuracy in gas identification and concentration prediction, distinguishing eight odors at varying concentrations. Using t-SNE and support vector algorithms, the system successfully resolved 24 mixed odors, as shown in Figure 8a–c. In practical applications, it accurately identified complex odors such as oranges and red wine as shown in Figure 8d–g, showcasing excellent pattern recognition capabilities and promising application prospects. Zhang et al. developed a portable POCT platform integrating a cross-reactive MXene-based sensor array [107]. By optimizing the MXene framework (MF) sensing layer through metal ion doping, sequence modulation, and ligand engineering, they successfully obtained characteristic response profiles for 13 urinary VOCs. Results indicated that the SVM algorithm achieved 91.7% accuracy in discriminating between healthy and diseased samples, effectively distinguishing conditions such as diabetic complications and liver injury, with performance significantly surpassing other machine learning algorithms. This platform provides a novel strategy for non-invasive disease diagnosis.

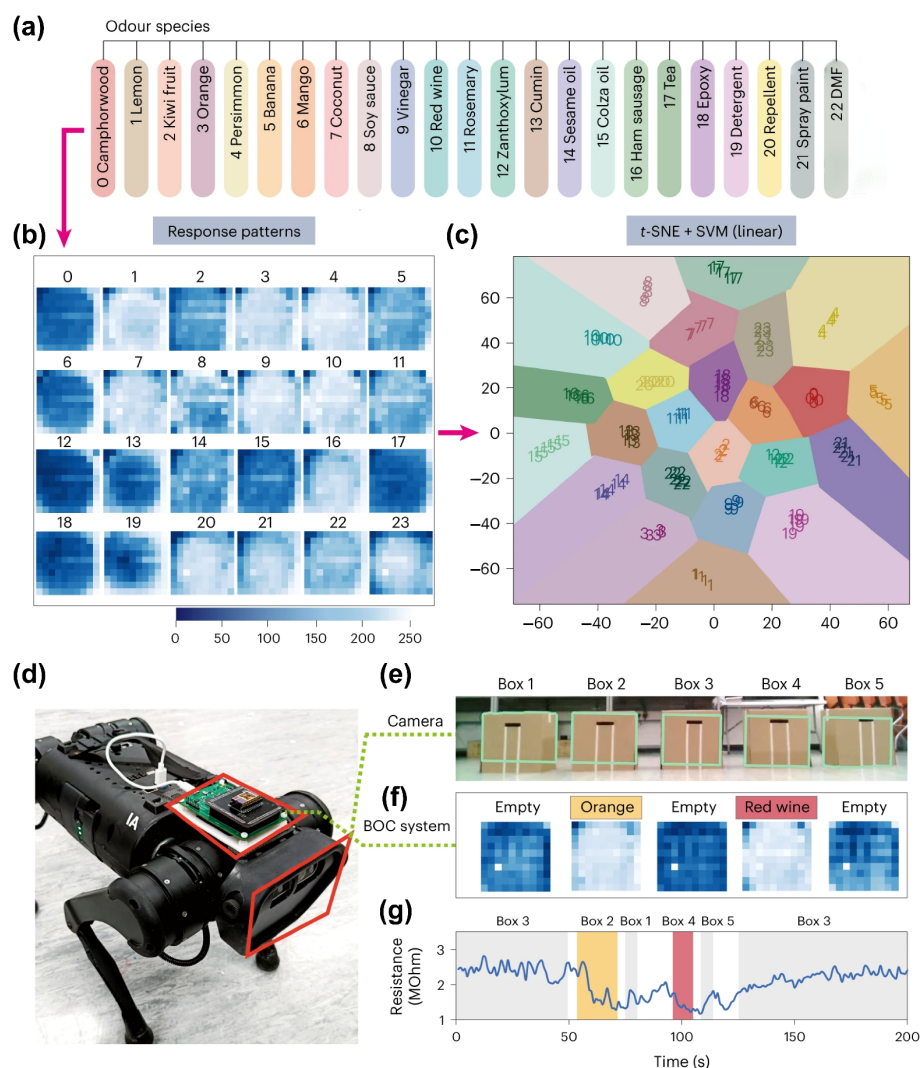


Figure 8. Bio-inspired olfactory system integrated into a quadrupedal mobile robot. (a–c) The chip’s cross-reactive sensitivity combined with AI algorithms enables the identification of 24 distinct odor components in mixed samples. (d–g) The olfactory chip operates in tandem with visual sensors mounted on the robotic dog. Reprinted with permission from Ref. [106]. Copyright 2024, the Author(s), under exclusive license to Springer Nature Limited.

5. Application of Resistive Gas Sensors

Currently, resistive gas sensors have been widely employed across various societal domains, playing a crucial role. In environmental monitoring and industrial safety, this technology enables intelligent production and early-warning safety functions. In healthcare monitoring and smart wearable devices, it provides real-time data acquisition and scientific diagnostic support, demonstrating significant application value.

5.1. Environmental and Air Pollution Monitoring

Resistive sensors can assess air quality by detecting harmful gases and particulate pollutants, thereby providing critical data to improve living and working environments. For instance, formaldehyde (HCHO), a major indoor pollutant, is conventionally detected using portable sensors based on metal/metal oxide catalysts [108]. However, these devices often suffer from insufficient long-term stability due to the CO poisoning of gas-sensitive materials. To address this challenge, Guo et al. developed an electrochemical sensor with a Cr-Pd catalyst, as shown in Figure 9, which enables selective detection of 72 ppb HCHO within 200 s via an efficient electro-oxidation process [109].

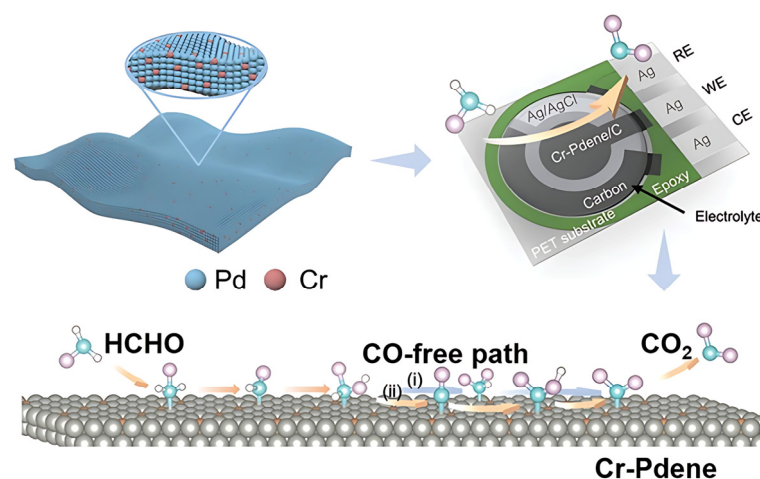


Figure 9. Ultrathin Cr-Pdene layer for formaldehyde monitoring. Reprinted with permission from Ref. [109]. Copyright 2021, Wiley.

5.2. Industrial Safety and VOCs Detection

In industrial settings such as petrochemical and rubber manufacturing facilities, the detection of volatile aromatic hydrocarbons (VAHs)—typical occupational carcinogens—poses significant challenges. Although conventional metal oxide semiconductor (MOS) sensors are capable of detecting VAHs, they suffer from limitations including poor selectivity and susceptibility to interference from highly reactive gases such as ethanol and formaldehyde. To address these issues, Lee et al. developed a $\text{CeO}_2/\text{Rh-SnO}_2$ bilayer sensor array [110]. Their study revealed that the CeO_2 overlayer effectively suppresses interference from highly reactive gases through selective catalytic oxidation while maintaining high sensitivity toward VAHs. This design significantly enhances the discrimination capability between aromatic and non-aromatic gases.

