



Recent advances in room-temperature hydrogen sulfide gas sensors: materials design, interface engineering, and sensing mechanisms

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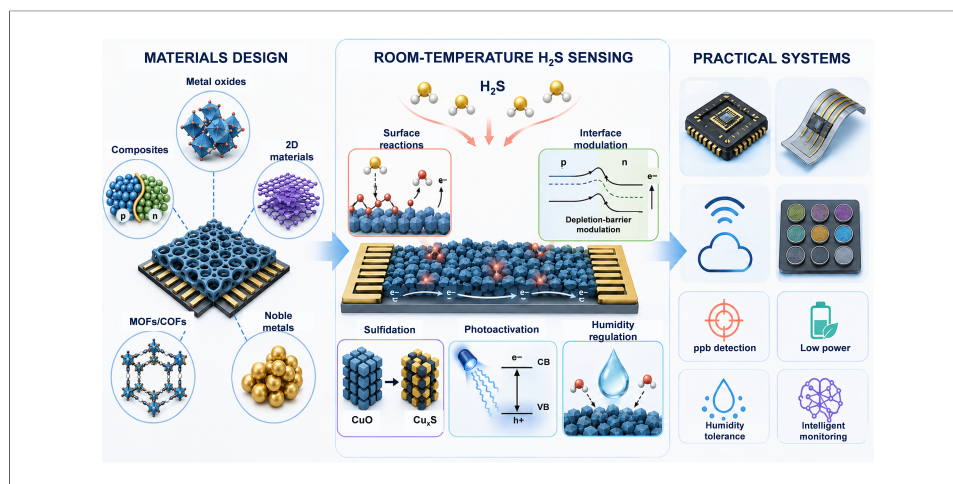
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Abstract

Hydrogen sulfide (H_2S) is a highly toxic, corrosive, and flammable gas generated from industrial production, petroleum refining, wastewater treatment, municipal waste, and anaerobic decomposition of organic matter. Reliable H_2S monitoring is therefore essential for environmental safety, industrial process control, and human health protection. Conventional chemiresistive H_2S sensors based on metal oxide semiconductors often require elevated operating temperatures, which increase power consumption and restrict device miniaturization, flexible integration, and long-term deployment. Room-temperature H_2S sensors have consequently attracted increasing attention as low-power sensing platforms. This review summarizes recent progress in room-temperature H_2S sensing across single-component semiconductors, composite heterojunctions, two-dimensional materials and their heterostructures, metal-organic-framework-based materials, noble-metal-sensitized systems, and photoactivated sensors. Representative preparation methods, structure-performance relationships, and key sensing parameters are compared. Particular emphasis is placed on sensing mechanisms and supporting evidence, including oxygen-adsorption-mediated conductivity modulation, H_2S -induced sulfidation, interfacial

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barrier modulation, defect-related activation, noble-metal-mediated catalytic and electronic sensitization, photoinduced carrier and photothermal effects, and framework-mediated transduction. Humidity interference and mitigation are further discussed, together with advances in micro electromechanical system (MEMS) devices, flexible and self-powered platforms, wireless sensing, sensor arrays, electronic noses, and AI-assisted identification. Finally, challenges and future directions are highlighted, including ppb-level detection, reversibility, humidity tolerance, complex-gas selectivity, long-term stability, standardized evaluation, real-sample validation, and intelligent-system integration. This review provides a systematic framework for developing reliable, low-power, and application-oriented room-temperature H₂S sensors.

INTRODUCTION

H₂S is colorless, highly corrosive, and extremely toxic, with a characteristic rotten-egg odor at even low concentrations^[1,2]. The main sources of H₂S include industrial emissions, petroleum and natural gas processing, wastewater treatment, municipal waste, and anaerobic bacterial decomposition. Exposure to low H₂S concentrations can cause eye and respiratory irritation as well as neurological discomfort, whereas exposure to high concentrations can lead to respiratory paralysis, loss of consciousness, and death^[3]. Thus, sensitive, selective, and rapid H₂S detection is required for occupational safety, environmental monitoring, food-spoilage assessment, and potential breath analysis.

Chemiresistive metal-oxide-semiconductor (MOS) sensors are attractive because of their simple structure, low cost, and compatibility with microfabrication. However, most require temperatures above 100 °C to accelerate oxygen adsorption, surface reactions, and desorption; high-performing examples can operate at 200–400 °C^[4,5]. This energy demand complicates portable, wearable, and distributed sensing.

Room-temperature H₂S sensing has therefore been pursued through material, interface, and external-activation strategies. ZnO, WO₃, CuO, and In₂O₃ benefit from morphology and defect regulation^[6–12]; composites exploit interfacial charge redistribution and, especially in CuO-containing p-n systems, H₂S-driven surface chemistry^[13–18]. Graphene derivatives^[19–27], TMDs^[28–35], MXenes^[36–38], covalent organic frameworks (COFs)^[39–41], metal-organic frameworks (MOFs)^[42–47], noble metals^[48–58], and photoactivation^[59–61] provide accessible adsorption sites, efficient transport, molecular recognition, catalytic activation, or carrier control.

Recent room-temperature H₂S sensing research has increasingly focused on low-power operation, humidity tolerance, ppb-level detection, and flexible or miniaturized device integration. Accordingly, sensor performance should be evaluated not only by response magnitude but also by detection limit, response and recovery kinetics, long-term stability, humidity tolerance, and practical device compatibility^[13,62,63].

Nevertheless, high response under controlled conditions does not guarantee reliable practical operation. At room temperature, adsorbed water can compete with H₂S and oxygen species, alter surface hydroxylation and interfacial charge transfer, and cause baseline drift. It may either inhibit H₂S adsorption or promote its ionization, hydrolysis, and water-mediated charge transport. Humidity management should therefore regulate water accessibility and water-surface interactions rather than simply suppress water adsorption^[64–69]. Practical deployment also requires integration of sensing materials with electrodes, packaging, power, signal processing, and communication modules. micro electromechanical system (MEMS), flexible and self-powered devices, wireless systems, sensor arrays, electronic noses, and machine-learning-assisted identification are important for application-oriented H₂S monitoring^[70–74].

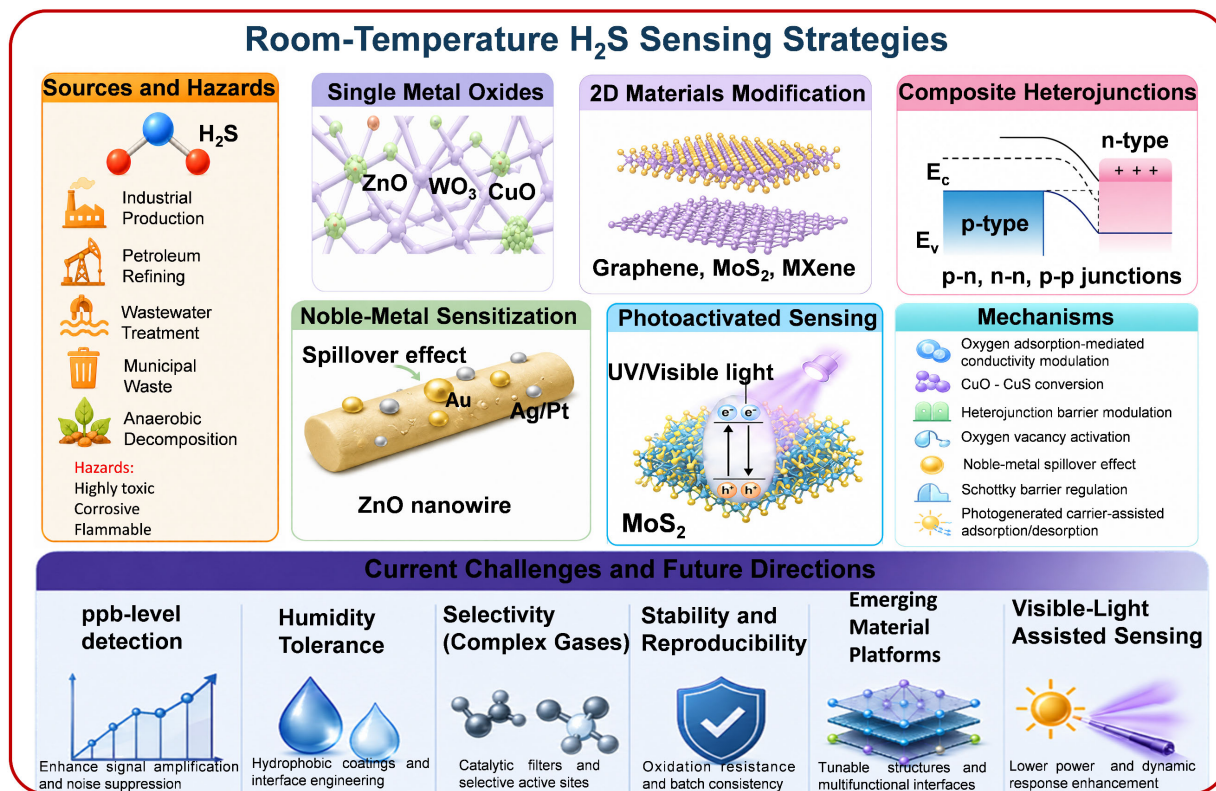


Figure 1. Roadmap of representative material strategies for room-temperature H₂S sensing and their target performance outcomes.

In this review, recent advances in room-temperature H₂S sensors are systematically summarized according to sensing materials and functionalization strategies, including single-material-based sensors, conventional composite and heterojunction sensors, two-dimensional material platforms and their heterostructures, noble-metal-sensitized sensors, and photoactivated sensing systems. For consistency throughout this review, room temperature (RT) encompasses both operating temperatures of 20–30 °C and conditions explicitly described by the original authors as room or ambient temperature when no numerical value is reported. Operating temperatures above 30 °C are reported using their specific values. For each material category, representative preparation methods, structural features, sensing performance, structure-property relationships, and mechanistic interpretations are critically compared, with particular attention to the evidence supporting the proposed sensing pathways. The review then discusses humidity interference and mitigation strategies, followed by device design, MEMS and flexible integration, self-powered and wireless sensing, sensor arrays, electronic noses, and AI-assisted gas identification. Finally, current challenges and future opportunities are evaluated in terms of ppb-level detection, reversibility, humidity tolerance, mixed-gas selectivity, standardized performance evaluation, long-term reproducibility, total system power, real-sample validation, and scalable intelligent monitoring [Figure 1].

SINGLE-MATERIAL-BASED GAS SENSORS

ZnO-based gas sensors

Zinc oxide (ZnO) is a typical n-type MOS with a wide bandgap of 3.37 eV, high exciton binding energy, high electron mobility, strong ultraviolet absorption, and good chemical stability^[75–77]. These features make ZnO one of the most widely studied sensing materials. At room temperature, the H₂S response of pristine ZnO is generally limited by insufficient surface reaction kinetics, therefore, nanostructure engineering is essential for increasing active adsorption sites and shortening diffusion pathways^[78,79]. Wang *et al.* fabricated ZnO nanorod thick films by a hydrothermal method and controlled the ZnAc₂/NaOH ratio to regulate

morphology and selectivity^[12]. The resulting sensor showed preferential ethanol response at 350 °C but selective H₂S detection at room temperature, with $R_a/R_g = 1.7$ ^[12], whereas vapor-grown vertically aligned nanorods formed a porous flower-like network that increased exposed area^[78]. Other comb-like, prismatic, and belt-like ZnO architectures likewise demonstrate that anisotropic and porous structures can improve H₂S accessibility^[6,80,81].

Overall, ZnO enables room-temperature H₂S detection, but its performance remains limited by sluggish oxygen-mediated surface reactions, highlighting the importance of defect and nanostructure engineering.

WO₃-based gas sensors

Tungsten trioxide (WO₃) is a chemically stable n-type metal-oxide semiconductor that has been extensively investigated for H₂S sensing^[82–84]. Its H₂S response mainly originates from oxygen-mediated surface reactions that modulate carrier concentration and conductivity. Nanostructured WO₃ films and colloidal quantum dots have shown improved low-temperature H₂S sensing owing to increased surface exposure and enhanced surface-controlled charge transport^[11,85]. Hoel *et al.* further reported a 250-fold increase in conductivity toward 5 ppm H₂S at room temperature using WO₃ nanoparticles^[8]. These results indicate that particle sizes approaching the Debye length are beneficial.

Pristine WO₃ remains limited by sluggish room-temperature activation and incomplete recovery. Its sensing performance is strongly governed by the relationship between particle size and Debye length, together with W⁵⁺/W⁶⁺ redox states and oxygen-vacancy distributions.

CuO-based gas sensors

Copper oxide (CuO) is a narrow bandgap p-type semiconductor and one of the most effective room-temperature H₂S sensing materials^[10,86]. In addition to oxygen-mediated reactions, H₂S can form conductive copper sulfide species and thus create additional conduction paths^[10,87,88]. Porous CuO nanosheets and biotemplated tubular structures have demonstrated that accessible surface sites, shortened diffusion pathways, and Cu/CuS-related conductive pathways can improve room-temperature H₂S sensing^[10,88]. More notably, sea-anemone-like CuO nanoarrays achieved a response of 24.08 toward 5 ppb H₂S with negligible responses to common interfering gases^[87]. Their high sensitivity was attributed to nanotentacle diameters approaching the Debye length and point-to-point contacts that amplified modulation of the hole-accumulation layer, while the preferential reaction of H₂S with chemisorbed oxygen contributed to selectivity. These results highlight the importance of coupling gas-accessible CuO architectures with Debye-length-scale conduction channels.

Despite its high H₂S sensitivity, pristine CuO often suffers from incomplete recovery, baseline drift, and poor reversibility because of H₂S-induced sulfide formation. Competitive water adsorption can further destabilize its response and baseline. Although MEMS and surface-acoustic-wave platforms improve power efficiency and portability^[89,90], the central challenge remains controlling reversible CuO/Cu_xS conversion while maintaining strong H₂S affinity and humidity resistance.

In₂O₃-based gas sensors

Indium oxide (In₂O₃) is a typical n-type MOS with high electrical conductivity, good chemical stability, and abundant oxygen-vacancy-related active sites. Early studies demonstrated the evolution of In₂O₃-based H₂S sensors from high-temperature nanocrystalline materials to porous nanotubes and nanowires capable of room-temperature operation^[91,92]. The improved performance of the latter was associated with their gas-accessible one-dimensional architecture and H₂S-induced surface sulfuration.

More importantly, ordered porous In_2O_3 ultrathin films exhibited an ultrahigh room-temperature response through a proposed humidity-assisted mechanism. Ambient water promoted H_2S hydrolysis, chemisorbed oxygen desorption, and the formation of a conductive surface water layer, thereby markedly increasing sensor conductance^[93]. Porous In_2O_3 nanoparticles achieved a response of 26,268.5 toward 1 ppm H_2S with a detection limit of 1 ppb at room temperature, while UV-generated holes were proposed to promote oxygen desorption and narrow the electron-depletion layer, thereby regulating surface conductivity^[59]. In_2O_3 nanocubes, colloidal quantum dots, and oxidized thin films have also demonstrated that crystal size, ligand-mediated surface states, and film structure strongly influence H_2S adsorption and carrier transport^[94–96]. These findings identify porous architecture, sulfuration, surface oxygen regulation, and humidity-assisted reactions as the principal factors governing room-temperature H_2S sensing by In_2O_3 .

For practical room-temperature operation, In_2O_3 -based H_2S sensors still require further improvement in reversibility, humidity calibration, and quantitative reliability. The sulfuration of In_2O_3 and humidity-induced H_2S hydrolysis can greatly amplify the sensing signal, but they may also cause baseline drift and recovery instability if not well controlled. Future studies should therefore clarify the coupled roles of surface oxygen species, hydroxyl groups, $\text{In}_2\text{O}_3/\text{In}_2\text{S}_3$ conversion, and surface-state-regulated charge transport. In addition, ligand engineering in In_2O_3 quantum dots and thickness/orientation control in In_2O_3 thin films may provide effective routes toward fast, stable, and low-power room-temperature H_2S detection.

As summarized in Table 1, single-material sensors achieve room-temperature H_2S detection mainly through increased surface accessibility and enhanced charge modulation. Porous architectures and dimensions approaching the Debye length increase active-site exposure and amplify surface-induced conductivity changes. However, their sensing pathways remain material-dependent. ZnO and WO_3 rely primarily on oxygen-mediated surface reactions and are limited by sluggish kinetics. CuO achieves high sensitivity through H_2S -induced CuO -to- Cu_xS conversion, but excessive sulfuration compromises recovery and repeatability. In_2O_3 combines oxygen-mediated reactions, humidity-assisted hydrolysis, and partial sulfuration, producing high responses but also pronounced humidity dependence and baseline instability. Future priorities should therefore focus on improving surface reactivity in ZnO and WO_3 , balancing H_2S affinity with reversible sulfuration in CuO , and regulating humidity-related reactions in In_2O_3 . These material-specific challenges must be addressed to balance response, recovery, selectivity, humidity tolerance, and long-term stability.

