



Surfactant-mediated oxygen-vacancy engineering of defect In_2O_3 for ppb-level ozone sensing at low operating temperature

Dongqing Pang^a, Ruijie Xie^{a,b,c}, Jinhan Mo^{a,b,c,*}

^a Key Laboratory of Coastal Urban Resilient Infrastructures (Ministry of Education), College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China

^b State Key Laboratory of Subtropical Building and Urban Science, Shenzhen University, Shenzhen 518060, China

^c Key Laboratory of Coastal Urban Soil-Water Environmental Evolution, Ministry of Ecology and Environment (under construction), Shenzhen University, Shenzhen 518060, China

ARTICLE INFO

Keywords:

Ozone sensor
Metal oxide semiconductor
Oxygen vacancy control
Multielectron migration
Indium Oxide

ABSTRACT

Indoor ozone (O_3) and its reaction products jointly increase the burden of diseases on the human body. Metal-oxide semiconductor (MOS) sensors are attractive for miniaturization and ease of integration. However, practical O_3 sensing remains challenging due to low response and relatively high detection limits, especially in ppb-level actual environments. In this study, we fabricated oxygen vacancy-rich indium oxide ($\text{O-In}_2\text{O}_3$) nano-materials, which significantly enhanced the response and reduced the detection limit. The $\text{O-In}_2\text{O}_3$ sensor exhibited a response of 162.23 toward 130 ppb O_3 at an operating temperature of 44°C , approximately 33.50 times higher than that of In_2O_3 (4.84). In addition, $\text{O-In}_2\text{O}_3$ had a detection limit of 10 ppb with a response of 29.96, approximately a 10.40-fold enhancement over In_2O_3 . More attractively, *in-situ* Fourier transform infrared spectroscopy analysis indicated that the oxygen vacancy enrichment promoted the adsorption of O_3 by the gas-sensitive material and facilitated the reduction reaction of O_3 , which may result from the three-electron reduction pathway, thereby providing a mechanistic explanation for the observed performance improvement.

1. Introduction

Over the past few decades, rapid urbanization and industrial expansion have intensified episodic ozone (O_3) pollution, making it a major global air-quality concern [1,2]. O_3 in the environment can enter indoor spaces through opening windows for ventilation or mechanical ventilation systems [3,4]. Approximately 60% of indoor O_3 reacts with indoor chemicals, forming various ozone reaction products, including formaldehyde, nonyl alcohol, and hydrogen peroxide [5,6]. Exposure of indoor occupants to O_3 and its reaction products can cause respiratory, cardiovascular, and lung diseases in humans [7–9]. The World Health Organization (WHO) recommends that the 8-hour average O_3 concentration should not exceed approximately 50 ppb ($100 \mu\text{g}/\text{m}^3$) [10]. However, some studies have shown that even at indoor O_3 concentrations far below the current regulatory standards, the effects of O_3 and its reaction products on heart and lung health have been observed [11,12]. Therefore, accurate O_3 monitoring in both residential spaces and industrial workplaces is important for early warning, exposure control,

and risk management [13,14].

Metal oxide semiconductor (MOS) gas sensors have attracted much attention for O_3 detection due to their low fabrication cost, facile integration, and high chemical stability [15–18]. In a typical MOS sensing mechanism, target gas molecules adsorb on the surface of the gas-sensitive material and interact with chemisorbed oxygen species, leading to charge transfer and modulation of the semiconductor's carrier density [19,20]. This process demonstrates a measurable resistance change that enables O_3 detection [21]. MOS sensing materials include both n-type and p-type semiconductors. Representative n-type oxides include SnO_2 [22], ZnO [23], In_2O_3 [24], and WO_3 [25], whereas typical p-type oxides include Co_3O_4 [26], Mn_3O_4 [27], CuO [28], and NiO [29]. Among these materials, In_2O_3 has shown significant advantages for oxidizing-gas sensing [30–32]. Sui et al. [33] reported cubic bixbyite-type indium oxide ($\text{C-In}_2\text{O}_3$) with a response of 5.7 toward 100 ppb O_3 , due to the narrow band gap and the enrichment of chemisorbed oxygen. However, the In_2O_3 sensor exhibited a relatively low response to some target gases at ppb levels, and the detection limit under actual operating conditions was also relatively high.

* Corresponding author at: Key Laboratory of Coastal Urban Resilient Infrastructures (Ministry of Education), College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China.

E-mail address: mojinhan@szu.edu.cn (J. Mo).

<https://doi.org/10.1016/j.snb.2026.140816>

Received 3 July 2026; Received in revised form 18 August 2026; Accepted 31 August 2026

Available online 1 September 2026

0925-4005/© 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Because the adsorption of target gas molecules and the subsequent charge-transfer process are key determinants of the response and detection limit of MOS gas sensors, various strategies have been explored to enhance their sensing performance. Representative approaches include constructing heterostructures to promote interfacial charge redistribution [34], regulating morphology to increase the number of accessible active sites [35], introducing dopants to modulate carrier concentration and electronic structure [36], and constructing bimetallic oxide systems to optimize surface reaction pathways [37–39]. Liu et al. [40] developed bimetallic $\text{In}_6\text{WO}_{12}$ nanospheres with a large specific surface area and abundant gas diffusion channels. They further optimized the surface reaction path of NO_2 through gold atom clusters, enabling the $\text{In}_6\text{WO}_{12}$ sensor to exhibit a significant response to 2 ppm NO_2 at room temperature, reaching 203, which is 54.8 times that of the original $\text{In}_6\text{WO}_{12}$, significantly improving the sensing performance of NO_2 . Zhang et al. [41] synthesized In_2O_3 hollow microtubes decorated with ZnO nanoparticles derived from metal-organic frameworks (MOFs). The combined effects of Zn-related oxygen-vacancy formation and an n-n heterojunction formed at the $\text{In}_2\text{O}_3/\text{ZnO}$ interface enabled a response of 26.12 toward 1 ppm O_3 at 150°C .