Additionally, two-dimensional transition metal dichalcogenides (TMDs) have emerged as promising candidates for toxic gas detection due to their atomic-scale thickness, tunable bandgaps, and high surface-to-volume ratios. For instance, WS_2/TiO_2 quantum dot hybrids exhibit a high NH_3 response ($\Delta R/R_a = 56.69\%$ at 500 ppm) with rapid recovery (seconds scale) at room temperature, leveraging interfacial charge transfer and depletion layer modulation [111]. Similarly, $\text{SnS}_2/\text{SnO}_2$ hierarchical heterojunctions demonstrate enhanced NO_2 sensing (51.1% response to 1 ppm at 100 °C) and selectivity through synergistic geometric/electronic effects and S–Sn–O chemical bridges [112]. These TMD hybrids overcome traditional MOS limitations by enabling low-temperature operation and minimizing interference via tailored heterojunction engineering.

For VOCs detection, recent studies [113,114] have employed SnO_2 hollow spheres as sensing materials with machine learning optimization. Among various machine learning models, the random forest algorithm demonstrated superior performance, achieving accurate identification of all target VOCs. As shown in Figure 10a, 16-fold cross-validation results confirmed the model's effectiveness in addressing gas selectivity challenges. Figure 10b further illustrates the prediction performance for specific VOCs, with prediction errors of 9.98% for formaldehyde, 7.24% for acetone, 6.66% for toluene, and 4.65% for methanol.

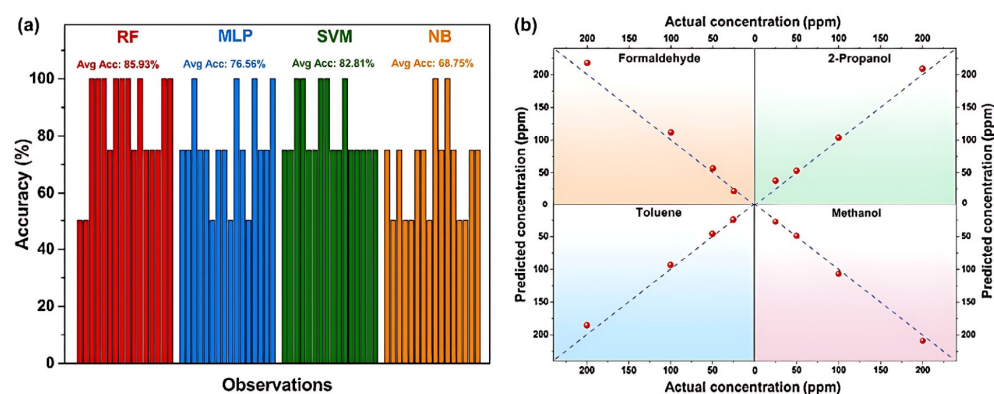


Figure 10. (a) Comparative classification accuracy of four machine learning techniques. (b) Quantitative concentration prediction for each VOC. Adapted with permission from Ref. [114]. Copyright 2022, Elsevier.

5.3. Healthcare and Breath Analysis

In modern healthcare, **there is a growing interest in utilizing** bedside testing systems to assess patients' respiration and bodily fluids, enabling non-invasive, low-cost, and rapid medical diagnostics. However, this approach struggles to detect weak signals from early-stage diseases, and screening based on a single biomarker is unreliable for disease diagnosis. Therefore, developing multifunctional sensors capable of synchronous multi-dimensional monitoring of biological signals is crucial. Inspired by synaptic structures, Zhou et al. designed a biomimetic sensing layer composed of ZIF-L@Ti₃CNT_x composite material [115], where zeolitic imidazolate framework (ZIF) flower-like particles were in situ grown on Ti₃CNT_x nanosheets, as shown in Figure 11. Based on this architecture, they further developed a wearable medical monitoring platform. This platform integrates non-overlapping gas-strain dual-mode sensing technology, efficiently monitoring dimethylamine (DMA) biomarkers in the exhaled breath of Parkinson's disease patients and motor dysfunction-related tremors, demonstrating excellent dual-mode detection performance. Meanwhile, Jin's team fabricated an NH₃ sensor array for halitosis diagnosis [97]. These research-stage sensing technologies demonstrate the potential to provide novel non-invasive screening tools for oral diseases in the future.

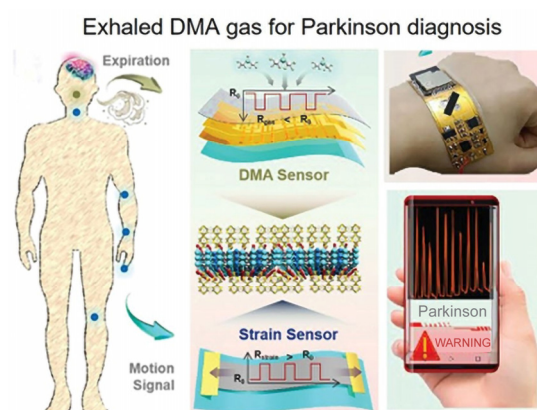


Figure 11. Flexible dual-mode gas and strain sensor for point-of-care health monitoring in Parkinson's disease. Reprinted with permission from Ref. [115]. Copyright 2023, the Authors. Advanced Science published by Wiley-VCH GmbH.

5.4. Smart Cities and Wearable Systems

With the advancement of Internet of Things (IoT) technology, gas sensor detection systems have been widely applied in remote urban air quality monitoring and real-time environmental detection via personal wearable devices, forming a comprehensive air

quality monitoring network. Wireless sensor networks (WSNs) can significantly enhance the spatio-temporal resolution of gas detection, enabling real-time monitoring in specialized environments [116]. Fan et al. developed a self-powered integrated nano-gas sensor (SINGOR) based on a three-dimensional Pd/SnO₂ thin film [117], which, combined with a PCA-SVM algorithm, enables precise identification of gases such as H₂ and formaldehyde within a 0–85% humidity range. By constructing a wireless sensor network, this system achieves accurate localization of gas leaks in household environments. Dou et al. designed a dual-mode sensing chip based on an aggregation-induced emission (AIE) probe [118], as illustrated in Figure 12. This chip employs an aggregation–disaggregation mechanism to achieve colorimetric-fluorescent dual-response detection of dichloropropanol (DCP) vapor, with a detection limit as low as 1.7 ppb, and has been successfully integrated into wearable devices for continuous two-week monitoring. This addresses the challenge of traditional sensors being prone to passivation or false positives due to interference from atmospheric components such as aromatic compounds and esters.