TWO-DIMENSIONAL MATERIAL PLATFORMS AND THEIR HETEROSTRUCTURES

Two-dimensional materials are particularly attractive for room-temperature H_2S sensing because their atomically thin structures provide high surface accessibility and allow adsorption-induced charge transfer to directly modulate the conduction channel^[31,32,111,112]. Different material families contribute distinct functions. Graphene and reduced graphene oxide (rGO) provide continuous conductive networks, improve oxide dispersion, and introduce oxygen-containing adsorption sites^[23,113,114]. Transition metal dichalcogenides (TMDs) offer tunable semiconducting channels, exposed edge sites, and chalcogen vacancies that regulate H_2S adsorption and interfacial charge transfer^[28,115,116]. MXenes combine high electrical conductivity with chemically active surface terminations, enabling rapid signal transport and tunable gas-surface interactions^[61,117,118]. Two-dimensional COFs (2D COFs) further provide ordered pores, designable recognition sites, and conjugated frameworks for molecularly regulated adsorption and transduction^[39–41]. When coupled with metal oxides, these materials are not merely structural supports. They can suppress oxide aggregation, improve gas diffusion and carrier transport, and create electronically active heterointerfaces whose barriers or space-charge regions are modulated by H_2S exposure. Their sensing performance therefore depends strongly on defect density, layer stacking, surface chemistry, and interface quality.

Table 1. Representative single-material room-temperature H₂S sensors

Material	Preparation method	O. T. (°C)	Conc. (ppm)	Response	Tres/Trec	LOD	Key feature/mechanism	Ref.
ZnO	Hydrothermal	RT	0.05	1.7 ^a	-	-	Morphology-controlled selectivity	[12]
ZnO	CVD	RT	4	6 ^a	22/540 s	100 ppb	Anisotropic morphology increases adsorption sites	[6]
ZnO	sol-gel	RT	0.75	73.3% ^b	93/90 s	30ppb	<i>In-situ</i> synthesis strengthens electrode contact	[97]
WO ₃	Gas deposition	RT	35	3500 ^c	10 min/-	-	Nanoparticle film and high surface area	[8]
CuO	Hydrothermal	RT	0.2	5.01 ^a	336/543 s	10 ppb	Porosity and CuO/CuS-related conductive pathways	[10]
CuO	<i>In-situ</i> growth	RT	0.005	24.08 ^a	102/539 s	1.52 ppb	Nanotentacle diameter close to Debye length	[87]
CuO	Hydrothermal	RT	1	365.2 ^a	55.2/2106 s	0.1 ppb	Reversible CuO-to-CuS phase transition boosts conductance shift	[98]
In ₂ O ₃	Colloidal template	RT	50	2.4 × 10 ^{5a}	140/1440 s	-	Ordered porous film and humidity-induced H ₂ S hydrolysis	[93]
In ₂ O ₃	High-temperature Pyrolysis	37 °C	5	1.2 ^a	6/10 s	-	Surface-state-regulated transport and ligand exchange	[95]
In ₂ O ₃	Thermal oxidation of In films	RT	5	68% ^b	18/504 s	100 ppb	Thickness-dependent morphology and abundant surface oxygen	[96]

Response^a = R_a/R_g or R_g/R_a , R_a : resistance of the sensor in air, R_g : resistance of the sensor exposed to H₂S gas; Response^b = $\Delta R/R_a \times 100\%$ or $\Delta R/R_g \times 100\%$, ΔR : the change in resistance, which equals $|R_a - R_g|$; Response^c = G_{gas}/G_{air} or G_{air}/G_{gas} , G_{air} : conductance of the sensor in air, G_{gas} : conductance of the sensor exposed to H₂S gas. O. T.: operating temperature; Conc.: concentration; LOD: limit of detection; Tres/Trec: response time/recovery time; RT: room temperature; “-” Indicates that the article does not report this performance metric.

COMPOSITE MATERIAL-BASED GAS SENSORS

Composite heterostructures have been developed to overcome the sluggish kinetics, limited response, and incomplete recovery of single-component sensors at room temperature^[99,100]. Cu₂O/ZnO heterostructures achieved a response of 8.53×10^4 toward 1 ppm H₂S with a detection limit of 10 ppb at room temperature. Post-exposure S 2p X-ray photoelectron spectroscopy (XPS) revealed sulfur-containing species, supporting H₂S-induced surface sulfidation. On this basis, weakening of the p-n interfacial barrier and formation of additional sulfide-related conductive pathways were proposed to account for the pronounced resistance modulation^[101]. CuO-nanocluster-decorated flower-like In₂O₃ exhibited a response of 18,108 toward 10 ppm H₂S, a response time of 4 s, and a detection limit of 10 ppb at 25 °C. Density functional theory (DFT) calculations supported enhanced H₂S adsorption and interfacial charge transfer, while p-n barrier modulation and possible CuO sulfidation were proposed as additional contributions^[102]. These results demonstrate that CuO-containing composites enhance H₂S sensing through coupled surface sulfidation, interfacial barrier modulation, and gas-accessible nanostructures.

Beyond CuO-based systems, other oxide heterostructures have also improved room-temperature H₂S sensing through enhanced gas transport and interfacial charge modulation. MoO₃/MnO₂ n-n heterostructures achieved a theoretical detection limit of 4.58 ppb and maintained relatively stable performance over 30%-90% relative humidity (RH)^[103]. SnO₂@ZnO heterostructures combined hierarchical diffusion pathways, H₂S-induced surface reactions, and interfacial charge transfer, as supported by spectroscopic characterization and DFT calculations^[2]. Core-shell n-SnO₂@p-SnO heterojunctions achieved a response of 66.7 toward 30 ppm H₂S with a response time of 1 s^[104]. SnO₂ quantum-dot-decorated α -Fe₂O₃ hollow cubes further demonstrated the contribution of porous heterointerfaces to oxygen adsorption and carrier transport^[105].

Conducting polymer/oxide composites offer an alternative route for room-temperature H₂S sensing by coupling polymer conductivity modulation with oxide surface activity and interfacial charge transfer, as

Table 2. Representative composite materials for room-temperature H₂S sensing

Material	O. T. (°C)	Conc. (ppm)	Response	Tres/Trec	LOD	Key feature/mechanism	Ref.
CuO/TiO ₂	RT	100	46.81% ^b	-	3 ppm	Flexible nanochannel structure; barrier modulation	[100]
CuO/In ₂ O ₃	RT	5	9,170 ^a	-	-	Electrospun fibers; strong CuO-H ₂ S interaction	[16]
ZnO/CuO	RT	1	3,672 ^a	-/<15 s	-	Rapid response with strong CuO-H ₂ S interaction	[13]
PANI/ZnO	RT	2	11.5% ^b	63/12 s	100 ppb	Conductive polymer charge-transfer mechanism	[107]
CuO/In ₂ O ₃	RT	10	58,000 ^a	2 s/-	50 ppb	2D porous nanosheets; CuO sensitization; p-n heterojunction;	[108]
CdS/Co ₃ O ₄	RT	10	1.04 ^c	86/51 s	200 ppb	p-n heterojunction; hierarchical porous nanoflower structure; increased gas-accessible active sites	[109]
GC/Fe ₂ O ₃	50 °C	1	25.2 ^a	26/2430 s	1 ppb	Bio-template hierarchical tubes; graphitized carbon decoration; abundant oxygen vacancies; moisture resistance	[110]
Cu ₂ O/ZnO	RT	0.01	61 ^d	-	10 ppb	p-n barrier modulation; Cu ₂ S conductive pathways; breath validation	[101]
MoO ₃ /MnO ₂	RT	1	5.71 ^a	40/42 s	4.58 ppb	Oxygen vacancies; adsorbed oxygen; interfacial charge transfer	[103]
SnO ₂ @SnO	RT	30	66.7 ^a	1/174 s	850 ppb	Coupled depletion/space-charge modulation; humidity-assisted reaction	[104]

Response ^a = R_a/R_g or R_g/R_a ; R_a : resistance of the sensor in air, R_g : resistance of the sensor exposed to H₂S gas; Response ^b = $\Delta R/R_a \times 100\%$ or $\Delta R/R_g \times 100\%$, ΔR : the change in resistance, which equals $|R_a - R_g|$; Response ^c = $\Delta R/R_a$, ΔR : the change in resistance, which equals $|R_a - R_g|$; Response ^d = $(I_{gas} - I_{air})/I_{air} \times 100\%$, I_{air} and I_{gas} represent the currents in ambient air and the target gas atmosphere under the bias of 1 V. O. T.: operating temperature; Conc.: concentration; LOD: limit of detection; Tres/Trec: response time/recovery time; RT: room temperature; “-” Indicates that the article does not report this performance metric.

demonstrated by the improved response and kinetics of PANI/ZnO relative to its individual components^[106,107].

As summarized in Table 2, oxide/oxide and polymer/oxide composites improve room-temperature H₂S sensing primarily by coupling surface reactions with heterointerfacial charge modulation. Recent designs have evolved from simple component mixing toward controlled core-shell, hollow, and hierarchical porous architectures that increase the utilization of functional interfaces. CuO-loaded porous In₂O₃ nanosheets exemplify this strategy by combining accessible diffusion pathways with CuO/In₂O₃ interfacial modulation^[108]. However, the resulting response depends strongly on component ratio, interface continuity, phase stability, and the reversibility of H₂S-induced chemical changes. Future work should therefore prioritize reproducible interface construction and distinguish the contributions of heterojunction-barrier modulation, surface sulfuration, and conductive-network changes under humid and mixed-gas conditions.

Graphene-based gas sensors

Functionalized graphene and rGO have been widely investigated as functional components in H₂S sensors because their high specific surface area and favorable charge-transport properties can promote gas adsorption and transduce adsorption-induced charge transfer into measurable electrical signals^[25,119,120]. Rather than acting as passive supports, they can serve as conductive scaffolds, nanocrystal-growth templates, and interfacial charge-transfer media. In particular, the residual oxygen-containing groups and structural defects of rGO provide adsorption and anchoring sites, while its conductive network facilitates carrier transport between semiconductor components. In oxide/rGO composites, these effects can be coupled with heterojunction-barrier modulation and changes in surface oxygen adsorption, thereby amplifying H₂S-induced resistance variations. The resulting performance depends strongly on the reduction degree, defect density, layer stacking, and interfacial contact of rGO.

Early studies showed that functionalized graphene could regulate the nucleation and dispersion of Cu₂O nanocrystals while providing conductive pathways for room-temperature H₂S sensing^[26]. Liu *et al.* subsequently constructed a well-defined Cu₂O/graphene heterojunction that achieved responses of 24,125.8% toward 500 ppb H₂S and 386% toward 5 ppb H₂S at 20 °C^[19]. Other graphene/oxide composites have further demonstrated that rGO can improve oxide dispersion, adsorption-site accessibility, and carrier transport, while dopants, hollow structures, and heterointerfaces provide additional pathways for H₂S activation and resistance modulation^[21,22,27]. More recently, Amith *et al.* integrated an rGO-Er₂O₃/Co₃O₄ composite with a low-cost disc electrode^[114]. The optimized sensor achieved a response of 75% toward 10 ppm H₂S, response and recovery times of 47 and 11 s, and stability exceeding 100 days^[114]. These studies show that graphene-based modification has evolved from simple conductivity enhancement toward coordinated control of oxide growth, charge transport, and heterointerfacial properties. However, reliable performance still requires precise regulation of rGO reduction, defect density, layer restacking, humidity sensitivity, and graphene/oxide interface quality.

Comparable improvements in response magnitude and response/recovery kinetics have also been reported for SnO₂ quantum-wire/rGO, CeO₂/graphene, and WO₃/rGO composites, further supporting the role of graphene in facilitating carrier transport and interfacial resistance modulation^[24,25,121].

Transition-metal dichalcogenide-based gas sensors

TMDs, particularly MoS₂ and WS₂, have attracted widespread attention in the field of room-temperature H₂S sensing due to their semiconductor layered structures, which feature tunable bandgaps, abundant edge sites, and defect-sensitive surface chemistry^[30,122]. Kundu *et al.* demonstrated that the response of liquid-phase-exfoliated WS₂ nanosheets was strongly dependent on gas flow rate, highlighting the importance of mass transport and testing conditions for ultrathin sensing layers^[9]. MoS₂-GO hybrids further achieved a response of 39.16% toward 100 ppm H₂S at 28 °C with a response time of 6.13 s^[123]. Coupling TMDs with metal oxides provides additional interfacial amplification. Porous CuO/MoS₂ p-n heterostructures improved H₂S response and selectivity through increased surface accessibility and interfacial charge modulation^[18]. Huo *et al.* constructed In₂O₃@MoS₂ heterojunction fibers that exhibited a response of 460.61 toward 50 ppm H₂S and a detection limit of 3 ppb at room temperature^[28]. Beyond MoS₂, MOF-derived α -Fe₂O₃ hollow nanospheres decorated with MoSe₂ nanoflowers achieved a response of 57.7 toward 30 ppm H₂S with response and recovery times of 50 and 53 s^[124]. These studies demonstrate that TMD-based heterostructures combine edge- and defect-mediated adsorption with oxide-supported gas diffusion and junction-induced charge modulation. Further progress requires reproducible control of layer stacking, defect density, interfacial structure, humidity interference, and room-temperature desorption.

MXene-based gas sensors

MXenes, particularly Ti₃C₂T_x, are attractive for low-power H₂S sensing because of their high electrical conductivity, chemically active surface terminations, and tunable interfacial properties. Recent studies have extended their role beyond conductive additives by integrating molecular enrichment, termination-dependent adsorption, and external activation^[125-127]. Ding *et al.* assembled Co-MOF nanoparticles on Ti₃C₂T_x nanosheets to form a 0D-2D heterostructure in which the porous MOF enriched H₂S molecules and the MXene provided rapid electron transport^[125]. The sensor achieved a response of 11.1 toward 400 ppb H₂S with an experimental detection limit of 50 ppb, demonstrating the value of coupling molecular preconcentration with conductive transduction^[125]. Ti₃C₂T_x-organic composites further preserved the inherent H₂S selectivity of MXene while producing a 30-fold enhancement in sensing response^[128]. DFT calculations indicated that mixed O, OH, and F terminations strongly influenced H₂S adsorption and charge transfer, emphasizing that termination composition is a critical determinant of MXene sensing behavior^[128]. Han *et al.* developed an near-infrared (NIR)-activated MXene/PbS heterostructure that achieved a response

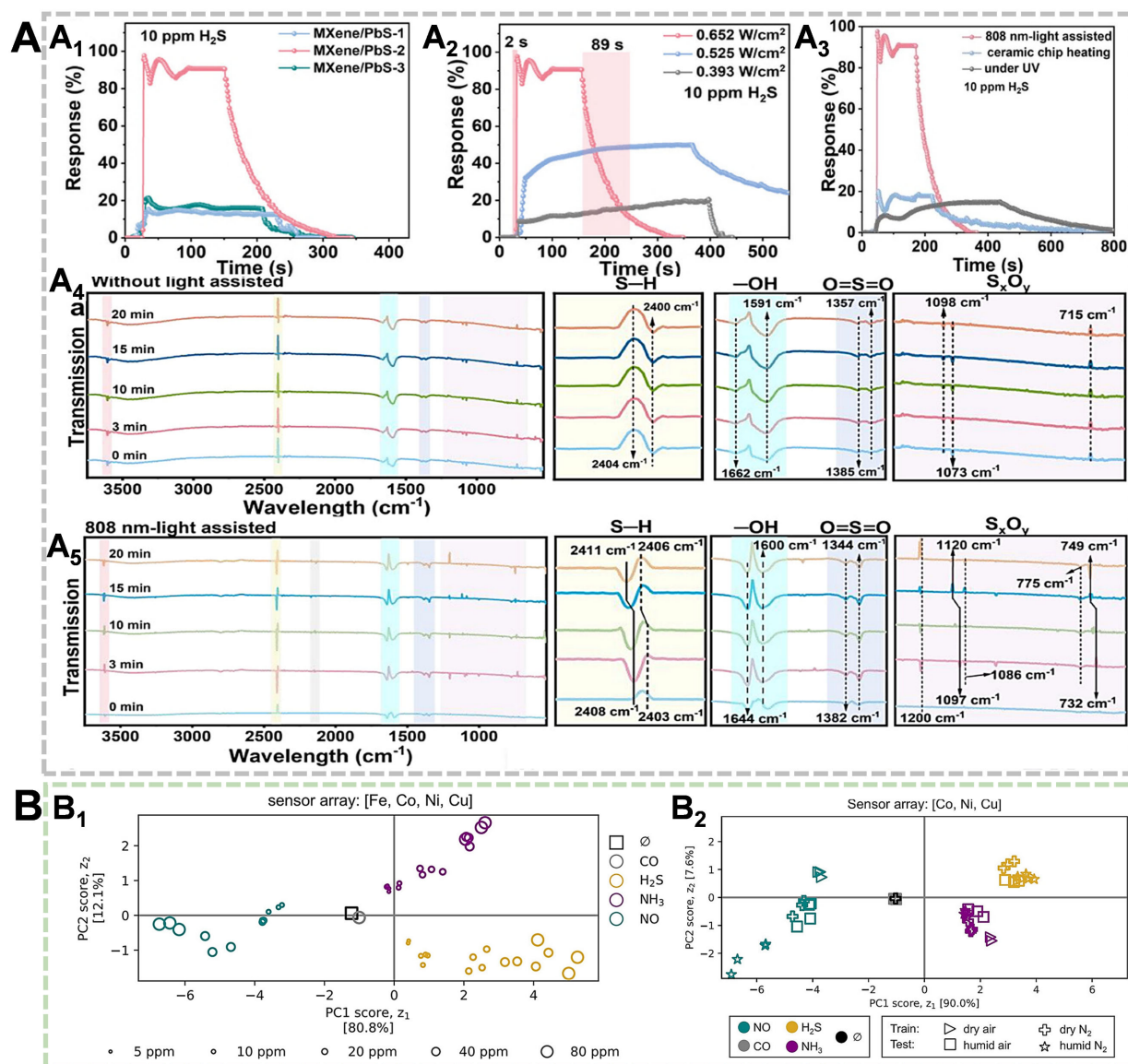


Figure 2. Performance and mechanisms of 2D-material-based H₂S sensors. (A) MXene/PbS responses to 10 ppm H₂S under NIR irradiation (0.525 W cm⁻², A₁), varied 808 nm power (A₂), and NIR, matched-temperature heating, and UV conditions (A₃), with *in situ* DRIFTS under dark and NIR conditions (A₄-A₅). Reproduced with permission from Ref.^[126]. Copyright 2025, Wiley-VCH; (B) PCA plots of the M-COF-DC-8 (M = Fe, Co, Ni, Cu) array responses, evaluating discrimination of the carrier gas, NO, CO, H₂S, and NH₃ and their different concentrations (B₁); PCA plot evaluating discrimination of NO, CO, H₂S, and NH₃ (80 ppm) by the M-COF-DC-8 (M = Co, Ni, Cu) array under humidity, with compressed response vectors under dry (training) and humid (projected onto dry-trained PCs) conditions (B₂). Reproduced from Ref.^[39], under CC BY 4.0 license. For Figure 2A₁-A₃, response (%) = (R_{air} - R_{gas})/R_{air} × 100%, where R_{air} and R_{gas} denote the resistances in air and H₂S, respectively. DRIFTS: Diffuse reflectance infrared Fourier transform spectroscopy; NIR: near-infrared; PCA: principal component analysis; UV: ultraviolet; COF: covalent organic framework; PC: principal component.