Among these methods, oxygen-vacancy engineering was particularly significant because the controlled introduction of oxygen vacancies can regulate the electronic band structure and surface-state density [42], thereby enhancing the adsorption of O_3 molecules and facilitating charge transfer [43,44]. Wang et al. [45] synthesized an oxygen-rich In_2O_3 film by in-situ growth of MIL-68 (In) on a ceramic tube and subsequent calcination. The abundant oxygen vacancies and high surface adsorbed oxygen content in the material delivered a response of 14.1 toward 5 ppm Cl_2 at 50°C , which offered significant advantages over previously reported In_2O_3 -based Cl_2 sensors. Despite these advances, achieving strong O_3 adsorption and efficient interfacial charge transport at low temperatures remains challenging. This limitation continues to hinder MOS sensors in ppb-level O_3 detection, where both response and detection limit must be substantially improved.

In this study, an O- In_2O_3 nanomaterial with high surface oxygen vacancies was prepared to overcome the limitations of MOS sensors in the detection of low-concentration O_3 . The increase in the number of oxygen vacancies provided more adsorption sites for O_3 adsorption and reduced the detection limit of O_3 . Moreover, oxygen vacancies could act as electron donors, promoting the occurrence of reduction reactions, thereby enhancing the response of O_3 sensing. In summary, oxygen vacancy enrichment not only improved the adsorption capacity of the sensing material but also supplied additional electrons that participate in surface reactions, promoting the continuous accumulation of chemically adsorbed oxygen species. These chemically adsorbed oxygen species further reacted with O_3 , which might enable a three-electron reduction pathway that significantly enhances the sensing performance under low-temperature conditions. This work systematically elucidated the adsorption and reaction mechanism of O_3 on gas-sensitive materials from the perspective of oxygen vacancy engineering and provided design guidelines for precise O_3 sensing technology.

2. Experimental section

2.1. Materials and characterization

Indium chloride tetrahydrate ($\text{InCl}_3 \cdot 4\text{H}_2\text{O}$, 99.99%) was purchased from Chengdu Dianchun Technology Co., LTD. Ethylenediamine (En; $\text{C}_2\text{H}_8\text{N}_2 \cdot \text{H}_2\text{O}$, >98.0%) and 1-Hexadecyl-3-methylimidazolium chloride ([C16Mim] Cl, >96%) were purchased from Aladdin Ind. Co. Ltd. In addition, deionized (DI) water and absolute ethanol were employed, and all chemical reagents were used as received without further purification. Toluene was purchased from Guangdong Guangshi Reagent Technology Co., Ltd. (China, purity $\geq 99.5\%$). Benzene was purchased from Macklin (China, purity $\geq 99.5\%$). Tetrachloroethylene was purchased from Macklin (China, purity 99%).

X-ray powder diffraction (XRD) patterns of the as-prepared samples were collected with a Bruker AXS D8 Advance. X-ray diffraction (XRD) patterns were recorded using $\text{Cu K}\alpha 1$ radiation ($\lambda = 1.5406 \text{ \AA}$) in the 2θ range of $20^\circ - 70^\circ$ with a scanning rate of 5° min^{-1} . The morphologies of the as-synthesized samples were characterized using a field-emission scanning electron microscope (SEM, HITACHI SU-70) and a transmission electron microscope (TEM, Carl Zeiss AG Supra 55 Sapphire). Energy-dispersive X-ray spectroscopy (EDS) analysis was also performed using TEM attachments. The compositions of the products were analyzed by XPS (Thermo K-ALPHA). Bruker EMX Plus measured EPR spectra.

2.2. Synthesis of In_2O_3 and oxygen vacancy-rich In_2O_3 (O- In_2O_3) nanomaterials

In_2O_3 and oxygen vacancy-rich In_2O_3 (denoted as O- In_2O_3) were synthesized via a hydrothermal approach followed by calcination (schematic shown in Fig. 1). For In_2O_3 , 0.15 g $\text{InCl}_3 \cdot 4\text{H}_2\text{O}$ was dissolved in a mixed solvent of ethylenediamine (En) and DI water with a volume ratio of 25:15. The solution was magnetically stirred for 30 min to obtain a homogeneous mixture. Then, the resulting solution was transferred into a 100 mL Teflon-lined stainless steel autoclave reactor and heated at 220°C for 20 h. After naturally cooling to room temperature, the precipitate was collected by filtration, washed repeatedly with DI water, and dried at 60°C in air. Finally, the obtained precursor was subsequently calcined in air at 400°C for 1 h with a heating rate of 1°C min^{-1} in a muffle furnace to yield the In_2O_3 nanomaterials. The synthesis of O- In_2O_3 followed an identical procedure, except that before the hydrothermal process, 0.12 g [C16Mim] Cl needed to be dissolved in the mixture of $\text{InCl}_3 \cdot 4\text{H}_2\text{O}$ and ethylenediamine-water.

2.3. Sensor fabrication and gas-sensing measurements

For sensor fabrication, 50 mg of the synthesized nanomaterial was dispersed in 1 mL of DI water to form a homogeneous suspension. The homogeneous mixture was drop-cast onto a ceramic substrate equipped with interdigitated gold electrodes and a nickel-chromium alloy microheater (Fig. S1). The coated sensor was aged at 300°C for 24 h to stabilize the baseline resistance and improve adhesion between the sensing film and the substrate. All measurements were performed under controlled laboratory conditions with a relative humidity of 2.0% and an ambient temperature of 27°C .