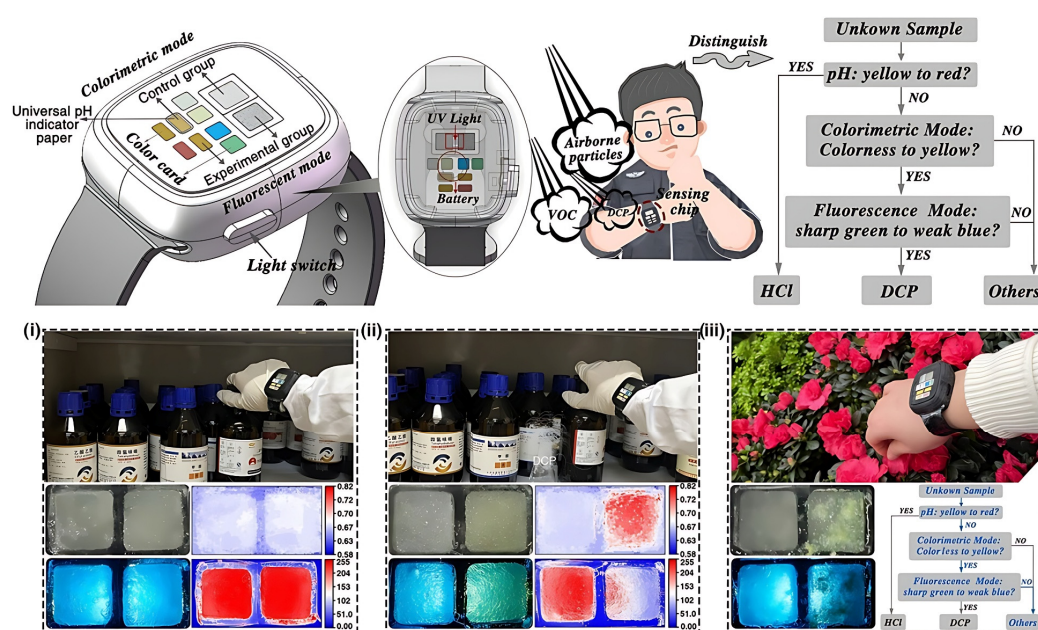


Figure 12. Schematic diagram and logic discrimination plot of a portable sensing platform for dual-mode recognition of the nerve agent simulant dichloropropanol vapor. Reprinted with permission from Ref. [118]. Copyright 2024, Wiley.

6. Conclusions and Perspectives

Resistive gas sensors have undergone substantial advancements in recent decades, driven by innovations in both core material development and artificial intelligence-integrated applications. These improvements have profoundly enhanced daily life and societal safety operations. The evolution of gas-sensitive materials—the fundamental component of resistive gas sensors—has been pivotal in addressing increasingly complex detection requirements across diverse fields. Research has expanded from traditional metal oxides such as SnO₂ and ZnO to carbon-based materials including graphene and carbon nanotubes, as well as conductive polymers like polyaniline and polypyrrole. Advanced material engineering strategies, such as nano-structuring techniques to create porous films and nanowires, along with modification through noble metal or rare-earth element doping, have significantly increased specific surface area and gas adsorption activity. Composite material systems, particularly metal oxide/graphene heterojunctions, have further optimized detection accuracy and response kinetics. Despite these advances, critical challenges remain in long-term stability and interference resistance. Future progress may leverage emerging biomimetic approaches such

as molecularly imprinted polymers alongside novel two-dimensional materials like MXenes to achieve next-generation performance enhancements.

However, the following key challenges persist for real-world deployment:

- (1) **High Power Consumption:** Elevated operating temperatures (200–400 °C) for metal oxide sensors increase energy demands and limit integration in portable systems.
- (2) **Humidity Cross-Sensitivity:** Water vapor adsorption alters baseline resistance by >20% at 70%RH, obscuring target gas signals in humid environments.
- (3) **Drift-Induced Calibration Burden:** Long-term material degradation causes signal drift, necessitating frequent recalibration that disrupts continuous monitoring.
- (4) **Fabrication Inconsistency:** Nanomaterial synthesis variations yield >30% performance deviation in sensor arrays, hindering mass production.

To address these, we propose the following:

- (1) **Hybrid Material Systems:** We emphasize room-temperature operable heterojunctions to eliminate microheaters while maintaining ppb-level sensitivity.
- (2) **Embedded AI Compensation:** We recommend integrating machine learning algorithms into sensor nodes for real-time humidity/drift correction.
- (3) **Structural Optimization and Standardization:** We advocate MEMS-based batch fabrication with optimized geometries to enhance response speed and batch consistency.
- (4) **Multimodal Sensing Fusion:** We highlight the coupling of resistive units with complementary transducers to decouple overlapping gas responses. In practical applications, resistive-type gas sensors have demonstrated wide-ranging utility across multiple domains, including environmental monitoring of hazardous gases such as VOCs and NO_x, healthcare diagnostics, intelligent residential systems, and precision agriculture. To enhance selectivity and interference resistance, sensor arrays coupled with machine learning algorithms have been developed to achieve precise identification of mixed gases. The integration of edge computing and embedded artificial intelligence has further advanced real-time monitoring capabilities, facilitating their incorporation into IoT ecosystems. Looking ahead, the convergence of self-smart resistive gas sensors with low-power chip technology is expected to expand their utility in wearable devices and industrial safety applications.

Moving forward, resistive gas sensors will continue evolving toward greater intelligence and integration, emerging as an interdisciplinary field that combines materials science, embedded computing, wireless sensor networks, and IoT technologies. The standardization of manufacturing processes and optimization of long-term reliability will be pivotal for industrial-scale production, ultimately accelerating the commercialization of these sensors across broader application scenarios.

Based on current research trends, future efforts may focus on:

- (1) **Adaptive Sensing Systems:** We suggest exploring lightweight algorithms for on-device learning to autonomously calibrate drift and humidity interference, potentially reducing maintenance costs.
- (2) **Hybrid Sensing Platforms:** We propose combining resistive units with low-cost optical/electrochemical modules to improve cross-validation capability for complex gas mixtures.
- (3) **Energy Harvesting Integration:** We recommend investigating micro-energy harvesters (e.g., solar/motion) to alleviate power constraints in wearable applications.
- (4) **Accessible Manufacturing:** We encourage developing inkjet printing or roll-to-roll processes for low-cost sensor array fabrication.

These directions could help overcome existing limitations while promoting wider adoption in community health monitoring and smart home applications.