of 90% toward 10 ppm H₂S, response and recovery times of 2 and 89 s, and stable operation for up to 60 days [Figure 2A]^[126]. Its enhanced performance was attributed to improved NIR absorption and carrier separation within the heterostructure, together with photothermal acceleration of surface reaction and desorption kinetics. These studies show that MXene-based sensors are evolving into multifunctional platforms that integrate adsorption, charge transport, and external activation. Practical application, however, still requires improved control over oxidation, surface-termination stability, layer restacking, humidity interference, and batch-to-batch reproducibility.

Two-dimensional covalent organic framework-based gas sensors

2D COFs are crystalline porous polymers with molecularly tunable pores, recognition sites, π -conjugated backbones, and charge-transport properties. Meng *et al.* developed the intrinsically conductive nickel-phthalocyanine COF Ni-COF-DC-8 with a bulk conductivity of $2.51 \times 10^{-3} \text{ S m}^{-1}$ ^[40]. The corresponding chemiresistive sensor exhibited a response of 62% toward 40 ppm H₂S and a theoretical detection limit of 204 ppb, with the signal attributed to charge transfer between H₂S and the nickel-phthalocyanine units^[40]. Benedetto *et al.* subsequently constructed an array of isostructural M-COF-DC-8 materials containing Fe, Co, Ni, or Cu centers. Cu-COF-DC-8 achieved the highest response of approximately 99% toward 80 ppm H₂S and a theoretical detection limit of 28 ppb in dry N₂, while the array enabled discrimination among H₂S, NO, CO, and NH₃ under both dry and humid conditions [Figure 2B]^[39]. Beyond chemiresistive sensing, a nanoporous COF optical-waveguide film achieved a response time below 2 s and a detection limit of 1.07 ppb through proton transfer at triazine-containing sites and the resulting refractive-index change^[41]. These studies demonstrate that COFs can regulate both molecular recognition and signal transduction through framework-level design. Their practical development, however, requires improved conductivity, crystallinity, film uniformity, reversibility, and humidity stability.

In summary, graphene/rGO, TMDs, MXenes, and 2D COFs share high surface accessibility and short gas-diffusion pathways, but differ substantially in their sensing functions. Graphene and rGO mainly provide conductive networks and heterointerfacial charge transport, while their performance is sensitive to reduction degree, layer restacking, and humidity-induced drift. TMDs contribute semiconducting channels, edge sites, and chalcogen vacancies for H₂S adsorption and interface modulation, although defect reproducibility and slow desorption remain concerns. MXenes combine high conductivity with termination-dependent adsorption and interfacial chemistry, but oxidation and batch-dependent surface composition limit stability. COFs offer molecularly designable pores and coordination sites for selective H₂S recognition, while insufficient conductivity and poor film uniformity constrain electrical transduction. Coupling these materials with metal oxides or other functional phases can integrate gas accessibility with interfacial charge modulation, but the resulting enhancement depends strongly on defect density, layer stacking, surface chemistry, and interface quality. Future studies should therefore prioritize reproducible material preparation, operando analysis of interface evolution, and standardized evaluation under humid and long-term operating conditions.

METAL-ORGANIC FRAMEWORK-BASED GAS SENSORS

MOFs are versatile platforms for room-temperature H₂S sensing because their pore environments, metal sites, and coordination structures can be tailored to regulate gas adsorption, molecular enrichment, and chemical reactivity^[44,45]. MOF-based sensing materials can be divided into three categories according to framework retention and charge-transport behavior. Pristine MOFs preserve their coordination frameworks and mainly utilize pore confinement, open metal sites, and host-guest interactions for H₂S recognition. Conductive MOFs additionally contain intrinsic charge-transport pathways that directly convert gas-framework interactions into chemiresistive signals^[42,47]. MOF-derived materials sacrifice the original framework during thermal or chemical conversion but inherit its morphology and metal distribution, producing porous oxides, carbon-containing phases, or heterostructures with accessible defects and interfaces^[124,129]. These three categories therefore emphasize molecular recognition, direct electrical transduction, and structural inheritance, respectively, providing complementary routes for low-power H₂S sensing.

Pristine MOF-based gas sensors

Pristine and framework-retaining MOFs provide permanent porosity, tunable pore environments, and accessible metal sites for H₂S enrichment and molecular recognition. Luo *et al.* compared MIL-100(Fe), HKUST-1(Cu), and bimetallic MOF-919(Fe-Cu), among which MOF-919 exhibited the highest response of

931.6% toward 10 ppm H₂S and a detection limit of 0.31 ppm at room temperature^[44]. The improvement was attributed to suitable pore dimensions and cooperative Fe/Cu adsorption sites, demonstrating that metal-site chemistry is as important as surface area in determining MOF sensing behavior. A porous Cu-MOF was also employed as the sensing electrode in a K₂Fe₄O₇-based mixed-potential sensor, achieving a detection limit below 5 ppb at room temperature. Electrode passivation extended stable operation to 66 cycles by suppressing the accumulation of sulfur-containing products^[43]. In a different transduction mode, Cu-modified MOF-808 enabled reversible colorimetric detection of 100 ppm H₂S through Cu²⁺/Cu⁺ redox conversion, with response times of 1.3–2.2 min and thermal regeneration under moist air^[45]. These studies demonstrate that intact MOFs can combine pore-confined enrichment and metal-site chemistry with electrical, mixed-potential, or optical readout. Their practical use remains constrained by low intrinsic conductivity, humidity-dependent adsorption, slow desorption, and sulfur-induced deactivation of active metal sites.

Conductive MOF-based gas sensors

Unlike conventional MOFs with limited intrinsic conductivity, conductive metal-organic frameworks (cMOFs) combine permanent porosity and accessible coordination sites with framework-mediated charge-transport pathways, enabling direct chemiresistive transduction of gas-framework interactions^[42,130,131]. Two-dimensional cMOFs based on square-planar metal nodes and π -conjugated ligands are particularly attractive because charge transport can proceed through in-plane π -d conjugation and interlayer π - π stacking. Jeon *et al.* compared six 2,3,6,7,10,11-hexasubstituted triphenylene-based metal-organic frameworks (M-HXTP; M = Co, Ni, or Cu) and found that the Cu-containing cMOFs exhibited the strongest H₂S responses^[42]. Spectroscopic characterization and DFT calculations linked the resistance modulation to H₂S oxidation, Cu reduction, and distortion of the conductive CuX₄ units. Zhao *et al.* further tuned the metal-node composition by constructing bimetallic Co_{1.8}Ni_{1.2}(HITP)₂, which showed a 7.5-fold higher response toward 5 ppm H₂S than Ni₃(HITP)₂^[47]. The sensor maintained a signal drift below 4.13% over 60 days in oxygen-deficient SF₆, indicating that metal-node engineering can regulate H₂S affinity, oxygen-independent charge transfer, and operational stability.

Beyond metal-node and ligand selection, 2D cMOF sensing can be regulated through morphology, layer stacking, and film processing. Solution-processable Ni₃(HITP)₂/NUS-8 MOF-on-MOF nanosheets (HITP: 2,3,6,7,10,11-hexaiminotriphenylene; NUS: National University of Singapore) enabled the fabrication of large-area, thickness-controlled films, as confirmed by the cross-sectional scanning electron microscope (SEM) images in Figure 3A₁–A₄. Kelvin probe force microscopy (KPFM) revealed different surface-potential contrasts for NUS-8 and Ni₃(HITP)₂/NUS-8 [Figure 3A₅ and A₆], consistent with interfacial charge redistribution. Following exposure to 10 ppm H₂S, the S 2p and N 1s XPS changes and the electron paramagnetic resonance (EPR) signal at $g \approx 2.0$ supported the formation of sulfur-containing species, modification of the N coordination environment, and generation of paramagnetic centers; the corresponding redox sensing mechanism is illustrated in Figure 3A₇–A₁₀. The resulting sensor achieved a room-temperature detection limit of approximately 6 ppb^[46]. Zeolitic imidazolate framework-67 (ZIF-67)-templated cobalt-2,3,6,7,10,11-hexahydroxytriphenylene (Co-HHTP) architectures improved electrical conduction, Co-site accessibility, and gas diffusion, achieving detection limits of 44 and 34 ppb for nanoparticles and nanosheets, respectively^[132]. Their response mainly arose from H₂S binding at exposed Co sites, where Co-S interactions reduced the effective hole concentration and increased resistance. 1,4,5,8,9,12-hexaazatriphenylenehexacarbonitrile (HATCN) intercalation between Cu₃(HHTP)₂ layers further introduced out-of-plane transport pathways and electron-deficient adsorption environments, enabling selective H₂S detection down to 120 ppb^[133]. These studies demonstrate that morphology, active-site accessibility,

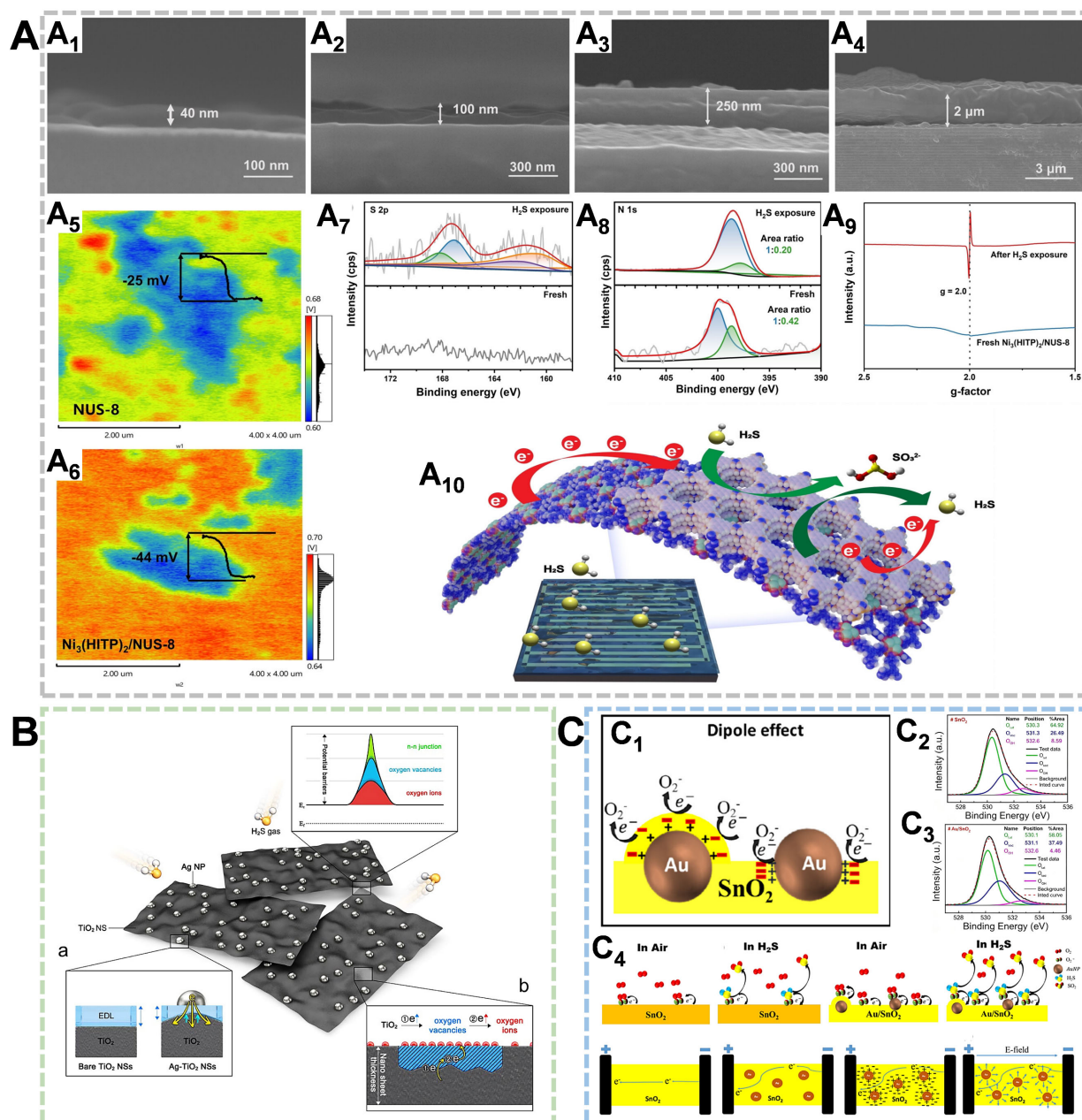


Figure 3. Structural characterization and proposed sensing mechanisms of MOF-based and noble-metal-sensitized H_2S sensors. (A) Cross-sectional SEM images of thickness-controlled $\text{Ni}_3(\text{HITP})_2/\text{NUS-8}$ films (A_1 – A_4); KPFM maps of pristine NUS-8 (A_5) and $\text{Ni}_3(\text{HITP})_2/\text{NUS-8}$ (A_6), S 2p and N 1s XPS spectra before and after exposure to 10 ppm H_2S (A_7 – A_8); EPR spectra (A_9); and the proposed redox sensing mechanism (A_{10}). Reproduced with permission from Ref.^[46]. Copyright 2024, Wiley-VCH; (B) Proposed sensing mechanism of Ag nanoparticle-decorated TiO_2 nanosheets, including Ag-to- TiO_2 electron transfer, defect-assisted electron transport, and potential-barrier formation. Reproduced from Ref.^[138], under CC BY 4.0 license; (C) Proposed Au/ SnO_2 interfacial dipole effect under low bias (C_1); O 1s XPS spectra of pristine SnO_2 (C_2) and Au/ SnO_2 (C_3); and the proposed surface-reaction and charge-transport mechanisms (C_4). Adapted from Ref.^[48], under CC BY 4.0 license. MOF: Metal-organic framework; SEM: scanning electron microscope; KPFM: Kelvin probe force microscopy; NUS: National University of Singapore; XPS: X-ray photoelectron spectroscopy; EPR: electron paramagnetic resonance.

interlayer coupling, and scalable film formation are critical to the sensing performance of 2D cMOFs.

Conductive-MOF heterostructures couple framework-mediated transport with the adsorption and electronic properties of secondary semiconductors. Sun *et al.* decorated $\text{Co}_3(\text{HITP})_2$ with SnO_2 nanoparticles, producing a flexible sensor with a response of 3.3 toward 50 ppm H_2S and a detection limit of 160 ppb at

room temperature under 25% RH^[134]. DFT and band-structure analyses attributed the enhancement to stronger H₂S adsorption, interfacial charge transfer, and heterojunction-mediated carrier modulation. Key limitations include anisotropic transport, layer stacking, humidity-dependent conductivity, limited film processability, and partially irreversible reactions at redox-active metal sites.

MOF-derived gas-sensing materials

MOF-derived sensing materials are produced by converting MOF precursors into metal oxides, carbon-containing phases, or multicomponent heterostructures. Although the coordination framework is destroyed, the derivatives can retain the precursor morphology, porosity, and homogeneous metal distribution while generating small crystallites, defects, and accessible diffusion pathways. Jiang *et al.* converted CuBDC into hollow rod-shaped CuO, which exhibited a response of 330 toward 1 ppm H₂S at 20 °C and a theoretically estimated detection limit in the ppt range^[135]. The enhancement was attributed to the porous hollow architecture, optimized oxygen-vacancy concentration, and strong CuO-H₂S interaction. This example demonstrates that MOF templating can suppress oxide aggregation and preserve gas-accessible internal structures.