The O_3 -sensing performance evaluation system is illustrated in Fig. S2. In brief, low-concentration O_3 is generated through vacuum ultraviolet (VUV) irradiation, and the ozone concentration is controlled by adjusting the proportion of the mixed air. Finally, the ozone concentration within the test platform is monitored by the 2B Technologies Model 205. The target VOCs are generated using the injection pump-assisted evaporation method [46]. The liquid VOCs (including benzene, toluene, and tetrachloroethylene) are loaded into a sealed syringe and continuously injected into the micro-evaporation chamber via an injection pump (LSP01-2A, Longer, China). The evaporation chamber is maintained at 125°C to ensure a stable vaporization process. The VOC concentration is regulated by adjusting the injection rate, and the specific calculation method is shown in Eq. (1). The sensing performance toward O_3 was assessed using an SMT1028 gas-testing platform (Maimu, China). The sensor response (S) of oxidizing gases and reductive gases was defined, respectively, as $S_{\text{oxidizing}} = R_g / R_a$ and $S_{\text{reductive}} = R_a / R_g$, where R_g and R_a were the sensor resistances in the target gas and in air, respectively. The response time (t_{res}) was defined as the time required for 90% of the total change in resistance upon O_3 exposure, while the recovery time (t_{rec}) was the time required to recover 90% of the baseline resistance after O_3 removal. The operating temperature refers to the surface temperature of the gas-sensitive sensing film.

$$C = 24.62 \rho \text{ pP/MQ} \quad (1)$$

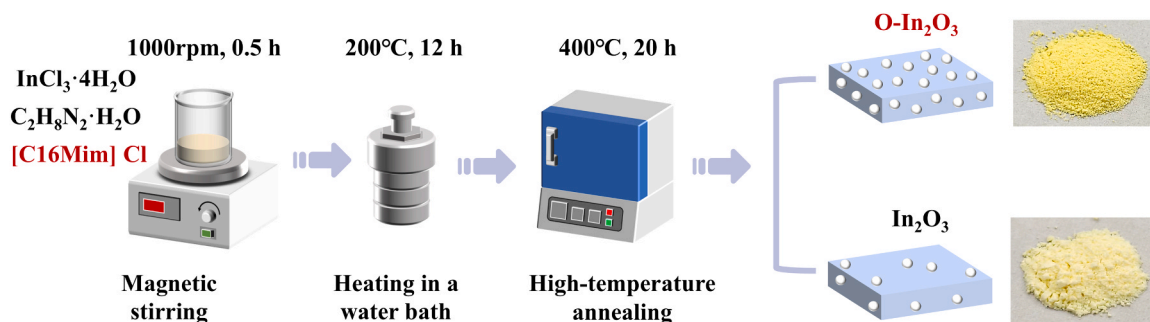


Fig. 1. Schematic diagram for the preparation of $\text{O-In}_2\text{O}_3$ and In_2O_3 .

where, C is the VOC concentration, ppm; ρ is the density of the VOC liquid, mg/m^3 ; q is the liquid injection rate, m^3/s ; P is the purity of the source liquid; Q is the total gas flow rate, m^3/s ; M is the molar mass of VOCs, g/mol .