Author Contributions: Conceptualization, P.W. and H.W.; investigation, P.W.; writing—original draft preparation, P.W.; data curation: P.W., J.Z. and H.X.; writing—review and editing, P.W. and H.W.; supervision, H.W., S.X. and X.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 22175112.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the Shanghai University of Engineering Science, and Shanghai Jiao Tong University. We thank the institutions and the funding agency for their support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Shen, Y.; Wei, Y.; Zhu, C.; Cao, J.; Han, D.-M. Ratiometric Fluorescent Signals-Driven Smartphone-Based Portable Sensors for Onsite Visual Detection of Food Contaminants. *Coord. Chem. Rev.* **2022**, *458*, 214442. [\[CrossRef\]](#)
- Zhu, J.; Chen, L.; Ni, W.; Cheng, W.; Yang, Z.; Xu, S.; Wang, T.; Zhang, B.; Xuan, F. NiO/ZnO Nanocomposites for Multimodal Intelligent MEMS Gas Sensors. *ACS Sens.* **2025**, *10*, 2531–2541. [\[CrossRef\]](#) [\[PubMed\]](#)
- Jiang, K.; Zeng, M.; Wang, T.; Wu, Y.; Ni, W.; Chen, L.; Yang, J.; Hu, N.; Zhang, B.; Xuan, F.; et al. Gas Sensor Drift Compensation Using Semi-Supervised Ensemble Classifiers with Multi-Level Features and Center Loss. *ACS Sens.* **2025**, *10*, 2906–2918. [\[CrossRef\]](#) [\[PubMed\]](#)
- Peng, J.; Mei, H.; Yang, R.; Meng, K.; Shi, L.; Zhao, J.; Zhang, B.; Xuan, F.; Wang, T.; Zhang, T. Olfactory Diagnosis Model for Lung Health Evaluation Based on Pyramid Pooling and SHAP-Based Dual Encoders. *ACS Sens.* **2024**, *9*, 4934–4946. [\[CrossRef\]](#)
- Mei, H.; Peng, J.; Wang, T.; Zhou, T.; Zhao, H.; Zhang, T.; Yang, Z. Overcoming the Limits of Cross-Sensitivity: Pattern Recognition Methods for Chemiresistive Gas Sensor Array. *Nano-Micro Lett.* **2024**, *16*, 269. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ni, W.; Wang, T.; Wu, Y.; Liu, X.; Li, Z.; Yang, R.; Zhang, K.; Yang, J.; Zeng, M.; Hu, N.; et al. Multi-Task Deep Learning Model for Quantitative Volatile Organic Compounds Analysis by Feature Fusion of Electronic Nose Sensing. *Sens. Actuators B Chem.* **2024**, *417*, 136206. [\[CrossRef\]](#)
- Wang, B.; Yu, Q.; Zhang, S.; Wang, T.; Sun, P.; Chuai, X.; Lu, G. Gas Sensing with Yolk-Shell LaFeO₃ Microspheres Prepared by Facile Hydrothermal Synthesis. *Sens. Actuators B Chem.* **2018**, *258*, 1215–1222. [\[CrossRef\]](#)
- Zainab, Y.; Mohd, N.H.; Ahsanul, K.; Zaiki, A. Gas sensors: A review. *Sens. Transducers* **2014**, *168*, 61–75.
- Tonezzer, M.; Izidoro, S.C.; Moraes, J.P.A.; Dang, L.T.T. Improved Gas Selectivity Based on Carbon Modified SnO₂ Nanowires. *Front. Mater.* **2019**, *6*, 277. [\[CrossRef\]](#)
- Luo, Y.; Abidian, M.R.; Ahn, J.-H.; Akinwande, D.; Andrews, A.M.; Antonietti, M.; Bao, Z.; Berggren, M.; Berkey, C.A.; Bettinger, C.J.; et al. Technology Roadmap for Flexible Sensors. *ACS Nano* **2023**, *17*, 5211–5295. [\[CrossRef\]](#)
- Kim, D.-H.; Cha, J.-H.; Lim, J.Y.; Bae, J.; Lee, W.; Yoon, K.R.; Kim, C.; Jang, J.-S.; Hwang, W.; Kim, I.-D. Colorimetric Dye-Loaded Nanofiber Yarn: Eye-Readable and Weavable Gas Sensing Platform. *ACS Nano* **2020**, *14*, 16907–16918. [\[CrossRef\]](#)
- Wu, Z.; Wang, H.; Ding, Q.; Tao, K.; Shi, W.; Liu, C.; Chen, J.; Wu, J. A Self-Powered, Rechargeable, and Wearable Hydrogel Patch for Wireless Gas Detection with Extraordinary Performance. *Adv. Funct. Mater.* **2023**, *33*, 2300046. [\[CrossRef\]](#)
- Anju; Saini, L.K.; Pandey, M. Quantum Chemical Analysis of Porphyrin-Based Sensors: Adsorption and Sensing Capabilities of Pure, Protonated, and Metallic Porphyrins Insights into Volatile Organic Compounds (VOCs). *Mater. Today Commun.* **2024**, *41*, 110989. [\[CrossRef\]](#)
- Elia, E.A.; Stylianou, M.; Agapiou, A. Investigation on the Source of VOCs Emission from Indoor Construction Materials Using Electronic Sensors and TD-GC-MS. *Environ. Pollut.* **2024**, *348*, 123765. [\[CrossRef\]](#) [\[PubMed\]](#)
- Xiang, H.; Li, Z.; Zheng, H.; Jiang, X.; Wu, H.; Zhou, H.; Liu, H. Disposable, Strain-Insensitive, and Room-Temperature-Operated Flexible Humidity and VOC Sensor with Enhanced Sensitivity and Selectivity through Interface Control. *Sens. Actuators B Chem.* **2024**, *399*, 134831. [\[CrossRef\]](#)
- Yan, H.; Zhou, Y.-G. Electrical Sensing of Volatile Organic Compounds in Exhaled Breath for Disease Diagnosis. *Curr. Opin. Electrochem.* **2022**, *33*, 100922. [\[CrossRef\]](#)
- Pathak, A.K.; Viphavakit, C. A Review on All-Optical Fiber-Based VOC Sensors: Heading towards the Development of Promising Technology. *Sens. Actuators A Phys.* **2022**, *338*, 113455. [\[CrossRef\]](#)