MOF precursors enable compositionally uniform heterojunctions by preserving metal distribution and porous architectures during conversion. Ding *et al.* derived porous NiO-CuO structures containing multiple p-p junctions from a bimetallic MOF^[136]. The sensor exhibited responses of 3.99 and 11.0 toward 1 ppm H₂S in dry air and at 40% RH, respectively, with a detection limit of 50 ppb^[136]. The enhancement was attributed to inherited porosity, increased adsorbed oxygen, and NiO/CuO interfacial regulation. Cai *et al.* further derived a CeO₂/N-doped carbon p-n heterojunction that achieved a detection limit of 16 ppb and stable sensing at 80% RH through the combined effects of a built-in electric field, oxygen vacancies, and a hydrophobic carbon matrix^[129].

Coupling MOF-derived oxides with two-dimensional materials can improve carrier transport and interface utilization. Zhang *et al.* dispersed MIL-88-derived γ -Fe₂O₃ octahedra on rGO, producing a response of 520.73 toward 97 ppm H₂S at room temperature^[137]. The rGO network promoted charge transport and limited oxide aggregation, while porous γ -Fe₂O₃ provided accessible reaction sites. MOF-derived α -Fe₂O₃ hollow nanospheres decorated with MoSe₂ nanoflowers exhibited response and recovery times of 50 and 53 s toward 30 ppm H₂S through improved gas diffusion, additional adsorption sites, and interfacial charge modulation^[124]. These studies show that MOF derivation can integrate porous structures with conductive networks and heterointerfaces. Remaining challenges include calcination-induced shrinkage, phase variability, uncontrolled defect concentrations, slow recovery, and humidity-dependent reactions.

MOF-based H₂S sensors follow three distinct design routes with different advantages and limitations. Pristine MOFs exploit permanent pores and open metal sites for H₂S enrichment and molecular recognition, but their low conductivity, humidity-sensitive adsorption, slow desorption, and sulfur poisoning restrict reusable electrical sensing. Conductive MOFs introduce framework-mediated charge transport for direct chemiresistive transduction, although anisotropic conductivity, dense layer stacking, limited film processability, and redox-induced signal irreversibility remain problematic. MOF-derived materials sacrifice the original coordination framework but retain precursor morphology and metal distribution, enabling porous oxides, carbon-containing phases, and heterostructures with abundant defects and interfaces. Their performance is instead limited by calcination-induced shrinkage, phase variability, uncontrolled defect populations, and slow room-temperature recovery. Future priorities should therefore focus on protecting and regenerating active sites in pristine MOFs, controlling layer orientation and film assembly in conductive MOFs, and achieving reproducible phase and defect regulation during MOF conversion. Operando studies under humid H₂S exposure are particularly important for resolving framework reactions, sulfur

accumulation, and recovery pathways across these material classes.

NOBLE METAL-SENSITIZED GAS SENSORS

Noble-metal sensitization is widely used to improve the response, selectivity, and kinetics of room-temperature H₂S sensors. Representative systems employ Ag^[138–140], Au^[48,54,141], Pt^[142–144], and Pd^[116,145,146]. Their enhancement generally involves coupled chemical and electronic sensitization. Chemically, noble-metal nanoparticles promote O₂ and H₂S adsorption or activation and may transfer reactive species to the supporting semiconductor. Electronically, work-function differences induce interfacial charge redistribution and modify depletion regions, localized dipoles, or Schottky barriers, thereby amplifying resistance changes during H₂S exposure. On MXenes, TMDs, and graphene, noble metals can additionally interact with surface terminations or defect sites and regulate local carrier transport. Metals with strong sulfur affinity, particularly Ag, may further enhance H₂S capture through metal-sulfur interactions^[147]. Practical limitations include nanoparticle aggregation, sulfur-induced deactivation, humidity interference, support instability, and material cost.

Ag-sensitized sensors

Ag is attractive for H₂S sensing because of its electrical conductivity, catalytic activity, and strong affinity for sulfur-containing species. Ag nanowire/hollow polypyrrole nanotube composites achieved a detection limit of 10 ppb at room temperature^[55]. The proposed mechanism involved preferential H₂S adsorption and partial dissociation on Ag, followed by proton transfer to polypyrrole that increased its carrier concentration and conductivity. Ag-In₂O₃ nanorod composites further exhibited an ultrahigh response of 93,719 toward 20 ppm H₂S with a detection limit of 5 ppb^[58], while Ag incorporation into CeO₂/porous-Si films improved sensing stability and humidity tolerance^[140]. Lee *et al.* decorated TiO₂ nanosheets with Ag nanoparticles, increasing the response from 1.12 to 2.55 toward 20 ppm H₂S at 25 °C and improving selectivity over H₂, NH₃, and acetone^[138]. XPS analysis showed that the oxygen-vacancy-related and adsorbed-oxygen-related O 1s contributions increased from 16.18% to 26.14% and from 9.54% to 13.18%, respectively. Negative shifts of the Ag 3d peaks relative to bulk Ag further supported electron transfer from Ag to TiO₂. The proposed interfacial mechanism, including narrowing of the TiO₂ electron-depletion layer, defect-assisted electron transport, and modulation of inter-nanosheet potential barriers, is illustrated in Figure 3B^[138]. Ag-catalyzed H₂S dissociation, oxygen spillover, and possible silver-sulfide formation were additionally proposed to contribute to the enhanced response. These studies indicate that Ag sensitization can enhance H₂S sensing through sulfur-affinitive adsorption, catalytic oxygen activation, and support-dependent charge-transfer pathways.

Ag sensitization operates through three material-dependent pathways. Ag promotes O₂ and H₂S adsorption and activation, thereby increasing the reactivity of surface oxygen species^[138,139,148]. Ag/support charge redistribution also modifies carrier concentration and interfacial barriers, amplifying resistance changes^[56,138,139,148]. In addition, Ag-S affinity favors H₂S capture and the formation of Ag-S-related species in Ag/polymer and selected Ag/oxide systems^[55,138,148]. Their relative contributions depend on the Ag state, support, surface oxygen chemistry, and operating conditions. Although Ag-S interactions enhance affinity and selectivity, excessive sulfidation may impede desorption, baseline recovery, and long-term stability.

Au-sensitized sensors

Au sensitization enhances room-temperature H₂S sensing through coupled catalytic and electronic effects. Au nanoparticles promote oxygen adsorption and H₂S surface reactions, while their high work function relative to many n-type oxides induces interfacial electron transfer and Schottky-type barriers, thereby amplifying resistance modulation under limited thermal activation.

Au decoration markedly improves room-temperature ZnO sensing. Flower-like Au/ZnO nanorods achieved a response of 1,270 toward 6 ppm H₂S, 3.7 times that of pristine ZnO, although their response and recovery remained slow^[50]. Au-modified ZnO nanowires reached a response of 79.4 toward 5 ppm H₂S, representing a 16-fold enhancement, and shortened the recovery time from 860 to 170 s^[54]. These results demonstrate strong Au sensitization, although recovery remains dependent on morphology and surface-reaction reversibility.

Deb *et al.* developed a flower-petal-like Au/SnO₂ sensor for ppb-level H₂S detection at room temperature. At 0.5 V and 24 ± 1 °C, the sensor achieved an experimental detection limit of 2 ppb^[48]. Upon exposure to 500 ppb H₂S, the response increased from 35% ± 7% for pristine SnO₂ to 250% ± 30% for Au/SnO₂, while the recovery time decreased from 510 to 126 s^[48]. Figure 3C₁ illustrates the proposed low-bias interfacial dipole effect. The O 1s XPS spectra show an increase in the oxygen-vacancy-related contribution from 26.49% to 37.49% after Au incorporation [Figure 3C₂ and C₃], while Figure 3C₄ illustrates the overall gas-sensing mechanism. However, the contribution of localized interfacial dipoles remains a plausible interpretation that requires further experimental verification^[48].

Overall, Au sensitization enhances H₂S sensing through catalytic oxygen activation and Au/oxide interfacial electronic modulation. Unlike Ag, whose enhancement often involves strong Ag-S interactions and surface sulfidation, Au systems more commonly rely on Schottky-barrier regulation, morphology-dependent surface exposure, and low-bias interfacial polarization. Future studies should clarify the evolution of Au/oxide interfaces during repeated H₂S exposure and improve recovery, humidity tolerance, and scalable low-voltage device fabrication without sacrificing ultralow detection limits.

Pt-sensitized sensors

Pt sensitization of room-temperature H₂S sensors primarily combines catalytic oxygen activation, electron extraction, and interfacial barrier modulation^[52,57,142,143]. Xuan *et al.* integrated Pt with etched W-doped ZnO nanotubes grown *in situ* on FTO electrodes. The optimized Pt(1.5%)-ZnO sensor exhibited a response of 16.59 toward 5 ppm H₂S and detected concentrations down to 100 ppb^[57]. Pt 4f binding-energy shifts and increased chemisorbed oxygen supported electron transfer from ZnO to Pt and enhanced oxygen activation. Based on this evidence and the Pt/ZnO work-function difference, the enhancement was attributed to oxygen-spillover-mediated chemical sensitization and nano-Schottky-barrier-mediated electronic sensitization. This study demonstrates the benefit of coupling Pt sensitization with defect regulation and integrated device architecture^[57].

Pt size, dispersion, and electronic state critically influence H₂S sensing. Kou *et al.* decorated TiO₂@ZnFe₂O₄ nanotube arrays with Pt nanoclusters, achieving a response of 16.6 toward 10 ppm H₂S and a detection limit of 0.43 ppb at room temperature^[52]. The highly dispersed Pt generated oxygen vacancies and Pt^{δ+} species, enabling H₂S activation without heating or UV irradiation. Similarly, 0.3 wt.% Pt-SnO₂ mesoporous nanoflowers exhibited a response of 68 toward 1 ppm H₂S at 30 °C with a detection limit of 100 ppb^[143]. Their enhancement arose from efficient gas diffusion through the mesoporous structure and Pt-mediated catalytic sensitization and oxygen spillover.

Pt sensitization is progressing from simple nanoparticle decoration toward precise regulation of dispersion, cluster size, and valence state. Highly dispersed Pt species improve atomic utilization and electron extraction, enabling H₂S reactions under limited thermal activation. The central challenge is to stabilize these active states at low Pt loading while preventing aggregation and preserving catalytic and electronic sensitization during humid operation and repeated H₂S exposure.

Noble-metal-functionalized two-dimensional materials

Noble-metal functionalization has expanded from metal oxides to two-dimensional MXenes, TMDs, and graphene-based sensing layers. Their exposed surfaces, defects or terminations, and in-plane conductive pathways favor metal dispersion and amplify adsorption-induced electrical changes. Noble metals anchored at surface terminations, chalcogen vacancies, or other defect sites can provide catalytic and sulfur-affinitive centers, redistribute local carriers, and modulate contact resistance, thereby coupling H₂S adsorption more effectively to room-temperature electrical transduction.

MXenes are attractive noble-metal supports because their high conductivity and active surface terminations enable nanoparticle anchoring and rapid signal transduction. Xu *et al.* functionalized monolayer Ti₃C₂T_x with Ag nanoparticles to construct a room-temperature field-effect-transistor sensor^[56]. The device achieved a detection limit of 35 ppb over 0.05–10 ppm H₂S, response and recovery times of 34 and 58 s, and a response to 1 ppm H₂S more than 4.5 times that of pristine Ti₃C₂T_x^[56]. Ag-mediated chemical and electronic sensitization enhanced the response, while calibration curves obtained at 5%–80% RH enabled humidity-compensated quantification. In a fuel-cell-type sensor, Pt/Ti₃C₂ achieved a sensitivity of 0.162 $\mu\text{A ppm}^{-1}$ and a detection limit of 10 ppb. Its response decreased by only approximately 2% after 90 days, compared with 22.9% for Pt/C^[149]. Experiments and DFT calculations attributed this durability to Pt–O–Ti bonding and strong metal-support interactions, while Pt lowered the H₂S dissociation barrier^[149]. These studies establish MXenes as both conductive sensing channels and stable catalyst supports, although oxidation and termination-dependent behavior remain concerns.

Noble-metal functionalization creates active adsorption sites and tunes the electronic structure of TMDs. Verma *et al.* developed 5 at% Pd-doped MoS₂ films that exhibited a response of 276% toward 100 ppm H₂S, response and recovery times of 45 and 65.8 s, and a reported detection limit of 0.3 ppb at room temperature^[116]. Experiments and DFT calculations indicated that Pd altered the electronic structure of MoS₂ and strengthened H₂S adsorption and charge transfer. An oxygen-vacancy-rich MoS₂/Au@Cu₂O multi-heterostructure achieved a response of 201.6% toward 0.5 ppm H₂S after 5 s of exposure. Its enhancement arose from the combined contributions of defect-rich MoS₂, Au sensitization, Cu₂O–H₂S affinity, and multiple heterointerfaces^[150]. DFT calculations further predicted that Au, Ag, and Pt incorporation could strengthen H₂S adsorption and electronic modulation on monolayer WS₂, identifying Ag–WS₂ as a promising but experimentally unverified candidate^[151].

Graphene provides an ultrathin conductive channel highly sensitive to adsorption-induced charge transfer. Ag-decorated chemical vapor deposition (CVD) graphene enabled selective and repeatable room-temperature H₂S sensing with a reported detection limit below 100 ppb^[120]. The enhancement was attributed to Ag-assisted H₂S adsorption and dissociation, followed by charge transfer that modulated the graphene carrier density.

Overall, noble-metal/oxide sensors benefit from mature synthesis, tunable defect chemistry, and well-established Schottky- or depletion-layer modulation, while catalytic oxygen spillover accelerates surface reactions. Their performance may nevertheless be limited by metal aggregation, insufficient surface accessibility, and buried interfaces. Noble-metal-functionalized two-dimensional materials combine Ag, Au, Pt, or Pd sensitization with exposed surfaces and rapid in-plane transport. MXenes enable termination-mediated anchoring and strong metal-support interactions, TMDs provide defect-rich semiconducting channels, and graphene improves metal dispersion and carrier transport. Shared limitations include aggregation, sulfur-induced deactivation or overly strong H₂S binding, humidity-dependent transport, MXene oxidation, and poorly controlled metal loading. *Operando* characterization combined with site-controlled synthesis is needed to distinguish catalytic activation, metal-sulfur interactions, defect-assisted

adsorption, and interfacial charge modulation under realistic conditions.

PHOTOACTIVATED GAS SENSORS

Photoactivation reduces reliance on thermal energy and enables low-power H_2S sensing at room temperature^[152,153]. Ultraviolet, visible, or near-infrared irradiation generates carriers that regulate oxygen adsorption and desorption, interfacial charge transfer, and surface redox kinetics. Because illumination shifts the balance among carrier generation, recombination, and oxygen exchange, it may increase or decrease steady-state oxygen coverage depending on the material and operating conditions. Wavelength, intensity, and irradiation mode therefore provide controllable parameters for tuning sensing reactions. However, heater-free operation does not necessarily imply low total power because the illumination source and driving circuitry must also be included in energy assessments.

Photoactivation has improved room-temperature H_2S sensing across ultraviolet, visible, and near-infrared wavelengths. Among four light-emitting diodes (LEDs) evaluated for hollow CuO-SnO_2 nanotubes, 465 nm illumination produced the highest response. At 660 mW cm^{-2} , the sensor exhibited a response of 4.7 toward 10 ppm H_2S , a detection limit of 2.5 ppm, and response and recovery times of 21 and 61 s [Figure 4]^[154]. However, the unreported electrical input power, illumination-induced temperature rise, and total device consumption prevent a complete assessment of energy efficiency. Under UV irradiation, $\text{SnO}_2\text{@Y}_2\text{O}_3$ heterojunctions enhanced photocarrier separation and electron availability for oxygen activation. DFT calculations supported favorable H_2S adsorption and charge transfer, while the response enhancement was primarily attributed to photoinduced carrier separation and surface-oxygen regulation^[155]. For visible-light activation, $\text{Bi}_2\text{S}_3/\text{Sb}_2\text{S}_3$ heterostructures achieved a response of 23.3 toward 500 ppb H_2S at 60 mW cm^{-2} , approximately twice the dark response^[156]. Light-switching and intensity-dependent measurements confirmed the photoresponsive contribution, while KPFM-derived work-function differences supported the proposed role of a built-in electric field in carrier separation and oxygen-anion generation. Near-infrared-activated MXene/PbS further combined heterointerfacial carrier separation with localized photothermal heating to accelerate H_2S reaction and desorption^[126].

Overall, photoactivated H_2S sensors are progressing from light-assisted oxides toward heterostructures that couple photocarrier generation, interfacial charge separation, reactive oxygen species, and photothermal effects. However, illumination is not inherently low power because its energy cost depends on source efficiency, optical power density, illuminated area, irradiation mode, and driving power. LEDs favor compact and duty-cycled devices, whereas lasers provide high localized intensity at the cost of greater power consumption and system complexity. Photoelectronic and photothermal contributions must be distinguished by measuring the sensing-layer temperature and performing matched-temperature dark controls. Otherwise, enhanced response or recovery cannot be attributed solely to photogenerated carriers. Future studies should report the light-source type, wavelength, optical power density, irradiation mode, sensing-layer temperature, light-source electrical input power, sensor bias power, and total device power. Energy efficiency should also be compared with passive room-temperature sensing and duty-cycled heating.