3. Results and discussion

3.1. Characterization of synthesized $\text{O-In}_2\text{O}_3$ and In_2O_3

The morphology and microstructure of $\text{O-In}_2\text{O}_3$ and In_2O_3 were

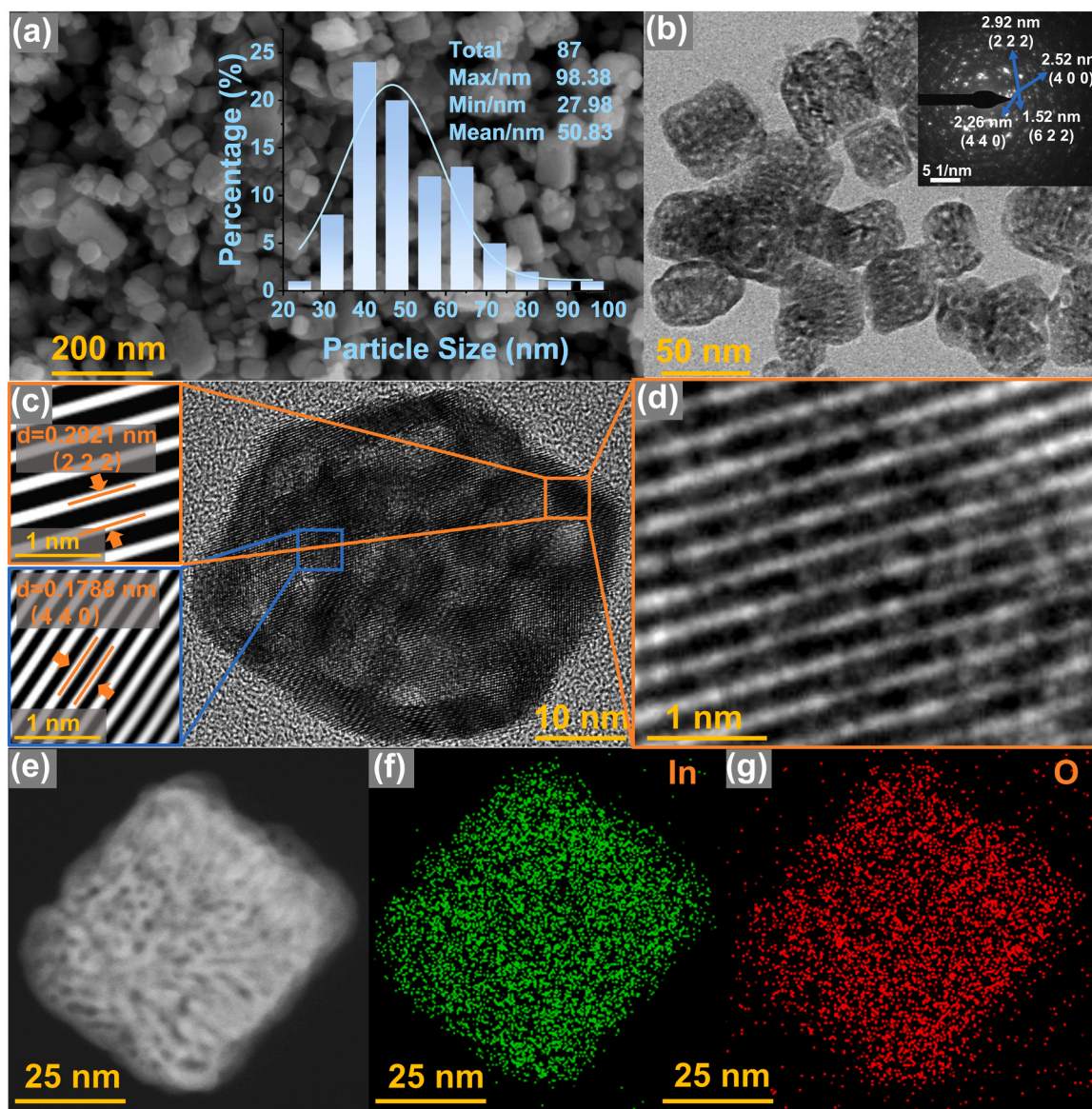


Fig. 2. (a) SEM image of $\text{O-In}_2\text{O}_3$, and the insert figure is the particle size distribution; (b) HRTEM image of $\text{O-In}_2\text{O}_3$ and the insert figure is the corresponding selection of electron diffraction; (c) HRTEM image of $\text{O-In}_2\text{O}_3$ and the lattice pattern analysis; (d) A local magnified view of the crystal lattice pattern of $\text{O-In}_2\text{O}_3$. (e-g) EDS mapping images of $\text{O-In}_2\text{O}_3$.

examined by scanning electron microscopy (SEM) and High-resolution TEM (HRTEM). As shown in Fig. 2a and Fig. S3, both O-In₂O₃ and In₂O₃ exhibited cubic morphology, but the grain size of O-In₂O₃ had slightly decreased. The HRTEM images of O-In₂O₃ (Fig. 2b) showed significant contrast variations in the nanocrystalline surface, which were commonly associated with oxygen vacancy-rich domains [47]. In contrast, the surface of In₂O₃ was relatively smooth with far fewer structural defects (Fig. S4). From the perspective of crystal structure analysis, selected-area electron diffraction (SAED) patterns further confirm that both samples possess single-crystalline characteristics (insets of Fig. 2b and Fig. S3). The diffraction spots can be indexed to the (2 2 2), (4 0 0), (4 4 0), and (6 2 2) planes, consistent with the cubic In₂O₃ phase identified in the XRD analysis (Fig. S5). The XRD patterns of O-In₂O₃ and In₂O₃ showed characteristic peaks, consistent with the standard JCPDS reference and confirming its cubic In₂O₃ (Fig. S5). Meanwhile, the peak positions of O-In₂O₃ deviated to the left from those of the standard carbide and In₂O₃ (respectively, 30.2°, 35.1°, 50.8°, and 60.4°), which was attributed to the lattice expansion caused by defects [48,49]. Meanwhile, the broadening of the diffraction peaks also confirmed the smaller grain size, which was consistent with the grain size analysis results obtained by SEM [50,51]. Importantly, no additional peaks were observed, indicating that defect enrichment was achieved without introducing secondary phases or changing the crystal structure.

HRTEM also provides direct evidence for localized lattice disorder in O-In₂O₃. As shown in Fig. 2c and Fig. 2d, clear lattice fringes were observed alongside localized distortions and discontinuities, consistent with a defect-rich lattice [52]. The measured interplanar spacings of 0.2921 nm and 0.1525 nm correspond well to the (2 2 2) and (6 2 2)

planes of cubic In₂O₃, respectively, further corroborating phase retention. Elemental mapping via energy-dispersive X-ray spectroscopy (EDS) (Fig. 2e-g and Fig. S6) demonstrated a uniform distribution of In and O throughout the O-In₂O₃ nanostructures, suggesting compositional homogeneity at the microscale. Overall, the above analyses verify the successful synthesis of O-In₂O₃ with a surface lattice defect.

Further, the presence and relative content of oxygen vacancies could be determined through electron paramagnetic resonance (EPR) and Raman analysis. Fig. 3a shows the EPR spectra of O-In₂O₃ and In₂O₃. Both samples exhibited a resonance signal at $g = 2.003$, which was characteristic of oxygen vacancies [53]. The signal intensity reflected the relative concentration of oxygen vacancies [54], and O-In₂O₃ displayed a significantly stronger signal compared with In₂O₃. This result provides direct spectroscopic evidence that the defects in O-In₂O₃ were oxygen vacancies and that their content was higher than that of In₂O₃. As shown in Fig. 3b, the peak at around 130 cm⁻¹ was ascribed to the In-O vibration of the InO₆ structure, and two peaks at 306 and 493 cm⁻¹ were assigned to the bending and stretching vibrations of the octahedral InO₆ in In₂O₃, respectively [55]. In addition, the peak centered at 368 cm⁻¹ was assigned to the stretching vibration of In-O-In, suggesting the existence of oxygen vacancies [56]. To further quantify the oxygen vacancies of O-In₂O₃ and In₂O₃, the intensity ratio I_2 / I_1 between the peaks at 306 cm⁻¹ (I_1) and 368 cm⁻¹ (I_2) was calculated [57]. O-In₂O₃ exhibited a larger I_2 / I_1 value (0.384) than In₂O₃ (0.327), consistent with an increased oxygen vacancy population and in agreement with the EPR results.