18. Acharyya, S.; Bhowmick, P.K.; Guha, P.K. Selective Identification and Quantification of VOCs Using Metal Nanoparticles Decorated SnO₂ Hollow-Spheres Based Sensor Array and Machine Learning. *J. Alloys Compd.* **2023**, *968*, 171891. [\[CrossRef\]](#)
19. Shen, Y.; Tissot, A.; Serre, C. Recent progress on MOF-based optical sensors for VOC sensing. *Chem. Sci.* **2022**, *13*, 13978–14007. [\[CrossRef\]](#)
20. Guo, M.; Zhao, T.; Cui, Z. Adsorption Behavior and Sensing Performance of VOCs on Monolayer XC (X = Ge, Si). *Surf. Interfaces* **2024**, *51*, 104607. [\[CrossRef\]](#)
21. Ghazi, M.; Janfaza, S.; Tahmooressi, H.; Tasnim, N.; Hoorfar, M. Selective Detection of VOCs Using Microfluidic Gas Sensor with Embedded Cylindrical Microfeatures Coated with Graphene Oxide. *J. Hazard. Mater.* **2022**, *424*, 127566. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Bogris, A.; Herdt, A.; Syvridis, D.; Elsaber, W. Mid-Infrared Gas Sensor Based on Mutually Injection Locked Quantum Cascade Lasers. *IEEE J. Select. Top. Quantum Electron.* **2017**, *23*, 8–14. [\[CrossRef\]](#)
23. Wang, C.; Yin, L.; Zhang, L.; Xiang, D.; Gao, R. Metal Oxide Gas Sensors: Sensitivity and Influencing Factors. *Sensors* **2010**, *10*, 2088–2106. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Chen, M.; Yao, W.; Deng, Q. Performance Evaluation of a Portable Infrared Gas Analyser Based on Fourier Infrared Spectral Analysis Technique. *Metrol. Sci. Technol.* **2025**, *69*, 53–59, 41.
25. Barsan, N.; Weimar, U. Conduction Model of Metal Oxide Gas Sensors. *J. Electroceram.* **2001**, *7*, 143–167. [\[CrossRef\]](#)
26. Korotcenkov, G. Metal Oxides for Solid-State Gas Sensors: What Determines Our Choice? *Mater. Sci. Eng. B* **2007**, *139*, 1–23. [\[CrossRef\]](#)
27. El-Muraikhi, M.D.; Ayesh, A.I.; Mirzaei, A. Review of Nanostructured Bi₂O₃, Bi₂WO₆, and BiVO₄ as Resistive Gas Sensors. *Surf. Interfaces* **2025**, *60*, 106003. [\[CrossRef\]](#)
28. Ghafarinia, V.; Amiri Raeiz, M.; Barami, S. A General Gas-Dependent Resistivity Model for Metal Oxide Semiconductor Gas Sensors Considering the Kinetics of Charge Transfer on the Surface. *Sens. Actuators B Chem.* **2023**, *395*, 134488. [\[CrossRef\]](#)
29. Gupta, S.; Zou, H. Implementing an Analytical Model to Elucidate the Impacts of Nanostructure Size and Topology of Morphologically Diverse Zinc Oxide on Gas Sensing. *Chemosensors* **2025**, *13*, 38. [\[CrossRef\]](#)
30. Hierlemann, A.; Gutierrez-Osuna, R. Higher-Order Chemical Sensing. *Chem. Rev.* **2008**, *108*, 563–613. [\[CrossRef\]](#)
31. Fine, G.F.; Cavanagh, L.M.; Afonja, A.; Binions, R. Metal Oxide Semi-Conductor Gas Sensors in Environmental Monitoring. *Sensors* **2010**, *10*, 5469–5502. [\[CrossRef\]](#)
32. Du, X.; Wang, Y.; Mu, Y.; Gui, L.; Wang, P.; Tang, Y. A New Highly Selective H₂ Sensor Based on TiO₂ /PtO–Pt Dual-Layer Films. *Chem. Mater.* **2002**, *14*, 3953–3957. [\[CrossRef\]](#)
33. Duan, P.; Wang, H.; Peng, Q.; Chen, S.; Zhou, H.; Duan, Q.; Jin, K.; Sun, J. Ultra-Effective Room Temperature Gas Discrimination Based on Monolithic Pd@MOF-Derived Porous Nanocomposites: An Exclusive Scheme with Photoexcitation. *J. Mater. Chem. A* **2024**, *12*, 3896–3909. [\[CrossRef\]](#)
34. Zhou, Q.; Sussman, A.; Chang, J.; Dong, J.; Zettl, A.; Mickelson, W. Fast Response Integrated MEMS Microheaters for Ultra Low Power Gas Detection. *Sens. Actuators A Phys.* **2015**, *223*, 67–75. [\[CrossRef\]](#)
35. Majhi, S.M.; Mirzaei, A.; Kim, H.W.; Kim, S.S.; Kim, T.W. Recent Advances in Energy-Saving Chemiresistive Gas Sensors: A Review. *Nano Energy* **2021**, *79*, 105369. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Xue, D.; Wang, J.; Li, X. A Front-Side Microfabricated Thermoresistive Gas Flow Sensor for High-Performance, Low-Cost and High-Yield Volume Production. *Micromachines* **2020**, *11*, 205. [\[CrossRef\]](#)
37. Zhang, R.; Pang, W.; Feng, Z.; Chen, X.; Chen, Y.; Zhang, Q.; Zhang, H.; Sun, C.; Yang, J.J.; Zhang, D. Enabling Selectivity and Fast Recovery of ZnO Nanowire Gas Sensors through Resistive Switching. *Sens. Actuators B Chem.* **2017**, *238*, 357–363. [\[CrossRef\]](#)
38. Mousavi, S.; Zeinali, S. VOC s detection using resistive gas nanosensor based on MIL-101(Cr) as a metal organic framework. *Sens. Actuators A Phys.* **2022**, *346*, 113810. [\[CrossRef\]](#)
39. Chen, H.; Zhao, Y.; Shi, L.; Li, G.-D.; Sun, L.; Zou, X. Revealing the Relationship between Energy Level and Gas Sensing Performance in Heteroatom-Doped Semiconducting Nanostructures. *ACS Appl. Mater. Interfaces* **2018**, *10*, 29795–29804. [\[CrossRef\]](#)
40. Niu, F.; Zhou, F.; Wang, Z.; Wei, L.; Hu, J.; Dong, L.; Ma, Y.; Wang, M.; Jia, S.; Chen, X.; et al. Synthesizing Metal Oxide Semiconductors on Doped Si/SiO₂ Flexible Fiber Substrates for Wearable Gas Sensing. *Research* **2023**, *6*, 0100. [\[CrossRef\]](#)
41. Ren, W.; Zhao, C.; Niu, G.; Zhuang, Y.; Wang, F. Gas Sensor Array with Pattern Recognition Algorithms for Highly Sensitive and Selective Discrimination of Trimethylamine. *Adv. Intell. Syst.* **2022**, *4*, 2200169. [\[CrossRef\]](#)
42. Zhang, D.; Liu, J.; Jiang, C.; Liu, A.; Xia, B. Quantitative Detection of Formaldehyde and Ammonia Gas via Metal Oxide-Modified Graphene-Based Sensor Array Combining with Neural Network Model. *Sens. Actuators B Chem.* **2017**, *240*, 55–65. [\[CrossRef\]](#)
43. Yamazoe, N.; Shimano, K. Theory of Power Laws for Semiconductor Gas Sensors. *Sens. Actuators B Chem.* **2008**, *128*, 566–573. [\[CrossRef\]](#)
44. Sivaperuman, K.; Thomas, A.; Thangavel, R.; Thirumalaisamy, L.; Palanivel, S.; Pitchaimuthu, S.; Ahsan, N.; Okada, Y. Binary and Ternary Metal Oxide Semiconductor Thin Films for Effective Gas Sensing Applications: A Comprehensive Review and Future Prospects. *Prog. Mater. Sci.* **2024**, *142*, 101222. [\[CrossRef\]](#)