The mechanisms summarized in Table 3 are supported with varying levels of directness. BET analysis, microscopy, and structure-dependent comparisons can establish morphology- and diffusion-related effects but cannot identify the dominant surface reaction. Sulfidation-induced phase conversion requires *operando*, *in situ*, or pre- and post-exposure XPS, Raman, XRD, or TEM evidence. Oxygen-vacancy-mediated activation should be supported by EPR, O_2 -TPD, conductivity measurements, and controlled defect series because O 1s fitting alone is insufficient. Heterojunction and Schottky-barrier modulation can be examined using UPS/KPFM, work-function measurements, I-V characteristics, and impedance spectroscopy, although

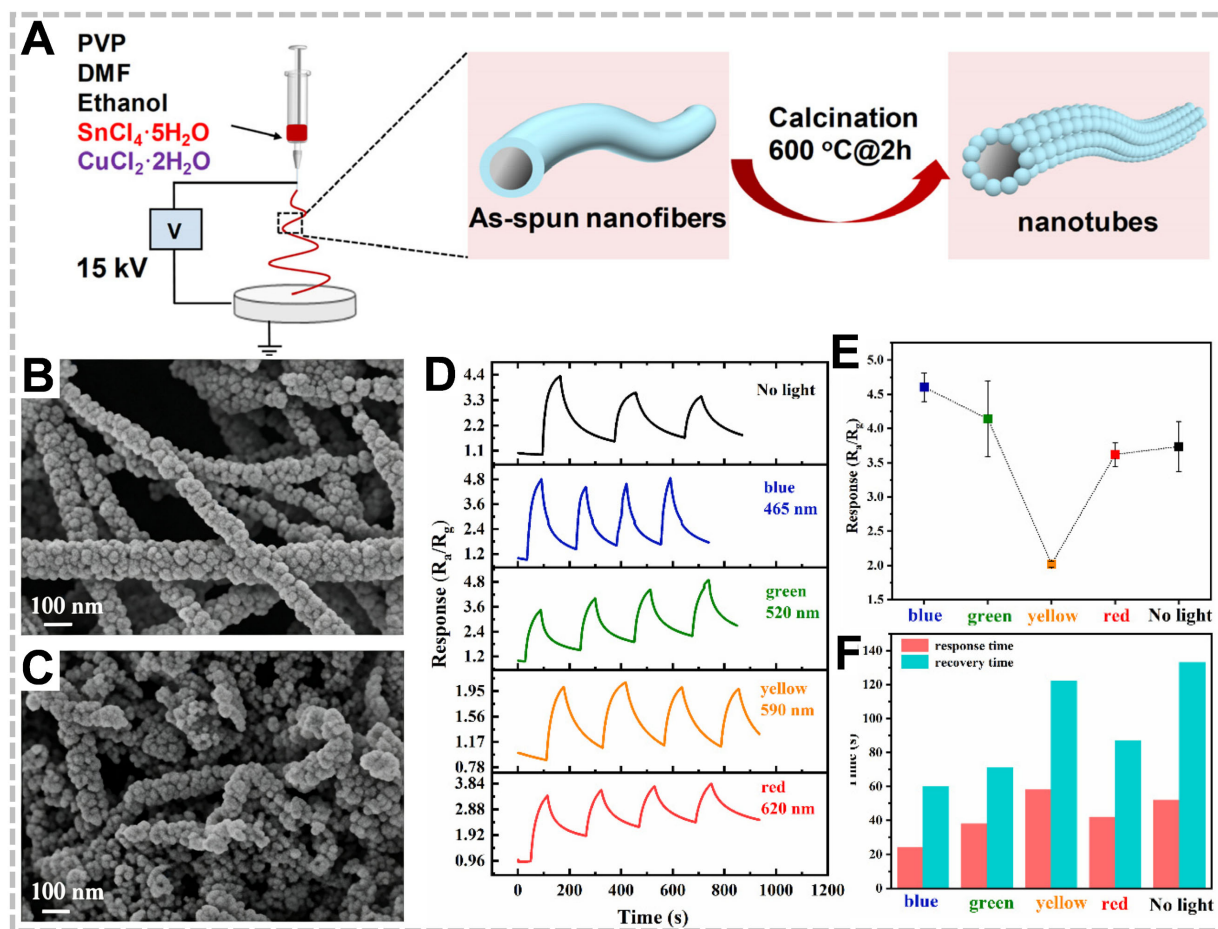


Figure 4. Performance of photoactivated-based H_2S sensors. Schematic illustration of the material preparation process (A); SEM images of pure SnO_2 (B) and CuO-SnO_2 (C) samples; real-time response (D), mean response (E) and response/recovery times (F) for 10 ppm H_2S under various visible-light activation. Figure 4 is reproduced from Ref. [154], under CC BY 4.0 license. PVP: Polyvinylpyrrolidone; DMF: N,N-dimethylformamide; SEM: scanning electron microscope; R_a/R_g : resistance in air/resistance in test gas; ppm: parts-per-million.

detailed band-bending models remain inferential. Noble-metal spillover, photocarrier transfer, and reactive-oxygen-species generation require stronger validation through operando spectroscopy, product analysis, action spectra, selective trapping, or matched-temperature controls. For porous frameworks, *in situ* Raman/XPS and conductivity measurements can distinguish coordination or redox processes from physical adsorption. DFT provides atomic-level support for adsorption and charge transfer but does not constitute direct experimental verification. Because multiple pathways may coexist, mechanistic conclusions should rely on converging structural, spectroscopic, electrical, and theoretical evidence rather than sensing performance alone.

HUMIDITY INTERFERENCE AND MITIGATION STRATEGIES

Humidity critically affects room-temperature H_2S sensing by altering active sites, surface oxygen, charge transfer, and baseline conductivity. Water often competes with H_2S and adsorbed oxygen for surface sites, reducing target-gas adsorption and causing baseline drift. For example, in Yb-doped Bi_2S_3 nanoribbons, raising RH from 8% to 91% lowered baseline resistance from 510 to 148 k Ω and decreased response to 100 ppb H_2S , attributed to competitive adsorption [65]. However, water does not invariably suppress H_2S sensing. In n- SnO_2 @p- SnO heterojunctions, H_2S reacts with hydrolysis products from adsorbed water, releasing electrons and improving response at 20%-60% RH [104]. More deliberately, defect-rich UiO-67/TiO_2 nanotube heterojunctions were designed to exploit adsorbed water to promote H_2S ionization, pore-confined capture,

Table 3. Major sensing mechanisms and evidence assessment for room-temperature H₂S sensors

Mechanism	Signal origin	Preferred evidence	Key limitation	Ref.
Morphology and diffusion regulation	More accessible sites and shorter diffusion paths	BET, microscopy, thickness/porosity series	Surface area alone cannot identify reaction pathway	[10,12,78,87]
Oxygen vacancy activation	Enhanced oxygen adsorption and carrier exchange	EPR, O ₂ -TPD, XPS, conductivity	O 1s fitting alone is insufficient	[103,155]
Sulfidation-induced phase conversion	Conductive sulfide formation and barrier collapse	<i>In situ</i> /quasi- <i>in situ</i> XPS, Raman, XRD, TEM	May cause irreversible drift and poisoning	[10,17,87,88]
Heterojunction / Schottky modulation	Gas-dependent barrier and depletion-width change	UPS/KPFM, I-V, impedance, work-function data	Idealized band diagrams may over-simplify contacts	[13-18,100,124,157]
Noble-metal catalysis/spillover	Catalytic H ₂ S dissociation or oxidation, oxygen spillover, metal-sulfur interaction, and interfacial electronic sensitization	TEM/HAADF-STEM, XPS/XAS, <i>in situ</i> spectroscopy, work-function measurements, particle-size/loading controls, and product analysis	Sulfur poisoning and aggregation affect stability	[48-58]
Photoactivation/photothermal effect	Photocarriers, ROS generation, thermal acceleration	Action spectra, matched-temperature controls, IR imaging, DRIFTS	Total optical/electrical power often underreported	[152-156,158]
Porous-framework-mediated electronic transduction	Coordination, redox, and pore-confined charge transfer	<i>In situ</i> Raman/XPS, conductivity, DFT, array patterns	Humidity and irreversible coordination may alter framework	[39-42,46,47,132,133]

BET: Brunauer–Emmett–Teller; EPR: electron paramagnetic resonance; XPS: X-ray photoelectron spectroscopy; TEM: transmission electron microscopy; HAADF-STEM: high-angle annular dark-field scanning transmission electron microscopy; XAS: X-ray absorption spectroscopy; ROS: reactive oxygen species; DRIFTS: diffuse reflectance infrared Fourier transform spectroscopy.

surface reactions, and charge transport, achieving a response of approximately 194 toward 10 ppm H₂S at 75% RH^[66]. These contrasting observations indicate that humidity effects depend strongly on material chemistry, surface structure, transduction pathway, and RH range and may therefore be suppressive, promotive, or non-monotonic. Accordingly, humidity-mitigation strategies should regulate water access and water-surface interactions rather than simply eliminate water adsorption, thereby suppressing excessive competitive adsorption and baseline drift without blocking H₂S transport or potentially beneficial moisture-assisted reactions.

Material-level humidity regulation includes hydrophobic surface design, porous adsorption layers, and phase or interface engineering. Dense hydrophobic coatings can suppress water uptake but may impede H₂S diffusion, whereas intrinsic hydrophobicity combined with controlled surface chemistry can reduce this trade-off. H₂-annealed and H₂O₂-treated ReS₂ films combined strongly bound chemisorbed oxygen with intrinsic hydrophobicity, showing negligible response variation over 13%–87% RH and a dry-to-wet response ratio of 1.0006 at 87% RH^[68]. Ce-doped rhombohedral/cubic In₂O₃ nanotubes maintained nearly constant responses over 20%–90% RH, suggesting that dopant-regulated oxygen chemistry and dual-phase interfaces can stabilize sensing behavior^[64]. Pt-Co₃O₄@SnO₂ core-shell nanofibers further integrated Pt sensitization, p-n junction modulation, and active oxygen species. Their response decreased by only 9%, 11%, and 22% at 60%, 80%, and 90% RH, respectively, and remained 385 at 90% RH^[69]. However, the baseline resistance decreased markedly with humidity, demonstrating that response retention does not necessarily indicate baseline stability. Humidity can also enhance nonresistive signals. A CuO@V₂C surface-acoustic-wave sensor exhibited repeatable H₂S sensing over 20–80% RH, while its frequency shift increased from 39.71 to 92.43 kHz as RH increased from 0% to 80%^[67]. This behavior was attributed to H₂S/H₂O co-adsorption, increased mass

loading, and water-mediated proton transport rather than moisture rejection. Humidity tolerance should therefore be evaluated using baseline drift, response and recovery kinetics, hysteresis, repeated RH cycling, and long-term stability under consistent operating conditions.

DEVICE DESIGN, SENSOR ARRAYS, AND INTELLIGENT SYSTEM INTEGRATION

High sensitivity under controlled laboratory conditions is insufficient for practical H₂S monitoring, which requires compact and stable systems tailored to concentration range, humidity, interfering gases, sampling method, power supply, signal readout, and communication^[73,74]. Application requirements differ substantially. Exhaled-breath analysis demands trace detection in highly humid, multicomponent matrices^[70,72], whereas food-spoilage monitoring requires continuous operation and timely warning in enclosed environments^[74,159]. Industrial safety prioritizes rapid alarms, wide dynamic range, post-exposure recovery, and sulfur resistance. Environmental monitoring instead requires stable low-concentration detection, temperature and humidity calibration, and selectivity in complex pollutant mixtures. MEMS, flexible, wearable, and self-powered platforms support miniaturized and portable monitoring^[73,74]. Sensor arrays and electronic noses convert cross-responsive signals into multidimensional fingerprints^[70,74], while machine learning enhances identification, concentration estimation, and drift correction. Coordinating materials, devices, and data processing is essential for translating room-temperature H₂S sensors into application-ready systems.

Device design and system integration

Device design determines whether a material response can be converted into a stable monitoring signal, requiring coordinated control of electrode geometry, film deposition, gas transport, packaging, power supply, readout, and communication. Huang *et al.* integrated a ZnO:Ga nanowire/nanosheet sensor with a suspended membrane, interdigitated electrodes, and a microheater on a silicon MEMS platform^[73]. The device detected 0.1–0.8 ppm H₂S and exhibited response and recovery times of 22.4 and 16.8 s toward 0.4 ppm^[73]. A complementary flexible and self-powered system combined an Ag–Zn galvanic cell with a leather-hydrogel electrolyte, open-circuit-voltage readout, Bluetooth, and cloud communication for monitoring periodontitis, meat spoilage, and H₂S leakage [Figure 5A]^[74]. These examples show that practical devices require not only miniaturization and low-power operation but also reproducible film-electrode interfaces, corrosion-resistant packaging, low-noise readout, and reliable wireless transmission

Sensor arrays, electronic noses, and AI-assisted identification

In complex atmospheres, the nominal selectivity of a single sensor may be insufficient for distinguishing H₂S from coexisting gases. Sensor arrays instead combine partially selective elements to generate differentiated response patterns, while an electronic nose integrates gas sampling, signal conditioning, data acquisition, and pattern-recognition algorithms. Shahid *et al.* developed a room-temperature single-chip electronic nose based on silicon field-effect transistors (Si-FETs) functionalized with VO₂, TiO₂, Au, and Pd^[160]. Combined with a polydimethylsiloxane (PDMS) microfluidic channel and a PCB-based readout system, the array produced distinct patterns for H₂S, NH₃, NO₂, and air, and linear discriminant analysis achieved an overall classification accuracy of 89.66%. Zhou *et al.* further constructed an eight-channel MEMS electronic nose incorporating temperature/humidity acquisition, pump control, signal conditioning, 4G transmission, and cloud connectivity^[161]. K-nearest-neighbor and random-forest models achieved 97% test-set accuracy for H₂S, NH₃, and their mixtures, while a neural network enabled quantitative prediction of both components^[161]. Long-term reliability was addressed by Gawande *et al.*, who used robust regression to correct the response drift of a six-sensor MEMS electronic nose after one year of operation^[71]. These approaches convert multidimensional signals into gas identity, concentration, and monitoring decisions; however, reliable evaluation requires independent train-test separation by experiment, device, or measurement date, together with external validation under variable humidity and mixed-gas conditions.

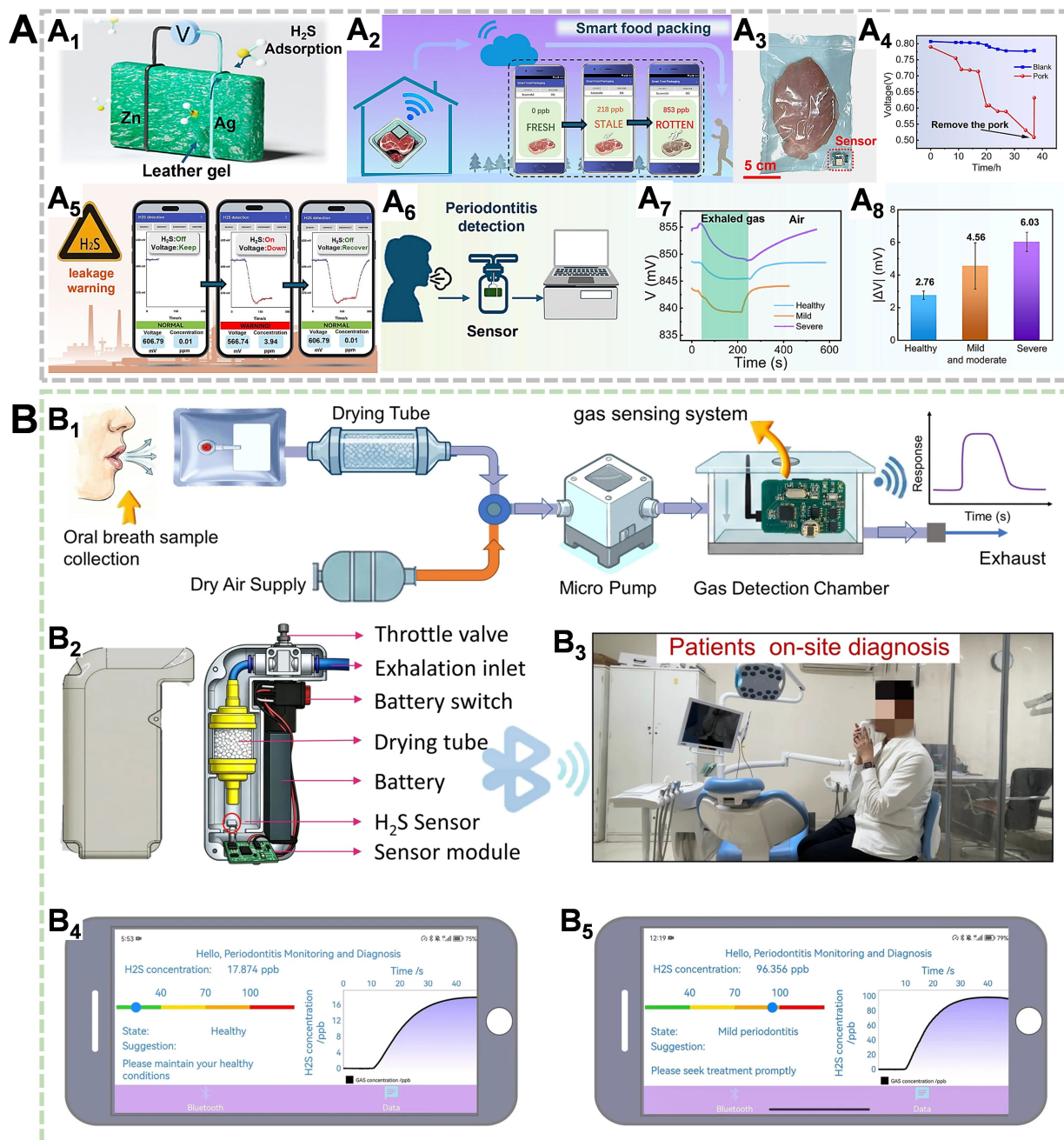


Figure 5. Device design and integration for intelligent H₂S sensing. (A) Self-powered wireless H₂S sensing platform showing the device and adsorption sites (A₁), smart food-packaging test and OCV evolution (A₂–A₄), wireless leakage alarm (A₅), and periodontitis monitoring (A₆–A₈). **Figure 5A** is reproduced with permission from Ref. [74]. Copyright 2026, Wiley-VCH; (B) Portable breath-analysis system for periodontitis diagnosis showing the detection protocol (B₁), analyzer structure (B₂), clinical measurement (B₃), and smartphone readout (B₄ and B₅). **Figure 5B** is reproduced from Ref. [65], under CC BY 4.0 license. OCV: Open-circuit voltage; ppb: parts-per-billion.