X-ray photoelectron spectroscopy (XPS) analysis further confirmed that O-In₂O₃ had a high content of oxygen vacancies. Fig. S7 presents the XPS spectra of O-In₂O₃ and In₂O₃, where the prominent peaks

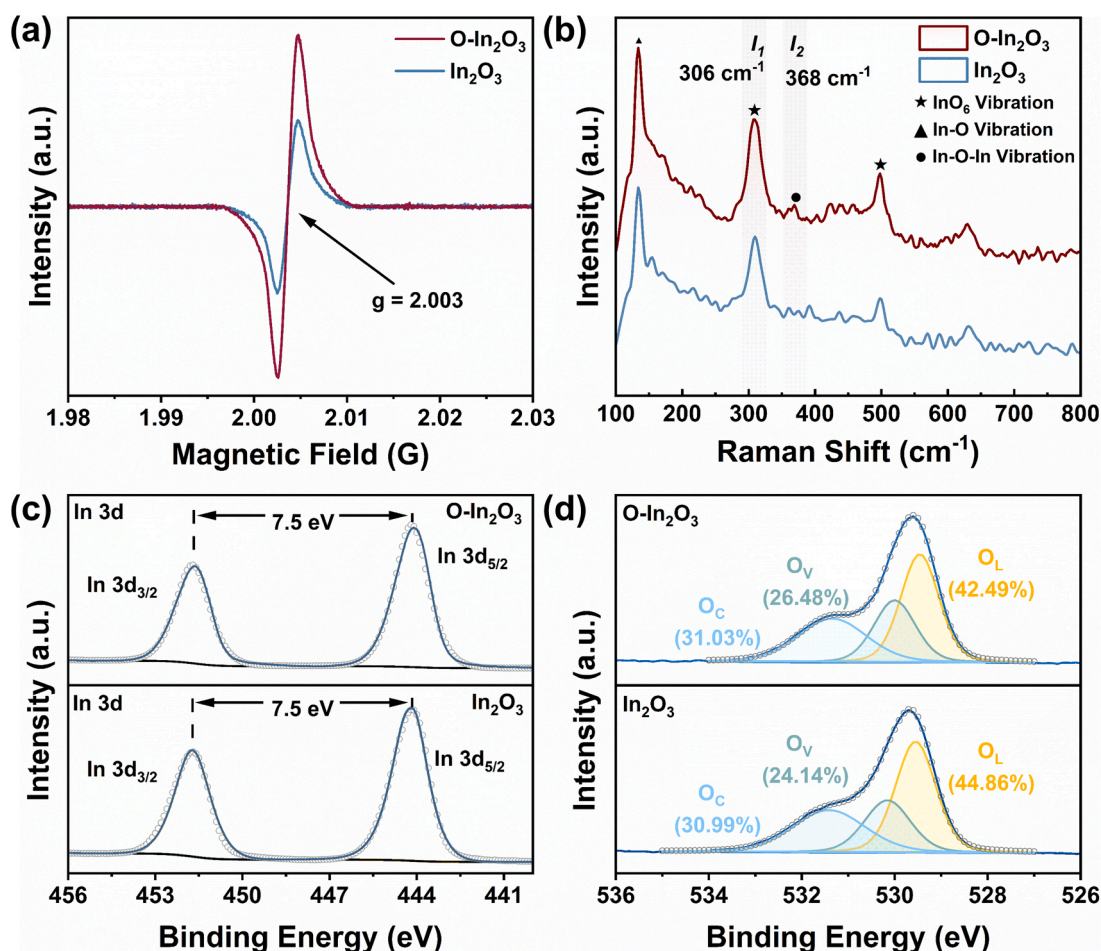


Fig. 3. (a) EPR spectra of O-In₂O₃ and In₂O₃; (b) Raman spectra of O-In₂O₃ and In₂O₃; XPS spectra of (c) In 3d and (d) O 1s of O-In₂O₃ and In₂O₃.

correspond to In and O. High-resolution In 3d spectra (Fig. 3c) display two distinct peaks at binding energies of 451.7 eV (In 3d_{3/2}) and 444.2 eV (In 3d_{5/2}) for both O-In₂O₃ and In₂O₃ [58]. The peak separation of 7.5 eV indicated that indium predominantly exists as In³⁺ in these samples [59]. This observation indicates that the increase in oxygen vacancies does not cause a measurable change in the bulk indium valence, and instead mainly perturbs the oxygen sublattice.

Fig. 3d displays the O1s spectra of O-In₂O₃. The O1s peak can be deconvoluted into three components corresponding to different chemical states: oxygen vacancies (O_V), lattice oxygen (O_L), and adsorbed oxygen (O_C). O_V, at ~530.16 eV, corresponds to oxygen vacancies, while O_L, at ~529.57 eV, represents lattice oxygen, and O_C, at ~531.48 eV, is attributed to surface hydroxyl groups [60]. For In₂O₃, O_L and O_C were considered to have negligible contributions to the gas-sensing response, whereas O_V plays a crucial role [61]. Higher O_V content facilitates greater oxygen adsorption on the material surface [62]. The O_V content in O-In₂O₃ was 26.48%, which was significantly higher than that in In₂O₃ (24.14%) and was consistent with the EPR results. The enriched O_V sites were expected to increase the density of active adsorption sites, thereby providing a structural basis for improved sensing performance.