45. Wang, X.; Li, S.; Xie, L.; Li, X.; Lin, D.; Zhu, Z. Low-Temperature and Highly Sensitivity H₂S Gas Sensor Based on ZnO/CuO Composite Derived from Bimetal Metal-Organic Frameworks. *Ceram. Int.* **2020**, *46*, 15858–15866. [\[CrossRef\]](#)
46. Yuan, W.; Shi, G. Graphene-based gas sensors. *J. Mater. Chem. A* **2013**, *1*, 10078. [\[CrossRef\]](#)
47. Lu, G.; Ocola, L.E.; Chen, J. Reduced graphene oxide for room-temperature gas sensors. *Nanotechnology* **2009**, *20*, 445502. [\[CrossRef\]](#)
48. Liu, B.; Liu, X.; Yuan, Z.; Jiang, Y.; Su, Y.; Ma, J.; Tai, H. A flexible NO₂ gas sensor based on polypyrrole/nitrogen-doped multiwall carbon nanotube operating at room temperature. *Sens. Actuators B Chem.* **2019**, *295*, 86–92. [\[CrossRef\]](#)
49. Miller, D.R.; Akbar, S.A.; Morris, P.A. Nanoscale metal oxide-based heterojunctions for gas sensing: A review. *Sens. Actuators B Chem.* **2014**, *204*, 250–272. [\[CrossRef\]](#)
50. Zhang, J.; Qin, Z.; Zeng, D.; Xie, C. Metal-Oxide-Semiconductor Based Gas Sensors: Screening, Preparation, and Integration. *Phys. Chem. Chem. Phys.* **2017**, *19*, 6313–6329. [\[CrossRef\]](#)
51. Zhang, C.; Luo, Y.; Xu, J.; Debliquy, M. Room temperature conductive type metal oxide semiconductor gas sensors for NO₂ detection. *Sens. Actuators A Phys.* **2019**, *289*, 118–133. [\[CrossRef\]](#)
52. Lee, E.; VahidMohammadi, A.; Prorok, B.C.; Yoon, Y.S.; Beidaghi, M.; Kim, D.-J. Room Temperature Gas Sensing of Two-Dimensional Titanium Carbide (MXene). *ACS Appl. Mater. Interfaces* **2017**, *9*, 37184–37190. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Bai, H.; Shi, G. Gas Sensors Based on Conducting Polymers. *Sensors* **2007**, *7*, 267–307. [\[CrossRef\]](#)
54. Yavari, F.; Koratkar, N. Graphene-Based Chemical Sensors. *J. Phys. Chem. Lett.* **2012**, *3*, 1746–1753. [\[CrossRef\]](#)
55. Wang, T.; Huang, D.; Yang, Z.; Xu, S.; He, G.; Li, X.; Hu, N.; Yin, G.; He, D.; Zhang, L. A Review on Graphene-Based Gas/Vapor Sensors with Unique Properties and Potential Applications. *Nano-Micro Lett.* **2016**, *8*, 95–119. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Kim, M.Y.; Choi, Y.N.; Bae, J.M.; Oh, T.S. Carbon Dioxide Sensitivity of La-Doped Thick Film Tin Oxide Gas Sensor. *Ceram. Int.* **2012**, *38*, S657–S660. [\[CrossRef\]](#)
57. Hunge, Y.M.; Yadav, A.A.; Kulkarni, S.B.; Mathe, V.L. A Multifunctional ZnO Thin Film Based Devices for Photoelectrocatalytic Degradation of Terephthalic Acid and CO₂ Gas Sensing Applications. *Sens. Actuators B Chem.* **2018**, *274*, 1–9. [\[CrossRef\]](#)
58. Abdelmounaïm, C.; Amara, Z.; Maha, A.; Mustapha, D. Effects of Molarity on Structural, Optical, Morphological and CO₂ Gas Sensing Properties of Nanostructured Copper Oxide Films Deposited by Spray Pyrolysis. *Mater. Sci. Semicond. Process.* **2016**, *43*, 214–221. [\[CrossRef\]](#)
59. Wang, Y.; Zhang, K.; Zou, J.; Wang, X.; Sun, L.; Wang, T.; Zhang, Q. Functionalized Horizontally Aligned CNT Array and Random CNT Network for CO₂ Sensing. *Carbon* **2017**, *117*, 263–270. [\[CrossRef\]](#)
60. Liu, X.; Cheng, S.; Liu, H.; Hu, S.; Zhang, D.; Ning, H. A Survey on Gas Sensing Technology. *Sensors* **2012**, *12*, 9635–9665. [\[CrossRef\]](#)
61. Zhang, J.; Jiao, M.; Duan, L.; Zheng, L.; Nguyen, V.; Hung, C.M.; Nguyen, D. Gas classification system based on hybrid waveform modulation technology on FPGA. *Sens. Actuators B Chem.* **2025**, *435*, 137637. [\[CrossRef\]](#)
62. Dey, A. Semiconductor Metal Oxide Gas Sensors: A Review. *Mater. Sci. Eng. B* **2018**, *229*, 206–217. [\[CrossRef\]](#)
63. Zhao, Y.; Yuan, Y.; Zhang, H.; Chen, Z.; Zhao, H.; Wu, G.; Zheng, W.; Xue, C.; Yin, Z.; Gao, L. A Fully Integrated Electronic Fabric-Enabled Multimodal Flexible Sensors for Real-Time Wireless Pressure-Humidity-Temperature Monitoring. *Int. J. Extrem. Manuf.* **2024**, *6*, 065502. [\[CrossRef\]](#)
64. Zong, B.; Wu, S.; Yang, Y.; Li, Q.; Tao, T.; Mao, S. Smart Gas Sensors: Recent Developments and Future Prospective. *Nano-Micro Lett.* **2025**, *17*, 54. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Weber, I.C.; Güntner, A.T. Catalytic filters for metal oxide gas sensors. *Sens. Actuators B Chem.* **2022**, *356*, 131346. [\[CrossRef\]](#)
66. Wilson, A.D.; Baietto, M. Applications and Advances in Electronic-Nose Technologies. *Sensors* **2009**, *9*, 5099–5148. [\[CrossRef\]](#)
67. Zhang, C.; Xu, K.; Liu, K.; Xu, J.; Zheng, Z. Metal Oxide Resistive Sensors for Carbon Dioxide Detection. *Coord. Chem. Rev.* **2022**, *472*, 214758. [\[CrossRef\]](#)
68. Xie, Q.; Liu, M.; Sun, B.; Song, P. Efficient Detection of Triethylamine by In₂O₃@Co₃O₄ Core-Shell Nanofibers Synthesized by Coaxial Electrospinning. *Sens. Actuators B Chem.* **2025**, *439*, 137831. [\[CrossRef\]](#)
69. Chojer, H.; Branco, P.T.B.S.; Martins, F.G.; Alvim-Ferraz, M.C.M.; Sousa, S.I.V. Development of Low-Cost Indoor Air Quality Monitoring Devices: Recent Advancements. *Sci. Total Environ.* **2020**, *727*, 138385. [\[CrossRef\]](#)
70. Kong, Y.; Li, Y.; Cui, X.; Su, L.; Ma, D.; Lai, T.; Yao, L.; Xiao, X.; Wang, Y. SnO₂ Nanostructured Materials Used as Gas Sensors for the Detection of Hazardous and Flammable Gases: A Review. *Nano Mater. Sci.* **2022**, *4*, 339–350. [\[CrossRef\]](#)
71. Potyrailo, R.A.; Go, S.; Sexton, D.; Li, X.; Alkadi, N.; Kolmakov, A.; Amm, B.; St-Pierre, R.; Scherer, B.; Nayeri, M.; et al. Extraordinary Performance of Semiconducting Metal Oxide Gas Sensors Using Dielectric Excitation. *Nat. Electron.* **2020**, *3*, 280–289. [\[CrossRef\]](#)
72. Kim, H.-J.; Lee, J.-H. Highly Sensitive and Selective Gas Sensors Using P-Type Oxide Semiconductors: Overview. *Sens. Actuators B Chem.* **2014**, *192*, 607–627. [\[CrossRef\]](#)