Application-oriented validation and deployment

Practical validation should reproduce the sample matrix, environmental conditions, sampling procedure, and decision criteria of the intended application. For on-site periodontitis screening, a portable analyzer based on Yb-doped Bi₂S₃ nanoribbons integrated oral-exhalation sampling, real-time H₂S detection, and smartphone-based readout, enabling the differentiation of healthy individuals from patients with periodontitis [Figure 5B]^[65]. For oral-health monitoring, a flexible Mo₂CT_x/MoSe₂ sensor coupled with molecular-sieve and silica-gel dehumidification distinguished breath samples from 15 patients with periodontitis and 15 healthy

controls. Measurements from six patients after treatment further indicated its potential for longitudinal monitoring^[72]. For food storage, an $\text{In}_2\text{O}_3/\text{SnO}_2$ H_2S sensor was combined with a commercial ethanol channel in a refrigerator-monitoring system, enabling real-time freshness assessment across multiple spoilage products^[159]. At the industrial scale, an electronic nose containing CuO -, SnO_2 -, and WO_3 -based sensors was trained using dynamic olfactometry as a reference and validated with samples from a municipal solid-waste treatment plant and two full-scale biofilters^[162]. Broader deployment requires larger clinical or field datasets, standardized sampling, application-specific alarm thresholds, continuous-operation testing, and long-term calibration and maintenance strategies.

Overall, practical H_2S monitoring requires coordinated development of application-specific devices, cross-responsive arrays, data-processing methods, and field validation. MEMS platforms support miniaturization but require stable packaging, while flexible and self-powered sensors improve portability at the cost of environmental robustness. Electronic noses address limited single-sensor selectivity through multidimensional response patterns but remain vulnerable to device variability, baseline drift, and insufficient training data. Future work should standardize device-level evaluation, validate systems using real samples, and develop data-processing frameworks that maintain accuracy under variable humidity, temperature, and background gases.

CONCLUSION AND OUTLOOK

This review summarizes recent advances in room-temperature H_2S gas sensors from the perspectives of sensing materials, structural design, device configuration, and sensing mechanisms. Single-component materials, including ZnO , WO_3 , In_2O_3 , CuO , and related semiconductors, have demonstrated the feasibility of room-temperature detection through morphology engineering, surface-reaction regulation, and defect optimization. CuO is particularly attractive because of its strong H_2S affinity and the possible formation of conductive Cu_xS species. Nevertheless, pristine materials still face insufficient response at low concentrations, incomplete recovery, humidity interference, and limited selectivity in complex environments.

Composite design provides a versatile route for addressing these limitations by combining heterojunction modulation, interfacial charge transfer, and complementary surface chemistry. CuO -based p-n heterojunctions, Fe_2O_3 -based composites, oxide/conducting-polymer systems, and other multicomponent structures generally outperform their single-material counterparts. Two-dimensional materials further expand this design space. Graphene and rGO facilitate carrier transport, TMDs provide active edge sites and tunable semiconducting interfaces, and MXenes offer high conductivity and chemically adjustable surface terminations. MOF-based platforms contribute pore-confined recognition, intrinsic framework transport, or porous defect-rich derivatives, while COFs provide molecularly tunable recognition sites. Noble-metal sensitization using Ag, Au, and Pt can strengthen H_2S interactions, catalytic activation, oxygen regulation, and interfacial electronic modulation. Photoactivation also reduces continuous heater demand, although the power consumed by illumination and readout must be included when evaluating device-level energy efficiency.

Translating these advances into practical monitoring systems requires application-specific and quantitatively defined benchmarks. As suggested research targets rather than universal acceptance criteria, trace-level sensors should pursue experimentally validated detection limits below 10 ppb, response and recovery times below approximately 30 and 120 s at relevant concentrations, response retention above 90% over at least three months, and reproducible performance during repeated exposure. Device-to-device and batch-to-batch variations should be explicitly quantified. Humidity tolerance should be evaluated over application-relevant ranges, while selectivity should be tested in realistic mixed-gas backgrounds rather than only against

individual interferents. Laboratory evaluation should be complemented by real-sample or field-relevant validation whenever possible. Response definitions, gas-flow conditions, calibration procedures, kinetic criteria, baseline drift, test atmosphere, stability duration, and total system power should also be reported consistently to enable meaningful comparisons.

Scalability, cost, and fabrication compatibility must be considered alongside sensing performance. Hydrothermal and solvothermal methods are accessible for batch synthesis but still face limitations in morphology reproducibility, film-thickness uniformity, precursor utilization, and electrode integration. MOF-based materials provide porous and compositionally tunable structures, although multistep synthesis, limited film processability, thermal conversion, structural shrinkage, and process-energy consumption may restrict large-scale production. Two-dimensional materials offer accessible surfaces and efficient charge transport, but scalable synthesis, oxidation resistance, restacking control, dispersion stability, and large-area film uniformity remain manufacturing barriers. Noble-metal sensitization must balance performance gains against metal loading, aggregation, cost, and recycling. Future studies should therefore report synthesis yield, batch variation, deposition area, film uniformity, device yield, processing temperature, material utilization, and compatibility with printing, spraying, electrodeposition, roll-to-roll processing, or wafer-level integration.

Future progress is unlikely to depend on a single material family or enhancement strategy. MXene/metal-oxide heterostructures, conductive MOFs and COFs, TMD-based interfaces, noble-metal-sensitized semiconductors, humidity-resistant architectures, and photoactivated systems provide complementary rather than universally superior solutions. Platform selection should reflect the target concentration, environmental conditions, reversibility, power demand, fabrication cost, device architecture, and intended application. Mechanisms involving oxygen vacancies, heterojunction barriers, Schottky contacts, catalytic spillover, phase conversion, and photocarrier transfer should be evaluated according to the strength of their evidence and verified through appropriate *in situ* or operando characterization. At the device level, sensing materials should be co-designed with low-power MEMS or flexible electrodes, corrosion-resistant packaging, controlled gas delivery, temperature and humidity compensation, wireless readout, sensor arrays, and drift-correction or pattern-recognition algorithms. Ultimately, validation in industrial safety, environmental monitoring, food storage, and breath analysis will determine whether material-level advances can be translated into reliable, low-power, reproducible, and manufacturable H₂S monitoring systems.

DECLARATIONS

Authors' contributions

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During the preparation of this manuscript, the AI tool ChatGPT (versions 5.5 and 5.6, released on 2026-04-24 and 2026-07-09) was used solely for language editing. AI-assisted tools were also employed to generate partial graphical elements for the graphical abstract and [Figure 1](#). The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

- Nagarjuna, Y.; Lin, J. C.; Wang, S. C.; Hsiao, W. T.; Hsiao, Y. J. AZO-based ZnO nanosheet MEMS sensor with different Al concentrations for enhanced H₂S gas sensing. *Nanomaterials. (Basel)*. **2021**, *11*, 3377. DOI PubMed PMC
- Bai, X.; Chen, J.; He, L.; et al. Pine-needle-like SnO₂@ZnO heterostructures for enhanced room temperature H₂S gas sensing. *Chem. Eng. J.* **2025**, *524*, 169494. DOI
- Batterman, S.; Grant-Alfieri, A.; Seo, S. H. Low level exposure to hydrogen sulfide: a review of emissions, community exposure, health effects, and exposure guidelines. *Crit. Rev. Toxicol.* **2023**, *53*, 244-95. DOI PubMed PMC
- Park, K.; Cho, H.; Lee, J.; Song, Y.; Kim, W.; Choa, Y. Design of highly porous SnO₂-CuO nanotubes for enhancing H₂S gas sensor performance. *Sens. Actuators. B.: Chem.* **2020**, *302*, 127179. DOI
- Galstyan, V.; Poli, N.; Comini, E. Highly sensitive and selective H₂S chemical sensor based on ZnO nanomaterial. *Appl. Sci.* **2019**, *9*, 1167. DOI
- Faisal, A. D. Synthesis of ZnO comb-like nanostructures for high sensitivity H₂S gas sensor fabrication at room temperature. *Bull. Mater. Sci.* **2017**, *40*, 1061-8. DOI
- Sood, T.; Thundiyl, R.; Anusha; Chattopadhyay, S.; Poornesh, P. Optimized nanostructured In₂O₃ gas sensors: harnessing annealing-induced defects and oxygen vacancies for ultra-sensitive and selective H₂S detection at trace levels. *RSC. Adv.* **2025**, *15*, 16555-69. DOI PubMed PMC
- Hoel, A.; Reyes, L.; Heszler, P.; Lantto, V.; Granqvist, C. Nanomaterials for environmental applications: novel WO₃-based gas sensors made by advanced gas deposition. *Curr. Appl. Phys.* **2004**, *4*, 547-53. DOI
- Kundu, S.; Gorthala, G.; Ghosh, R. Room temperature detection of H₂S by two dimensional WS₂ based chemiresistive sensors. *Sens. Actuators. B.: Chem.* **2024**, *416*, 136018. DOI
- Li, Z.; Wang, N.; Lin, Z.; et al. Room-temperature high-performance H₂S sensor based on porous CuO nanosheets prepared by hydrothermal method. *ACS. Appl. Mater. Interfaces.* **2016**, *8*, 20962-8. DOI
- Solis, J.; Saukko, S.; Kish, L.; Granqvist, C.; Lantto, V. Semiconductor gas sensors based on nanostructured tungsten oxide. *Thin. Solid. Films.* **2001**, *391*, 255-60. DOI
- Wang, C.; Chu, X.; Wu, M. Detection of H₂S down to ppb levels at room temperature using sensors based on ZnO nanorods. *Sens. Actuators. B.: Chem.* **2006**, *113*, 320-3. DOI
- Doan, T. L. H.; Kim, J.; Lee, J.; et al. Facile synthesis of metal-organic framework-derived ZnO/CuO nanocomposites for highly sensitive and selective H₂S gas sensing. *Sens. Actuators. B.: Chem.* **2021**, *349*, 130741. DOI
- He, M.; Xie, L.; Zhao, X.; Hu, X.; Li, S.; Zhu, Z. Highly sensitive and selective H₂S gas sensors based on flower-like WO₃/CuO composites operating at low/room temperature. *J. Alloys. Compd.* **2019**, *788*, 36-43. DOI
- Kong, X.; Li, Y. High sensitivity of CuO modified SnO₂ nanoribbons to H₂S at room temperature. *Sens. Actuators. B.: Chem.* **2005**, *105*, 449-53. DOI
- Liang, X.; Kim, T.; Yoon, J.; Kwak, C.; Lee, J. Ultrasensitive and ultrasensitive detection of H₂S using electrospun CuO-loaded In₂O₃ nanofiber sensors assisted by pulse heating. *Sens. Actuators. B.: Chem.* **2015**, *209*, 934-42. DOI
- Patil, L.; Patil, D. Heterocontact type CuO-modified SnO₂ sensor for the detection of a ppm level H₂S gas at room temperature. *Sens. Actuators. B.: Chem.* **2006**, *120*, 316-23. DOI

18. Zhang, D.; Wu, J.; Cao, Y. Ultrasensitive H₂S gas detection at room temperature based on copper oxide/molybdenum disulfide nanocomposite with synergistic effect. *Sens. Actuators. B.: Chem.* **2019**, *287*, 346-55. DOI
19. Liu, Z.; Song, J.; Wang, T.; et al. Ultrasensitive H₂S sensor based on Cu₂O/Graphene heterostructures at room temperature. *Appl. Surf. Sci.* **2025**, *702*, 163339. DOI
20. Ugale, A. D.; Umarji, G. G.; Jung, S. H.; et al. ZnO decorated flexible and strong graphene fibers for sensing NO₂ and H₂S at room temperature. *Sens. Actuators. B.: Chem.* **2020**, *308*, 127690. DOI
21. Balasubramani, V.; Sureshkumar, S.; Rao, T. S.; Sridhar, T. M. Impedance spectroscopy-based reduced graphene oxide-incorporated ZnO composite sensor for H₂S investigations. *ACS. Omega.* **2019**, *4*, 9976-82. DOI PubMed PMC
22. Liu, L.; Yang, M.; Gao, S.; et al. Co₃O₄ hollow nanosphere-decorated graphene sheets for H₂S sensing near room temperature. *ACS. Appl. Nano. Mater.* **2019**, *2*, 5409-19. DOI
23. Wang, H.; Zhou, F.; Zhang, R.; et al. Ppb-level H₂S gas sensor based on Li-doped CuO nanoparticles compounded on graphene at room temperature. *ACS. Sens.* **2026**, *11*, 2325-34. DOI
24. Peng, F.; Wang, S.; Yu, W.; et al. Ultrasensitive ppb-level H₂S gas sensor at room temperature based on WO₃/rGO hybrids. *J. Mater. Sci.: Mater. Electron.* **2020**, *31*, 5008-16. DOI
25. Song, Z.; Wei, Z.; Wang, B.; et al. Sensitive room-temperature H₂S gas sensors employing SnO₂ quantum wire/reduced graphene oxide nanocomposites. *Chem. Mater.* **2016**, *28*, 1205-12. DOI
26. Zhou, L.; Shen, F.; Tian, X.; Wang, D.; Zhang, T.; Chen, W. Stable Cu₂O nanocrystals grown on functionalized graphene sheets and room temperature H₂S gas sensing with ultrahigh sensitivity. *Nanoscale* **2013**, *5*, 1564-9. DOI
27. Shewale, P. S.; Yun, K. Synthesis and characterization of Cu-doped ZnO/RGO nanocomposites for room-temperature H₂S gas sensor. *J. Alloys. Compd.* **2020**, *837*, 155527. DOI
28. Huo, Y.; Qiu, L.; Wang, T.; et al. P-N Heterojunction formation: Metal sulfide@metal oxide chemiresistor for ppb H₂S detection from exhaled breath and food spoilage at flexible room temperature. *ACS. Sens.* **2024**, *9*, 3433-43. DOI
29. Zhang, H.; Zou, J.; Luo, S.; Huang, Y.; Fan, D. Research progress of gas sensors based on two-dimensional materials. *J. Shenzhen. Univ. Sci. Eng.* **2018**, *35*, 221. DOI
30. Kim, T.; Kim, Y.; Park, S.; Kim, S.; Jang, H. Two-dimensional transition metal disulfides for chemoresistive gas sensing: perspective and challenges. *Chemosensors* **2017**, *5*, 15. DOI
31. Wang, B.; Gu, Y.; Chen, L.; Ji, L.; Zhu, H.; Sun, Q. Gas sensing devices based on two-dimensional materials: a review. *Nanotechnology* **2022**, *33*, 252001. DOI
32. Xie, Y.; Zhang, Z.; Meng, F.; et al. Strategies and challenges for improving the performance of two-dimensional materials-based gas sensors. *Adv. Phys. X.* **2024**, *9*, 2288353. DOI
33. Hingangavkar, G. M.; Kadam, S. A.; Ma, Y.; Selvaraj, M.; Mulik, R. N.; Patil, V. B. On the behavior of MoS₂-rGO nanocomposites for chemiresistive H₂S detection at room temperature. *Sens. Actuators. B.: Chem.* **2024**, *399*, 134843. DOI
34. Sadaf, S.; Zhang, H.; Akhtar, A. MoS₂-NiO nanocomposite for H₂S sensing at room temperature. *RSC. Adv.* **2023**, *13*, 28564-75. DOI PubMed PMC
35. Alagh, A.; Annanouch, F. E.; Umek, P.; Bittencourt, C.; Colomer, J. F.; Llobet, E. An ultrasensitive room-temperature H₂S Gas sensor based on 3D assembly of Cu₂O decorated WS₂ nanomaterial. *IEEE. Sensors. J.* **2021**, *21*, 21212-20. DOI
36. Akhtar, A.; Yao, C.; Zhou, R.; et al. Hydrothermally synthesized MXene Ti₃C₂/Zn₂SnO₄ based nanocomposite for H₂S sensing at room temperature. *Ceram. Int.* **2024**, *50*, 12298-309. DOI
37. Mirzaei, A.; Lee, M. H.; Safaeian, H.; et al. Room temperature chemiresistive gas sensors based on 2D MXenes. *Sensors. (Basel).* **2023**, *23*, 8829. DOI PubMed PMC
38. Sadaf, S.; Zhang, H.; Akhtar, A. H₂S/butane dual gas sensing based on a hydrothermally synthesized MXene Ti₃C₂T_x/NiCo₂O₄ nanocomposite. *Molecules* **2023**, *29*, 202. DOI PubMed PMC
39. Benedetto, G.; Stolz, R. M.; Meng, Z.; et al. Conductive covalent organic frameworks as chemiresistive sensor arrays for the detection and differentiation of gasotransmitters. *J. Am. Chem. Soc.* **2025**, *147*, 43438-52. DOI PubMed PMC
40. Meng, Z.; Stolz, R. M.; Mirica, K. A. Two-dimensional chemiresistive covalent organic framework with high intrinsic conductivity. *J. Am. Chem. Soc.* **2019**, *141*, 11929-37. DOI PubMed
41. Nizamidin, P.; Du, X.; Gao, H.; Li, Y. A nanoporous covalent organic framework film-based optical waveguide sensor for H₂S gas detection. *ACS. Appl. Nano. Mater.* **2025**, *8*, 3876-86. DOI
42. Jeon, M.; Lee, J. S.; Kim, M.; et al. Triphenylene-Based 2D cMOFs: Unraveling the H₂S sensing mechanism and applications for a real-time wireless chemiresistive sensor. *ACS. Appl. Mater. Interfaces.* **2024**, *16*, 62382-91. DOI