3.2. O₃ sensing performance of O-In₂O₃

Because gas adsorption-desorption processes were governed by both thermodynamic driving forces and kinetic barriers, the operating temperature was a key parameter that determined the MOS sensor's response and dynamic behavior. The response of O-In₂O₃ and In₂O₃

sensors to 60 ppb O₃ was evaluated over the temperature range of 25°C to 66°C (Fig. 4a). The O-In₂O₃ sensor exhibited a higher response than the In₂O₃ sensor, highlighting the beneficial role of oxygen-vacancy enrichment. Notably, the response decreased as the operating temperature increased, consistent with the general behavior of oxidizing-gas sensing at low concentrations, where elevated temperature can accelerate desorption and reduce net surface coverage of reactive species [63]. Although the O-In₂O₃ sensor had the maximum response at room temperature (25°C), excessively low temperature led to incomplete desorption and thus poor recovery. As shown in Fig. 4b, when the recovery period was fixed at 10 min, the resistance recovery ratios were 28.0%, 51.0%, 97.8%, 94.8%, and 95.5% at 25°C, 34°C, 44°C, 52°C, and 60°C, respectively. Above 44°C, the recovery ratios remained relatively high (94.8–97.8%) without a clear monotonic dependence on temperature, indicating that the small variations are likely associated with experimental fluctuations. To balance response and recovery characteristics, 44°C was finally selected as the optimal operating temperature for subsequent measurements.

To clarify the influence of oxygen vacancies on the O₃ sensing behavior, the O₃ sensing performance of O-In₂O₃ and In₂O₃ sensors was systematically compared at 44°C. When exposed to 130 ppb O₃ (Fig. 4c), the resistance of O-In₂O₃ increased rapidly, yielding a response time of 463 s, which was 395 s shorter than that of In₂O₃. In addition, O-In₂O₃ exhibited a substantially faster recovery (96 s) than In₂O₃ (1627 s). The response value of O-In₂O₃ reached 162.23 at 130 ppb O₃, which was approximately 33.5 times higher than that of In₂O₃ (4.84). These significant differences indicate that high-density oxygen vacancies provided more surface active sites for O₃ adsorption and accelerated

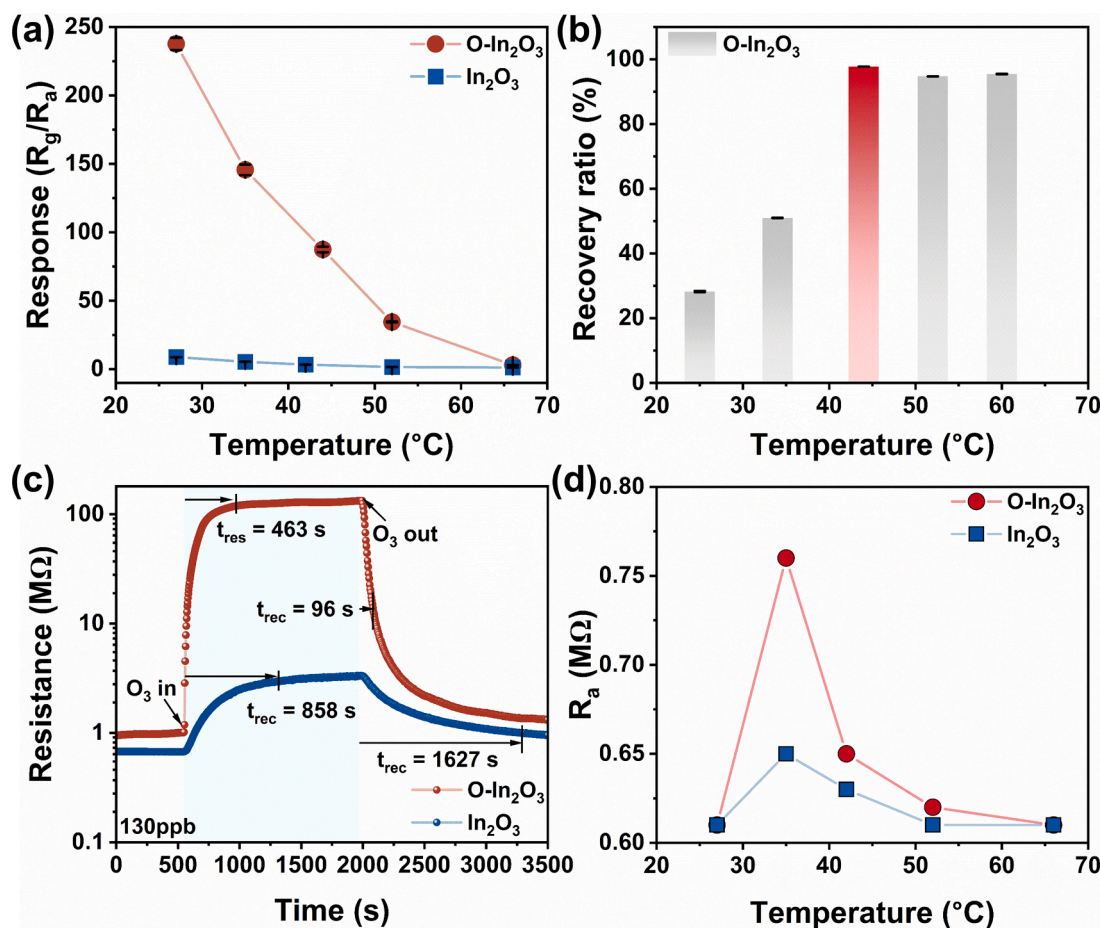


Fig. 4. (a) The response of O-In₂O₃ and In₂O₃ to 60 ppb O₃ at different operating temperatures; (b) The percentage of resistance recovery of O-In₂O₃ after responding to 60 ppb O₃ at different temperatures; (c) Response-recovery curves of gas sensors based on O-In₂O₃ and In₂O₃ toward 130 ppb O₃ at 44°C; (d) The R_a values of O-In₂O₃ and In₂O₃ under different operating temperatures.

interfacial charge transfer, thereby effectively improving response and recovery kinetics.