73. Wang, J.; Ni, G.; Liao, W.; Liu, K.; Chen, J.; Liu, F.; Zhang, Z.; Jia, M.; Li, J.; Fu, J.; et al. Subsurface Engineering Induced Fermi Level De-Pinning in Metal Oxide Semiconductors for Photoelectrochemical Water Splitting. *Angew. Chem. Int. Ed.* **2023**, *62*, e202217026. [[CrossRef](#)] [[PubMed](#)]
74. Liu, K.; Zhang, J. Synergistic Enhancement Effect on Surface Au Nanoparticles Decoration on Co-Doped SnO₂ Nanobelts: High-Response and Selection for VOC Gas Sensing. *Ceram. Int.* **2025**, *51*, 2861–2870. [[CrossRef](#)]
75. Wang, H.; Liu, J.; Wei, Z.; Hu, G.; Cui, Z.; Zhao, Z.; Zhang, Y.; Li, F.; Gong, F.; Wei, S. Engineering of Au Nanoparticles over Hollow MoS₂/C Nanoreactor for Enhanced TEA Sensing at Low Temperature. *Vacuum* **2024**, *224*, 113114. [[CrossRef](#)]
76. Hu, J.; Liu, X.; Zhang, J.; Gu, X.; Zhang, Y. Plasmon-Activated NO₂ Sensor Based on Au@MoS₂ Core-Shell Nanoparticles with Heightened Sensitivity and Full Recoverability. *Sens. Actuators B Chem.* **2023**, *382*, 133505. [[CrossRef](#)]
77. Zhang, L.; Xu, J.; Yang, X.; Lei, X.; Sun, H.; Huang, Y.; Lu, H.; Ai, T.; Ma, F.; Chu, P.K. Edge-Enriched CeO₂/MoS₂ Heterostructure with Coupled Interface for Enabling Selective Room-Temperature NO₂ Detection. *Sens. Actuators B Chem.* **2024**, *419*, 136443. [[CrossRef](#)]
78. Liao, Q.; Sun, Q.; Cao, C.; Hu, J.; Wang, Y.; Li, S.; Xu, J.; Li, G.; Zhu, Y.; Wang, D. One-Dimensional Hierarchical Core-Shell Metal Oxide semiconductor@WO₃ Nanocomposites for Ppb-Level Acetone Sensing. *Sens. Actuators B Chem.* **2024**, *415*, 136008. [[CrossRef](#)]
79. Guo, W.; Huang, L.; Liu, X.; Wang, J.; Zhang, J. Enhanced Isoprene Gas Sensing Performance Based on P-CaFe₂O₄/n-ZnFe₂O₄ Heterojunction Composites. *Sens. Actuators B Chem.* **2022**, *354*, 131243. [[CrossRef](#)]
80. Kurtishaj Hamzaj, A.; Donà, E.; M Santhosh, N.; Shvalya, V.; Košiček, M.; Cvelbar, U. Plasma-Modification of Graphene Oxide for Advanced Ammonia Sensing. *Appl. Surf. Sci.* **2024**, *660*, 160006. [[CrossRef](#)]
81. Wu, Y.; Wang, Z.; Xu, L.; Wang, H.; Peng, S.; Zheng, L.; Yang, Z.; Wu, L.; Miao, J.-T. Preparation of Silver-Plated Carbon Nanotubes/Carbon Fiber Hybrid Fibers by Combining Freeze-Drying Deposition with a Sizing Process to Enhance the Mechanical Properties of Carbon Fiber Composites. *Compos. Part A Appl. Sci. Manuf.* **2021**, *146*, 106421. [[CrossRef](#)]
82. Krishna, K.G.; Parne, S.; Pothukanuri, N.; Kathirvelu, V.; Gandhi, S.; Joshi, D. Nanostructured Metal Oxide Semiconductor-Based Gas Sensors: A Comprehensive Review. *Sens. Actuators A Phys.* **2022**, *341*, 113578. [[CrossRef](#)]
83. Kim, J.-Y.; Mirzaei, A.; Kim, J.-H. Effect of ZnO Thickness on Gas Sensing Behavior of WS₂-ZnO p-n Heterojunction Nanosheets towards Reducing Gases. *J. Alloys Compd.* **2024**, *984*, 173967. [[CrossRef](#)]
84. Bai, J.; Zhao, C.; Gong, H.; Wang, Q.; Huang, B.; Sun, G.; Wang, Y.; Zhou, J.; Xie, E.; Wang, F. Debye-Length Controlled Gas Sensing Performances in NiO@ZnO p-n Junctional Core-Shell Nanotubes. *J. Phys. D Appl. Phys.* **2019**, *52*, 285103. [[CrossRef](#)]
85. Kim, D.; Shin, W.; Hong, S.; Jeong, Y.; Jung, G.; Park, J.; Lee, J.-H. Effects of Electrode Structure on H₂S Sensing and Low-Frequency Noise Characteristics in In₂O₃-Based Resistor-Type Gas Sensors. *IEEE Sens. J.* **2022**, *22*, 6311–6320. [[CrossRef](#)]
86. Chen, T.-Y.; Chen, H.-I.; Hsu, C.-S.; Huang, C.-C.; Wu, J.-S.; Chou, P.-C.; Liu, W.-C. Characteristics of ZnO Nanorods-Based Ammonia Gas Sensors with a Cross-Linked Configuration. *Sens. Actuators B Chem.* **2015**, *221*, 491–498. [[CrossRef](#)]
87. Naganaboina, V.R.; Bonam, S.; Anandkumar, M.; Deshpande, A.S.; Singh, S.G. Improved Chemiresistor Gas Sensing Response by Optimizing the Applied Electric Field and Interdigitated Electrode Geometry. *Mater. Chem. Phys.* **2023**, *305*, 127975. [[CrossRef](#)]
88. Fàbrega, C.; Casals, O.; Hernández-Ramírez, F.; Prades, J.D. A Review on Efficient Self-Heating in Nanowire Sensors: Prospects for Very-Low Power Devices. *Sens. Actuators B Chem.* **2018**, *256*, 797–811. [[CrossRef](#)]
89. Pandit, N.A.; Alshehri, S.M.; Ahmad, T. CeO₂/ZrO₂ p-n heterojunction nanostructures for efficient NO₂ gas sensing. *J. Alloys Compd.* **2024**, *1004*, 175782. [[CrossRef](#)]
90. Ojha, B.; Aleksandrova, M.; Schwotzer, M.; Franzreb, M.; Kohler, H. Thermo-Cyclically Operated Metal Oxide Gas Sensor Arrays for Analysis of Dissolved Volatile Organic Compounds in Fermentation Processes: Part I—Morphology Aspects of the Sensing Behavior. *Sens. Bio-Sens. Res.* **2023**, *40*, 100558. [[CrossRef](#)]
91. Haugen, J.-E.; Tomic, O.; Kvaal, K. A Calibration Method for Handling the Temporal Drift of Solid State Gas-Sensors. *Anal. Chim. Acta* **2000**, *407*, 23–39. [[CrossRef](#)]
92. Hyeon, J.-S.; Kim, H.-J. Baseline Calibration Scheme Embedded in Single-Slope ADC for Gas Sensor Applications. *Electronics* **2024**, *13*, 1252. [[CrossRef](#)]
93. Lee, Y.S.; Chen, J. A Robust Semi-Supervised Learning Scheme for Development of within-Batch Quality Prediction Soft-Sensors. *Eng. Appl. Artif. Intell.* **2024**, *133*, 107920. [[CrossRef](#)]
94. Jirayupat, C.; Nagashima, K.; Hosomi, T.; Takahashi, T.; Samransuksamer, B.; Hanai, Y.; Nakao, A.; Nakatani, M.; Liu, J.; Zhang, G.; et al. Breath Odor-Based Individual Authentication by an Artificial Olfactory Sensor System and Machine Learning. *Chem. Commun.* **2022**, *58*, 6377–6380. [[CrossRef](#)]
95. Zong, B.; Xu, Q.; Mao, S. Single-Atom Pt-Functionalized Ti₃C₂T_x Field-Effect Transistor for Volatile Organic Compound Gas Detection. *ACS Sens.* **2022**, *7*, 1874–1882. [[CrossRef](#)]
96. Kim, I.; Kim, W.-S.; Kim, K.; Ansari, M.A.; Mehmood, M.Q.; Badloe, T.; Kim, Y.; Gwak, J.; Lee, H.; Kim, Y.-K.; et al. Holographic metasurface gas sensors for instantaneous visual alarms. *Sci. Adv.* **2021**, *7*, eabe9943. [[CrossRef](#)]