43. Li, Q.; Liu, X.; Zhang, Y.; et al. Passivation-enhanced mixed-potential Cu-MOF sensor for ppb-level H₂S detection and real-time food freshness evaluation. *Sens. Actuators. B.: Chem.* **2026**, *447*, 138908. DOI
44. Luo, K.; Tai, H.; Chittibabu, D. K. D.; et al. New improved metal-organic frameworks using dual metal centers: a novel H₂S gas sensing capability through synergistic interactions. *Sens. Actuators. B.: Chem.* **2025**, *443*, 138200. DOI
45. Marquardt, N.; Dahlke, M.; Schaate, A. Cu-MOF-808 as a sensing material for gaseous hydrogen sulfide. *Chempluschem* **2023**, *88*, e202300109. DOI PubMed
46. Wu, X.; Tian, X.; Zhang, W.; et al. Solution-processable MOF-on-MOF system constructed via template-assisted growth for ultratrace H₂S detection. *Angew. Chem. Int. Ed. Engl.* **2024**, *63*, e202410411. DOI
47. Zhao, X.; Jiang, S.; Zhang, Z.; et al. High-performance H₂S sensors to detect SF₆ leakage. *ACS. Sens.* **2024**, *9*, 5512-9. DOI
48. Deb, M.; Lu, C. J.; Zan, H. W. Achieving room-temperature ppb-level H₂S detection in a Au-SnO₂ sensor with low voltage enhancement effect. *ACS. Sens.* **2024**, *9*, 4568-77. DOI
49. Goncharov, T.; Nasriddinov, A.; Zubenko, A.; et al. Nanocrystalline SnO₂ functionalized with Ag(I) organometallic complexes as materials for low temperature H₂S detection. *Materials. (Basel).* **2021**, *14*, 7778. DOI PubMed PMC
50. Hosseini, Z.; Mortezaali, A.; Iraj, zad, A.; Fardindoost, S. Sensitive and selective room temperature H₂S gas sensor based on Au sensitized vertical ZnO nanorods with flower-like structures. *J. Alloys. Compd.* **2015**, *628*, 222-9. DOI
51. Khoshnood, F.; Manouchehri, S.; Yousefi, M. H. Sensing sub-ppm concentration of H₂S gas at room temperature using silver-doped SnO₂ nanocrystals. *J. Electron. Mater.* **2022**, *51*, 1804-12. DOI
52. Kou, R.; He, H.; Lu, Y.; et al. Boosting H₂S gas sensing performance of metal oxide semiconductors at room-temperature by the electron-extracting effect of Pt nanocluster. *Chem. Eng. J.* **2023**, *476*, 146546. DOI
53. Navale, S.; Shahbaz, M.; Mirzaei, A.; Kim, S. S.; Kim, H. W. Effect of Ag addition on the gas-sensing properties of nanostructured resistive-based gas sensors: an overview. *Sensors. (Basel).* **2021**, *21*, 6454. DOI PubMed PMC
54. Ramgir, N. S.; Sharma, P. K.; Datta, N.; et al. Room temperature H₂S sensor based on Au modified ZnO nanowires. *Sens. Actuators. B.: Chem.* **2013**, *186*, 718-26. DOI
55. Su, P.; Chai, X. Room-temperature ppb-level H₂S gas sensors based on Ag nanowire/hollow PPy nanotube nanocomposites. *Chemosensors* **2022**, *10*, 305. DOI
56. Xu, Q.; Zong, B.; Li, Q.; Fang, X.; Mao, S.; Ostrikov, K. K. H₂S sensing under various humidity conditions with Ag nanoparticle functionalized Ti₃C₂T_x MXene field-effect transistors. *J. Hazard. Mater.* **2022**, *424*, 127492. DOI
57. Xuan, J.; Zhao, G.; Gong, Q.; et al. Fabrication of in-situ grown and Pt-decorated ZnO nanoclusters on new-type FTO electrode for room-temperature detection of low-concentration H₂S. *J. Alloys. Compd.* **2021**, *860*, 158499. DOI
58. Yan, S.; Li, Z.; Li, H.; et al. Ultra-sensitive room-temperature H₂S sensor using Ag-In₂O₃ nanorod composites. *J. Mater. Sci.* **2018**, *53*, 16331-44. DOI
59. Li, Z.; Yan, S.; Zhang, S.; et al. Ultra-sensitive UV and H₂S dual functional sensors based on porous In₂O₃ nanoparticles operated at room temperature. *J. Alloys. Compd.* **2019**, *770*, 721-31. DOI
60. Thota, C.; Modigunta, J. K. R.; Reddeppa, M.; et al. Light stimulated room-temperature H₂S gas sensing ability of Cl-doped carbon quantum dots supported Ag nanoparticles. *Carbon* **2022**, *196*, 337-46. DOI
61. Xie, Y.; Sun, F.; Yang, Y.; et al. Gas-sensing mechanism and performances of Ti₃C₂T_x/CuO for H₂S at room temperature. *Chem. Eng. J.* **2025**, *519*, 165339. DOI
62. Wu, K.; Zhang, W.; Zheng, Z.; Debliquy, M.; Zhang, C. Room-temperature gas sensors based on titanium dioxide quantum dots for highly sensitive and selective H₂S detection. *Appl. Surf. Sci.* **2022**, *585*, 152744. DOI
63. Sun, H.; Cao, M.; Zhang, P.; et al. Magnetic-field-enhanced H₂S sensitivity of Cu₂O/NiO heterostructure ordered nanoarrays. *ACS. Sens.* **2022**, *7*, 1903-11. DOI
64. Guo, L.; Jiang, Y.; Cai, Y.; et al. Towards high-performance room-temperature H₂S sensors: crystal phase engineering and Ce doping in In₂O₃ nanotubes. *Sens. Actuators. B.: Chem.* **2026**, *458*, 139766. DOI
65. Guo, P.; Wang, K.; An, X.; et al. On-site periodontitis diagnosis via room-temperature oral exhalation H₂S sensor based on Yb-doped Bi₂S₃ nanoribbon. *Nanomicro. Lett.* **2026**, *18*. DOI PubMed PMC
66. Kou, R.; Zhang, Y.; Cai, Y.; et al. Moisture-promoted, defect-rich UiO-67/TiO₂ nanotube heterojunctions for ppb-level H₂S detection under ambient conditions. *ACS. Sens.* **2025**, *10*, 9447-56. DOI
67. Pasupuleti, K. S.; Pham, T. M. T.; Abraham, B. M.; et al. Room temperature ultrasensitive ppb-level H₂S SAW gas sensor based on hybrid CuO@V₂C MXene van der Waals heterostructure. *Adv. Compos. Hybrid. Mater.* **2025**, *8*, 1194. DOI

-
68. Peng, Q.; Zhang, Y.; Feng, W.; Yang, X.; Cheng, J. Humidity resistant room temperature H₂S sensor via surface-adsorbed oxygen modulation of ReS₂ nano-film. *Physica. B: Condensed. Matter.* **2026**, *720*, 418000. DOI
69. Song, X.; Wang, H.; Huang, W.; Lu, Y.; Wang, Z.; Wang, H. Rapid and high responsive Pt-Co₃O₄@SnO₂ core-shell nanofibers for room-temperature detection of H₂S in exhaled breath for non-invasive asthma diagnosis. *Chem. Eng. J.* **2026**, *533*, 174765. DOI
70. Duan, Q.; Zhang, W.; Li, L.; et al. W-CeO₂ nanospheres gas sensor array for accurate and selective H₂S detection in exhaled breath. *Chem. Eng. J.* **2024**, *479*, 147748. DOI
71. Gawande, T.; Deshmukh, R.; Deshmukh, S. MEMS-based electronic nose system for measurement of industrial gases with drift correction methodology. *Meas. Sci. Technol.* **2023**, *34*, 105110. DOI
72. Han, Q.; Hu, C.; Shi, F.; et al. Flexible Mo₂CT_x/MoSe₂ heterostructure sensors for ultrasensitive, room-temperature detection of exhaled H₂S in periodontitis diagnosis. *ACS. Sens.* **2025**, *10*, 5108-19. DOI
73. Huang, C.; Wu, C.; Hsueh, T. A room temperature ZnO:Ga NWs&NSs/MEMS H₂S gas sensor. *Mater. Sci. Semicond. Process.* **2025**, *187*, 109149. DOI
74. Zhong, W.; Yang, L.; Zhou, Y.; et al. A Self-Powered, Ultrasensitive, and flexible gas sensor based on tough and degradable leather hydrogel for portable wireless trace H₂S detection. *Adv. Funct. Mater.* **2026**, *36*, e32190. DOI
75. Gong, H.; Hu, J.; Wang, J.; Ong, C.; Zhu, F. Nano-crystalline Cu-doped ZnO thin film gas sensor for CO. *Sens. Actuators. B: Chem.* **2006**, *115*, 247-51. DOI
76. Hong, R.; Li, J.; Chen, L.; et al. Synthesis, surface modification and photocatalytic property of ZnO nanoparticles. *Powder. Technol.* **2009**, *189*, 426-32. DOI
77. Zhu, L.; Zeng, W. Room-temperature gas sensing of ZnO-based gas sensor: a review. *Sensor. Actuat. A-Phys.* **2017**, *267*, 242-61. DOI
78. Hosseini, Z.; zad, A. I.; Mortezaali, A. Room temperature H₂S gas sensor based on rather aligned ZnO nanorods with flower-like structures. *Sens. Actuators. B: Chem.* **2015**, *207*, 865-71. DOI
79. Kaiser, A.; Mauritz, T.; Bansmann, J.; Biskupek, J.; Herr, U.; Thonke, K. Mechanism of optical and electrical H₂S gas sensing of pristine and surface functionalized ZnO nanowires. *ACS. Omega.* **2024**, *9*, 50188-200. DOI PubMed PMC
80. Shinde, S.; Patil, G.; Kajale, D.; Gaikwad, V.; Jain, G. Synthesis of ZnO nanorods by spray pyrolysis for H₂S gas sensor. *J. Alloys. Compd.* **2012**, *528*, 109-14. DOI
81. Kaur, M.; Kailasaganapathi, S.; Ramgir, N.; et al. Gas dependent sensing mechanism in ZnO nanobelt sensor. *Appl. Surf. Sci.* **2017**, *394*, 258-66. DOI
82. Frühberger, B.; Grunze, M.; Dwyer, D. Surface chemistry of H₂S-sensitive tungsten oxide films. *Sens. Actuators. B: Chem.* **1996**, *31*, 167-74. DOI
83. Solis, J.; Saukko, S.; Kish, L.; Granqvist, C.; Lantto, V. Nanocrystalline tungsten oxide thick-films with high sensitivity to H₂S at room temperature. *Sens. Actuators. B: Chem.* **2001**, *77*, 316-21. DOI
84. Punginsang, M.; Zappa, D.; Comini, E.; et al. Selective H₂S gas sensors based on ohmic hetero-interface of Au-functionalized WO₃ nanowires. *Appl. Surf. Sci.* **2022**, *571*, 151262. DOI
85. Yu, H.; Song, Z.; Liu, Q.; et al. Colloidal synthesis of tungsten oxide quantum dots for sensitive and selective H₂S gas detection. *Sens. Actuators. B: Chem.* **2017**, *248*, 1029-36. DOI
86. Chen, J.; Wang, K.; Hartman, L.; Zhou, W. H₂S detection by vertically aligned CuO nanowire array sensors. *J. Phys. Chem. C.* **2008**, *112*, 16017-21. DOI
87. Huang, Z.; Wang, X.; Sun, F.; et al. Super response and selectivity to H₂S at room temperature based on CuO nanomaterials prepared by seed-induced hydrothermal growth. *Mater. Design.* **2021**, *201*, 109507. DOI
88. Zhang, J. Z.; Yan, Y. Synthesis of biomorphic tube-like CuO using pomelo white flesh as biotemplate and its sensing properties over H₂S at room temperature. *J. Mater. Sci.* **2017**, *52*, 13711-8. DOI
89. Verma, G.; Gupta, A. Sensing performance of room temperature operated MEMS gas sensor for ppb level detection of hydrogen sulfide: a review. *J. Micromech. Microeng.* **2022**, *32*, 094002. DOI
90. Zhao, L.; Che, J.; Cao, Q.; Shen, S.; Tang, Y. Highly sensitive surface acoustic wave H₂S gas sensor using electron-beam-evaporated CuO as sensitive layer. *Sens. Mater.* **2023**, *35*, 2293. DOI
91. Xu, J.; Wang, X.; Shen, J. Hydrothermal synthesis of In₂O₃ for detecting H₂S in air. *Sens. Actuators. B: Chem.* **2006**, *115*, 642-6. DOI
92. Xu, L.; Dong, B.; Wang, Y.; Bai, X.; Liu, Q.; Song, H. Electrospinning preparation and room temperature gas sensing properties of porous In₂O₃ nanotubes and nanowires. *Sens. Actuators. B: Chem.* **2010**, *147*, 531-8. DOI
93. Wang, Y.; Duan, G.; Zhu, Y.; et al. Room temperature H₂S gas sensing properties of In₂O₃ micro/nanostructured porous thin film and hydrolyzation-induced enhanced sensing mechanism. *Sens. Actuators. B: Chem.* **2016**, *228*, 74-84. DOI