Furthermore, as shown in Fig. 4d, the R_a values of both O-In₂O₃ and In₂O₃ initially increased and then decreased with the increasing operating temperature. The initial increase is attributed to enhanced oxygen adsorption at relatively low temperatures, where adsorbed oxygen molecules extracted more electrons from the conduction band, resulting in a thicker electron depletion layer and a larger sensor resistance [64]. At elevated operating temperatures, thermally activated electron transport became dominant. The increased free carrier concentration and enhanced electron mobility gradually offset the electron depletion effect induced by oxygen adsorption, thereby leading to a decrease in R_a [65]. Compared with In₂O₃, the O-In₂O₃ sensor exhibited a higher baseline resistance at intermediate temperatures, indicating that the increased oxygen vacancy density provided more active adsorption sites and promoted chemisorption of oxygen species, thereby further enlarging the electron depletion layer. As the operating temperature continued to increase, thermal activation gradually outweighed the effect of oxygen adsorption, causing the baseline resistances of the two sensors to converge.

Concentration-gradient tests further demonstrated the superior response of O-In₂O₃. As summarized in Fig. 5a, O-In₂O₃ maintains higher responses than In₂O₃ within the range of 10–130 ppb, indicating an amplified resistance modulation under weak O₃ exposure. The enhanced response mainly originates from the abundant oxygen vacancies on the surface of O-In₂O₃, which act as high-energy adsorption centers and electron donors that facilitate O₃ capture and subsequent reduction reactions, thereby significantly increasing the extent of electron depletion and resistance change. Meanwhile, compared with In₂O₃,

the O-In₂O₃ sensor exhibits a higher R_a . This increase can be attributed to the introduction of abundant oxygen vacancies induced by the surfactant-assisted synthesis process. The increased oxygen vacancy concentration promotes oxygen adsorption and facilitates the formation of a thicker electron depletion layer on the surface, resulting in a higher resistance state under an air atmosphere.

In addition, Fig. 5a also shows that the R_a of both sensors undergoes slight variations during the continuous detection of different concentrations of O₃, particularly at elevated gas concentrations. This behavior is mainly attributed to the gradual accumulation of strongly chemisorbed oxygen species and the incomplete desorption of reaction intermediates during prolonged operation. Owing to the higher concentration of surface oxygen vacancies, O-In₂O₃ exhibits stronger adsorption capability toward oxygen and O₃ molecules, which may lead to a slight shift in the R_a . Despite the slight baseline drift, the sensor still maintains satisfactory operational accuracy, indicating its potential applicability in practical O₃ monitoring.

Meanwhile, O-In₂O₃ enables ppb-level detection with a substantially lower limit of detection. As shown in Fig. 5b, at 10 ppb O₃, the O-In₂O₃ sensor still shows a response of 29.96, which is approximately 10.37 times that of the In₂O₃ sensor. Meanwhile, Fig. 5c shows that, compared with the O-In₂O₃ sensor, the In₂O₃ sensor shows only marginal differences in response within the concentration range of 10–30 ppb. These results underscore that oxygen vacancy engineering was particularly effective in addressing the intrinsic limitation of conventional In₂O₃ sensors for low-concentration O₃ detection.

The corresponding calibration curves (Fig. 5c) confirmed this trend: O-In₂O₃ exhibited a good linear correlation between response and O₃