97. Yuan, Z.; Luo, X.; Meng, F. Machine Learning-Assisted Research and Development of Chemiresistive Gas Sensors. *Adv. Eng. Mater.* **2024**, *26*, 2400782. [\[CrossRef\]](#)
98. Zhang, Q.; Zeng, R.; Lu, Y.; Zhang, J.; Zhou, W.; Yu, J. Machine Learning-Based Prediction of the Adsorption Energy of CO on Boron-Doped Graphene. *New J. Chem.* **2022**, *46*, 10451–10457. [\[CrossRef\]](#)
99. Wang, T.; Tan, X.; Wei, Y.; Jin, H. Accurate Bandgap Predictions of Solids Assisted by Machine Learning. *Mater. Today Commun.* **2021**, *29*, 102932. [\[CrossRef\]](#)
100. Liu, B.; Vu-Bac, N.; Zhuang, X.; Fu, X.; Rabczuk, T. Stochastic Integrated Machine Learning Based Multiscale Approach for the Prediction of the Thermal Conductivity in Carbon Nanotube Reinforced Polymeric Composites. *Compos. Sci. Technol.* **2022**, *224*, 109425. [\[CrossRef\]](#)
101. Geng, X.; Li, S.; Mei, Z.; Li, D.; Zhang, L.; Luo, L. Ultrafast Metal Oxide Reduction at Pd/PdO₂ Interface Enables One-Second Hydrogen Gas Detection under Ambient Conditions. *Nano Res.* **2023**, *16*, 1149–1157. [\[CrossRef\]](#)
102. Wang, B.; Li, W.; Lu, Q.; Zhang, Y.; Yu, H.; Huang, L.; Wang, T.; Liang, X.; Liu, F.; Liu, F.; et al. Machine Learning-Assisted Development of Sensitive Electrode Materials for Mixed Potential-Type NO₂ Gas Sensors. *ACS Appl. Mater. Interfaces* **2021**, *13*, 50121–50131. [\[CrossRef\]](#)
103. Krivetskiy, V.V.; Andreev, M.D.; Efitov, A.O.; Gaskov, A.M. Statistical Shape Analysis Pre-Processing of Temperature Modulated Metal Oxide Gas Sensor Response for Machine Learning Improved Selectivity of Gases Detection in Real Atmospheric Conditions. *Sens. Actuators B Chem.* **2021**, *329*, 129187. [\[CrossRef\]](#)
104. Iwata, K.; Abe, H.; Ma, T.; Tadaki, D.; Hirano-Iwata, A.; Kimura, Y.; Suda, S.; Niwano, M. Application of Neural Network Based Regression Model to Gas Concentration Analysis of TiO₂ Nanotube-Type Gas Sensors. *Sens. Actuators B Chem.* **2022**, *361*, 131732. [\[CrossRef\]](#)
105. Ogbeide, O.; Bae, G.; Yu, W.; Morrin, E.; Song, Y.; Song, W.; Li, Y.; Su, B.; An, K.; Hasan, T. Inkjet-Printed rGO/Binary Metal Oxide Sensor for Predictive Gas Sensing in a Mixed Environment. *Adv. Funct. Mater.* **2022**, *32*, 2113348. [\[CrossRef\]](#)
106. Wang, C.; Chen, Z.; Chan, C.L.J.; Wan, Z.; Ye, W.; Tang, W.; Ma, Z.; Ren, B.; Zhang, D.; Song, Z.; et al. Biomimetic Olfactory Chips Based on Large-Scale Monolithically Integrated Nanotube Sensor Arrays. *Nat. Electron.* **2024**, *7*, 157–167. [\[CrossRef\]](#)
107. Ding, X.; Zhang, Y.; Zhang, Y.; Ding, X.; Zhang, H.; Cao, T.; Qu, Z.; Ren, J.; Li, L.; Guo, Z.; et al. Modular Assembly of MXene Frameworks for Noninvasive Disease Diagnosis via Urinary Volatiles. *ACS Nano* **2022**, *16*, 17376–17388. [\[CrossRef\]](#)
108. Van Den Broek, J.; Klein Cerrejon, D.; Pratsinis, S.E.; Güntner, A.T. Selective Formaldehyde Detection at Ppb in Indoor Air with a Portable Sensor. *J. Hazard. Mater.* **2020**, *399*, 123052. [\[CrossRef\]](#)
109. Zhang, J.; Lv, F.; Li, Z.; Jiang, G.; Tan, M.; Yuan, M.; Zhang, Q.; Cao, Y.; Zheng, H.; Zhang, L.; et al. Cr-Doped Pd Metallene Endows a Practical Formaldehyde Sensor New Limit and High Selectivity. *Adv. Mater.* **2021**, *34*, 2105276. [\[CrossRef\]](#)
110. Jeong, S.-Y.; Moon, Y.K.; Wang, J.; Lee, J.-H. Exclusive Detection of Volatile Aromatic Hydrocarbons Using Bilayer Oxide Chemiresistors with Catalytic Overlayers. *Nat. Commun.* **2023**, *14*, 233. [\[CrossRef\]](#)
111. Qin, Z.; Ouyang, C.; Zhang, J.; Wan, L.; Wang, S.; Xie, C.; Zeng, D. 2D WS₂ Nanosheets with TiO₂ Quantum Dots Decoration for High-Performance Ammonia Gas Sensing at Room Temperature. *Sens. Actuators B Chem.* **2017**, *253*, 1034–1042. [\[CrossRef\]](#)
112. Hao, J.; Zhang, D.; Sun, Q.; Zheng, S.; Sun, J.; Wang, Y. Hierarchical SnS₂/SnO₂ Nanoheterojunctions with Increased Active-Sites and Charge Transfer for Ultrasensitive NO₂ Detection. *Nanoscale* **2018**, *10*, 7210–7217. [\[CrossRef\]](#) [\[PubMed\]](#)
113. Acharyya, S.; Jana, B.; Nag, S.; Saha, G.; Guha, P.K. Single Resistive Sensor for Selective Detection of Multiple VOCs Employing SnO₂ Hollowspheres and Machine Learning Algorithm: A Proof of Concept. *Sens. Actuators B Chem.* **2020**, *321*, 128484. [\[CrossRef\]](#)
114. Acharyya, S.; Nag, S.; Guha, P.K. Ultra-Selective Tin Oxide-Based Chemiresistive Gas Sensor Employing Signal Transform and Machine Learning Techniques. *Anal. Chim. Acta* **2022**, *1217*, 339996. [\[CrossRef\]](#)
115. Zhou, Q.; Geng, Z.; Yang, L.; Shen, B.; Kan, Z.; Qi, Y.; Hu, S.; Dong, B.; Bai, X.; Xu, L.; et al. A Wearable Healthcare Platform Integrated with Biomimetical Ions Conducted Metal–Organic Framework Composites for Gas and Strain Sensing in Non-Overlapping Mode. *Adv. Sci.* **2023**, *10*, 2207663. [\[CrossRef\]](#)
116. Meng, Z.; Stolz, R.M.; Mendecki, L.; Mirica, K.A. Electrically-Transduced Chemical Sensors Based on Two-Dimensional Nanomaterials. *Chem. Rev.* **2019**, *119*, 478–598. [\[CrossRef\]](#)
117. Song, Z.; Ye, W.; Chen, Z.; Chen, Z.; Li, M.; Tang, W.; Wang, C.; Wan, Z.; Poddar, S.; Wen, X.; et al. Wireless Self-Powered High-Performance Integrated Nanostructured-Gas-Sensor Network for Future Smart Homes. *ACS Nano* **2021**, *15*, 7659–7667. [\[CrossRef\]](#)
118. Xiao, F.; Lei, D.; Liu, C.; Li, Y.; Ren, W.; Li, J.; Li, D.; Zu, B.; Dou, X. Coherent Modulation of the Aggregation Behavior and Intramolecular Charge Transfer in Small Molecule Probes for Sensitive and Long-term Nerve Agent Monitoring. *Angew. Chem. Int. Ed.* **2024**, *63*, e202400453. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.