94. Li, Z.; Yan, S.; Sun, M.; et al. Significantly enhanced temperature-dependent selectivity for NO₂ and H₂S detection based on In₂O₃ nanocubes prepared by CTAB assisted solvothermal process. *J. Alloys. Compd.* **2020**, *816*, 152518. DOI
95. Yang, S.; Song, Z.; Gao, N.; et al. Near room temperature operable H₂S sensors based on In₂O₃ colloidal quantum dots. *Sens. Actuators. B: Chem.* **2019**, *286*, 22-31. DOI
96. Kumar Pradhan B, Kumar Mauraya A, Chatterjee K, Pal P, Kumar Muthusamy S. High-sensitive and fast-responsive In₂O₃ thin film sensors for dual detection of NO₂ and H₂S gases at room temperature. *Appl. Surf. Sci.* **2024**, *678*, 161111. DOI
97. Xuan, J.; Zhao, G.; Shi, X.; et al. *In-situ* fabrication of ZnO nanoparticles sensors based on gas-sensing electrode for ppb-level H₂S detection at room temperature*. *Chinese. Phys. B.* **2021**, *30*, 020701. DOI
98. Ping, Y.; Zhao, M.; Dan, Zhao.; et al. Construction of hierarchical CuO sphere-like structure for ppb-level H₂S sensing at room temperature. *J. Alloys. Compd.* **2025**, *1031*, 181095. DOI
99. Yamazoe, N.; Shimanoe, K. Basic approach to the transducer function of oxide semiconductor gas sensors. *Sens. Actuators. B: Chem.* **2011**, *160*, 1352-62. DOI
100. He, H.; Zhao, C.; Xu, J.; et al. Exploiting free-standing p-CuO/n-TiO₂ nanochannels as a flexible gas sensor with high sensitivity for H₂S at room temperature. *ACS. Sens.* **2021**, *6*, 3387-97. DOI
101. Chen, H.; Lv, L.; Xue, K.; Zhang, P.; Du, L.; Cui, G. Oral exhalation H₂S sensor based on Cu₂O/ZnO heterostructures. *ACS. Sens.* **2025**, *10*, 2579-88. DOI
102. Zhou, T.; Wang, Y.; Liu, Y.; et al. Ultrasensitive and selective room-temperature H₂S sensor based on CuO/In₂O₃ heterojunction via dual sensitization mechanism. *Sens. Actuators. B: Chem.* **2026**, *462*, 140017. DOI
103. Bai, H.; Feng, C.; Chen, Y.; et al. Chemiresistive room temperature H₂S gas sensor based on MoO₃ nanobelts decorated with MnO₂ nanoparticles. *Sens. Actuators. B: Chem.* **2024**, *420*, 136468. DOI
104. Xu, J.; Feng, J.; Ye, J.; et al. Core-shell n-SnO₂@p-SnO heterojunctions via on-chip annealing for ultrasensitive H₂S detection at room temperature. *J. Alloys. Compd.* **2025**, *1043*, 184217. DOI
105. Tang, J.; Wang, H.; Dong, W.; et al. SnO₂ QDs loaded α-Fe₂O₃ hollow cubes for H₂S room temperature detection and insights into their gas sensing mechanism. *Ceram. Int.* **2024**, *50*, 14151-60. DOI
106. Bai, H.; Shi, G. Gas sensors based on conducting polymers. *Sensors* **2007**, *7*, 267-307. DOI
107. Zhang, D.; Fan, X.; Hao, X.; Dong, G. Facile fabrication of polyaniline nanocapsule modified zinc oxide hexagonal microdiscs for H₂S gas sensing applications. *Ind. Eng. Chem. Res.* **2019**, *58*, 1906-13. DOI
108. Sun, Z.; Yang, X.; Yang, S.; et al. Ultrasensitive and ultra-selective room-temperature H₂S gas sensor based on CuO-loaded In₂O₃ 2D porous nanosheets. *J. Hazard. Mater.* **2025**, *493*, 138355. DOI
109. Xue, H.; Huang, F.; He, X.; et al. Hierarchical porous CdS-Co₃O₄ heterostructures for H₂S gas sensing at room temperature. *ACS. Appl. Nano. Mater.* **2025**, *8*, 18434-45. DOI
110. Cao, M.; Lei, H.; Jiang, H.; et al. Bio-template synthesis of graphitized carbon-decorated Fe₂O₃ hierarchical tubes for high-response and low-temperature H₂S detection. *Chem. Eng. J.* **2026**, *531*, 174072. DOI
111. Tang, X.; Du, A.; Kou, L. Gas sensing and capturing based on two-dimensional layered materials: overview from theoretical perspective. *WIREs. Comput. Mol. Sci.* **2018**, *8*, e1361. DOI
112. Varghese, S.; Varghese, S.; Swaminathan, S.; Singh, K.; Mittal, V. Two-dimensional materials for sensing: graphene and beyond. *Electronics* **2015**, *4*, 651-87. DOI
113. Eum, J. H.; Kwon, S. J.; Eo, S.; Kim, D. H. Tunable chemiresistive gas selectivity of thin-layered conductive metal-organic framework/reduced graphene oxide composites. *ACS. Sens.* **2026**, *11*, 3840-50. DOI PubMed
114. Amith, S. L.; Kovenan, C.; Richard, Y. A.; Radhakrishnan, K.; Piraman, S. Compact disc-based sensor utilizing Er₂O₃/Co₃O₄ nanorods anchored on rGO nanosheets for enhanced detection of hydrogen sulfide at room temperature. *J. Hazard. Mater.* **2026**, *507*, 141778. DOI PubMed
115. Jing, W.; Xiangzhao, Z.; Guoqiang, W.; et al. MoSe₂/In₂O₃ nanocomposite for room-temperature H₂S sensing: Theoretical design and experimental validation. *Sensor. Actuat. A-Phys.* **2025**, *394*, 116897. DOI
116. Verma, V. K.; Patel, C.; Mukherjee, S.; et al. Ultrasensitive and selective room temperature H₂S detection using Pd-doped MoS₂ synthesized via APCVD. *Sens. Actuators. B: Chem.* **2026**, *447*, 138812. DOI
117. Hilal, M.; Fayaz, H.; Ali, Y.; et al. Quantum-engineered Ti₃C₂T_x-QD@V₂CT_x hybrid composite with Ti-O-V interfacial bonding for extreme-humidity H₂S sensing. *Adv. Compos. Hybrid. Mater.* **2026**, *9*, 1646. DOI
118. Sun, Y.; Guo, W.; Wang, B.; et al. Construction of a Co₃(HITP)₂/Ti₃C₂ MXene heterojunction for selective sensing of H₂S with high resistance to humidity. *Sens. Actuators. B: Chem.* **2026**, *450*, 139224. DOI

-
119. Balandin, A. A. Thermal properties of graphene and nanostructured carbon materials. *Nat. Mater.* **2011**, *10*, 569–81. [DOI PubMed](#)
120. Ovsianyskyi, O.; Nam, Y.; Tsymbalenko, O.; Lan, P.; Moon, M.; Lee, K. Highly sensitive chemiresistive H₂S gas sensor based on graphene decorated with Ag nanoparticles and charged impurities. *Sens. Actuators. B: Chem.* **2018**, *257*, 278–85. [DOI](#)
121. Balasubramani, V.; Sridhar, T.; Liu, B. Impedance spectroscopy analysis on reduced graphene oxide and CeO₂ nanocomposites coated on screen-printed alumina substrate for highly selective H₂S gas detection at room temperature. *Ceram. Int.* **2024**, *50*, 4359–73. [DOI](#)
122. Ganatra, R.; Zhang, Q. Few-layer MoS₂: a promising layered semiconductor. *ACS. Nano.* **2014**, *8*, 4074–99. [DOI PubMed](#)
123. Hingangavkar, G. M.; Kadam, S. A.; Ma, Y.; Bandgar, S. S.; Mulik, R. N.; Patil, V. B. MoS₂-GO hybrid sensor: a discerning approach for detecting harmful H₂S gas at room temperature. *Chem. Eng. J.* **2023**, *472*, 144789. [DOI](#)
124. Pan, W.; Zhang, Y.; Yu, S.; Liu, X.; Zhang, D. Hydrogen sulfide gas sensing properties of metal organic framework-derived α-Fe₂O₃ hollow nanospheres decorated with MoSe₂ nanoflowers. *Sens. Actuators. B: Chem.* **2021**, *344*, 130221. [DOI](#)
125. Ding, J.; Wang, Q.; Liu, X.; Li, S.; Li, H. Ultrasensitive detection of hazardous gas at room temperature enabled by MOF@MXene 0D-2D heterostructure. *J. Hazard. Mater.* **2024**, *480*, 136261. [DOI](#)
126. Han, Y.; Yin, Z.; Zhuang, H.; et al. Synergistic effects of photoactivation and photothermal in MXene heterostructures for the enhanced H₂S detection capability. *Adv. Funct. Mater.* **2025**, *35*, e09735. [DOI](#)
127. Vovusha, H.; Amorim, R.; Bae, H.; Lee, S.; Hussain, T.; Lee, H. Sensing of sulfur containing toxic gases with double transition metal carbide MXenes. *Mater. Today. Chem.* **2023**, *30*, 101543. [DOI](#)
128. Hosseini-Shokouh, S. H.; Zhou, J.; Berger, E.; et al. Highly selective H₂S gas sensor based on Ti₃C₂T_x MXene-organic composites. *ACS. Appl. Mater. Interfaces.* **2023**, *15*, 7063–73. [DOI PubMed PMC](#)
129. Cai, H.; Yao, Y.; Zhang, Q.; Cui, Y.; Qian, G. Ultrasensitive room-temperature hydrogen sulfide sensing via built-in electric field in porous p-n heterojunction derived from N-doped cerium metal-organic framework. *Chem. Eng. J.* **2026**, *538*, 176687. [DOI](#)
130. Cline, E. L.; Noh, H.; Benedetto, G.; et al. Array of bimetallic metallophthalocyanine-based metal-organic frameworks for chemiresistive detection and differentiation of toxic gases. *Chem* **2026**, *12*, 103037. [DOI](#)
131. Lee, K.; Jo, Y. M.; Sohn, M. S.; et al. Photoactivated conductive MOF thin film arrays on micro-LEDs for chemiresistive gas sensing. *Nat. Commun.* **2025**, *16*, 9612. [DOI PubMed PMC](#)
132. Liu, J.; Yang, F.; Tian, X.; et al. Construction of hierarchical conductive metal-organic frameworks via template-directed synthesis strategy for ultratrace H₂S sensing. *ACS. Sens.* **2026**, *11*, 4600–7. [DOI](#)
133. Zhang, W.; Ji, C.; Liu, L.; et al. Intercalated conductive metal-organic frameworks constructed via donor-acceptor interactions for ultratrace gas sensing. *Mater. Today.* **2026**, *97*, 103381. [DOI](#)
134. Sun, Y.; Wang, B.; Wang, B.; et al. Coupling between conductive Co₃(HITP)₂ and SnO₂ NPs for heterogeneous architectures: toward sensitive chemiresistors for H₂S at room temperature. *Chem. Eng. J.* **2024**, *500*, 157253. [DOI](#)
135. Jiang, H.; Wang, X.; Wang, X.; et al. Ultra-low hydrogen sulfide gas detection of metal-organic framework derived hollowed-out rod-shaped copper oxide nanostructures. *Appl. Surf. Sci.* **2025**, *683*, 161628. [DOI](#)
136. Ding, Y.; Zhuang, Q.; Guo, X.; et al. NiO-CuO hydrangeas-like composite derived from Ni/Cu bimetallic MOFs for sensitive detection of H₂S at room temperature. *Appl. Surf. Sci.* **2023**, *612*, 155792. [DOI](#)
137. Zhang, C.; Zhang, S.; Yang, Y.; Yu, H.; Dong, X. Highly sensitive H₂S sensors based on metal-organic framework driven γ-Fe₂O₃ on reduced graphene oxide composites at room temperature. *Sens. Actuators. B: Chem.* **2020**, *325*, 128804. [DOI](#)
138. Lee, U. Y.; Kim, M. Y.; Lee, K. H.; et al. Surface reaction mechanism and characteristics of 2-dimensional TiO₂ and 0-dimensional Ag nanocomposites specialized for H₂S gas sensing at room temperature. *Sens. Actuators. Rep.* **2025**, *9*, 100290. [DOI](#)
139. Yan, Y.; Turdi, G.; Yimit, A.; Nizamidin, P. Ag-doped ZnFe₂O₄ nanoparticles for highly selective room-temperature H₂S detection: experiment and DFT study. *Mater. Sci. Semicond. Process.* **2026**, *208*, 110495. [DOI](#)
140. Abed, H. R.; Alwan, A. M. Effect of incorporating Ag nanoparticles within CeO₂/PS thin film on the structural, morphological, and room temperature H₂S gas sensing. *Chinese. Journal. of. Physics.* **2025**, *98*, 591–603. [DOI](#)
141. Kumar, A.; Joshi, N.; Samanta, S.; et al. Room temperature detection of H₂S by flexible gold-cobalt phthalocyanine heterojunction thin films. *Sens. Actuators. B: Chem.* **2015**, *206*, 653–62. [DOI](#)
142. Shen, Y.; Zhang, B.; Cao, X.; et al. Microstructure and enhanced H₂S sensing properties of Pt-loaded WO₃ thin films. *Sens. Actuators. B: Chem.* **2014**, *193*, 273–9. [DOI](#)
143. Sun, Y.; Zhao, Y.; Sun, H.; Jia, F.; Kumar, P.; Liu, B. Synthesis and room-temperature H₂S sensing of Pt nanoparticle-functionalized SnO₂ mesoporous nanoflowers. *J. Alloys. Compd.* **2020**, *842*, 155813. [DOI](#)
144. Zuo, P.; Wang, R.; Li, F.; Wu, F.; Xu, G.; Niu, W. A trace ppb-level electrochemical H₂S sensor based on ultrathin Pt nanotubes. *Talanta* **2021**, *233*, 122539. [DOI](#)

145. Xue, S.; Jin, Q.; Wang, X.; Lu, G. Microwave gas sensor based on differential planar resonator synergistically loaded with Pd-doped CdSnO₃ for enhanced H₂S detection. *IEEE. Electron. Device. Lett.* **2025**, *46*, 480-3. DOI
146. Sharma, P.; Bhattacharya, K.; Kumar, S.; Girija, K. Reliable and reversible detection of H₂S at room temperature engendered via Pd doping of ZnO films synthesized by SILAR method. *J. Alloys. Compd.* **2024**, *1003*, 175591. DOI
147. He, R.; Sun, Y.; Hou, Y.; et al. In-situ construction of Ag@Co-HHTP nanoparticles flexible sensor for H₂S monitoring at room-temperature. *Microchem. J.* **2026**, *228*, 119088. DOI
148. Wang, Y.; Li, J.; Zhang, D.; et al. Hydrothermal synthesis of Ag-doped WO₃-based H₂S room temperature sensors: unprecedented high and fast response. *Sens. Actuators. B.: Chem.* **2025**, *438*, 137811. DOI
149. Zong, H.; Li, X.; Zhang, Y.; et al. Pt/Ti₃C₂ electrode material used for H₂S sensor with low detection limit and high stability. *Chin. Chem. Lett.* **2025**, *36*, 110195. DOI
150. Zhang, F.; Wang, Q.; Jiao, C.; et al. Oxygen vacancies-rich MoS₂/Au@Cu₂O for highly selective and ultrafast detection of hydrogen sulfide. *J. Alloys. Compd.* **2026**, *1057*, 186867. DOI
151. Kong, D.; Ma, B.; Zhang, L.; et al. Metal (Au, Ag, Pt) Doping effects on the gas-sensing mechanism and characteristics of two-dimensional WS₂: a first-principle. *ACS. Appl. Electron. Mater.* **2024**, *6*, 958-68. DOI
152. Chen, H.; Liu, Y.; Xie, C.; Wu, J.; Zeng, D.; Liao, Y. A comparative study on UV light activated porous TiO₂ and ZnO film sensors for gas sensing at room temperature. *Ceram. Int.* **2012**, *38*, 503-9. DOI
153. Deb, S.; Mondal, A.; Ashok, Kumar. Reddy. Y. Review on development of metal-oxide and 2-D material based gas sensors under light-activation. *Curr. Opin. Solid. St. M.* **2024**, *30*, 101160. DOI
154. Zou, C.; Peng, C.; She, X.; Wang, M.; Peng, B.; Zhou, Y. Photoelectric H₂S sensing based on electrospun hollow CuO-SnO₂ nanotubes at room temperature. *Sensors. (Basel).* **2024**, *24*, 6420. DOI PubMed PMC
155. Sun, Y.; Cui, J.; Fu, S.; et al. Rare earth-driven photogenerated charge separation in SnO₂@Y₂O₃ heterojunctions for enhanced H₂S sensing at room temperature. *ACS. Appl. Mater. Interfaces.* **2025**, *17*, 15948-58. DOI
156. Yu, M.; Li, J.; Yin, D.; et al. Enhanced oxygen anions generation on Bi₂S₃/Sb₂S₃ heterostructure by visible light for trace H₂S detection at room temperature. *J. Hazard. Mater.* **2024**, *476*, 134932. DOI
157. Guo, X.; Ding, Y.; Liang, C.; et al. Humidity-activated H₂S sensor based on SnSe₂/WO₃ composite for evaluating the spoilage of eggs at room temperature. *Sens. Actuators. B.: Chem.* **2022**, *357*, 131424. DOI
158. Chinh, N. D.; Kim, C.; Kim, D. UV-light-activated H₂S gas sensing by a TiO₂ nanoparticulate thin film at room temperature. *J. Alloys. Compd.* **2019**, *778*, 247-55. DOI
159. Sun, Y.; Qian, K.; Yue, J.; et al. High-response In₂O₃/SnO₂ heterojunction sensor for detection of food spoilage gas H₂S in refrigerators. *Sens. Actuators. B.: Chem.* **2026**, *451*, 139341. DOI
160. Shahid, A.; Widdicombe, B.; Mokkapati, S.; Unnithan, R. R. Intelligent single-chip Si-FET based E-nose using metal and oxides functionalization. In *2025 IEEE 20th Nanotechnology Materials and Devices Conference (NMDC)*, Delhi, India, October 9-11, 2025; IEEE, 2025, pp 210-5. DOI
161. Shahid, Y.; Hu, Y.; Jiang, Y.; Xu, Z.; Yao, L. An electronic nose based on gas sensor microarray for malodorous pollutants detection. In *2026 6th International Conference on Sensors and Information Technology (ICSIT)*, Zhengzhou, China, April 24-26, 2026; IEEE, 2026, pp 116-20. DOI
162. Jońca, J.; Miller, U.; Szrek, J.; et al. Organometallic-derived metal oxide sensors for H₂S detection in an electronic nose for odor abatement assessment. *Sens. Actuators. B.: Chem.* **2026**, *448*, 138990. DOI

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