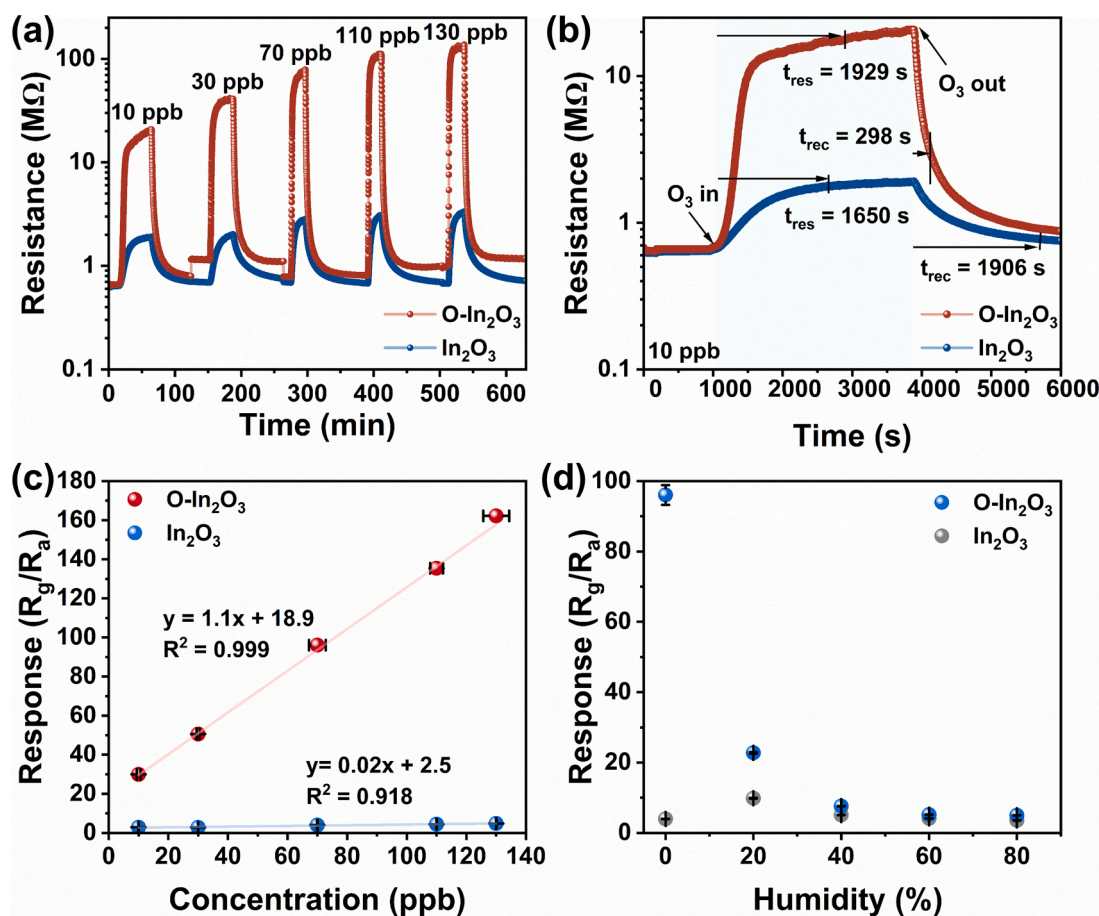


Fig. 5. (a) The response-recovery curves of O-In₂O₃ and In₂O₃ to different concentrations of O₃ at 44°C; (b) Resistance-recovery curves of O-In₂O₃ and In₂O₃ sensors towards 10 ppb O₃ at 44°C; (c) The fitted straight line between the O₃ concentration and the response of the O-In₂O₃ and In₂O₃ sensors at 44°C. (d) Response of O-In₂O₃ and In₂O₃ to 70 ppb O₃ at 44°C under different humidity conditions.

concentration over 10–130 ppb, enabling quantitative detection in the ppb regime. The linear fitting relationships for O-In₂O₃ and In₂O₃ were provided in Eqs. (2) and (3), respectively.

$$y = 1.1x + 18.9 \quad R^2 = 0.999 \quad (2)$$

$$y = 0.02x + 2.5 \quad R^2 = 0.918 \quad (3)$$

where, x means O₃ concentration, and y means the response.

Humidity was also a key environmental factor that affects the performance of gas sensors, as it can change the surface properties and conductivity of the sensor materials [66]. Under the environmental temperature of 27°C and the operating temperature of 44°C, we conducted tests on the response performance of O-In₂O₃ and In₂O₃ to O₃ under various humidity conditions, as shown in Fig. 5d. As the relative humidity increases from 0% to 80%, the responses of O-In₂O₃ and In₂O₃ sensors show a significant downward trend. However, when the humidity is between 20% and 80%, the changes in the responses of O-In₂O₃ and In₂O₃ sensors are relatively small. The reason for this phenomenon is mainly that, in a humid environment, water vapor molecules compete with gas molecules for adsorption, occupying the active sites originally used for gas adsorption. This physical adsorption effect reduces the effective adsorption area of the sensor for target gas molecules, thereby affecting its response performance [67]. Secondly, the accumulation of water on the sensitive layer surface forms a physical barrier, preventing sufficient contact between oxygen molecules and the surface of the sensitive layer. Since the formation of oxygen species on the sensor surface is crucial for the redox reaction on the sensor surface, this barrier reduces the gas sensing performance of the sensor [68].

The common methods for resisting humidity interference in MOS gas sensors mainly focus on inhibiting water molecule adsorption, reducing the generation of hydroxyl groups (-OH), and regulating the surface reaction process. On one hand, the application of hydrophobic materials such as PDMS and PrO_x can reduce the adsorption of water molecules on the sensitive material surface [69]; on the other hand, humidity absorbers such as NiO and CuO can be introduced to preferentially capture water [70], or variable-valent rare earth oxides such as Ce³⁺/Ce⁴⁺ and Pr³⁺/Pr⁴⁺ can be utilized to dynamically remove -OH generated by water adsorption through redox cycling [71]. Alternatively, the electronic structure of the MOS surface can be regulated by F⁻ doping to reduce the reactivity of chemisorbed oxygen with water, thereby also inhibiting humidity interference [72]. In addition, constructing heterojunctions such as SnO₂/NiO and In₂O₃/WO₃, and loading noble metals such as Pt, can enhance the target gas reaction through interface charge regulation and catalysis, improving the sensor's effective response in high-humidity environments [73]. In the subsequent research, we will further address the adverse effects of humidity on the response performance of semiconductor sensors.

To evaluate the feasibility of quantitative O₃ monitoring under practical conditions, the linear fitting equations (Eqs. (2) and (3)) derived for O-In₂O₃ and In₂O₃ sensors were used to convert sensor responses into real-time O₃ concentrations. These predictions were then benchmarked against a commercial reference O₃ monitor instrument for measuring O₃ concentration using ultraviolet spectroscopy technology (Dual-beam Technology, Model 205 Dual Beam Ozone Monitor) under the 100 ppb atmosphere and during programmed concentration variations. This comparison probes not only steady-state accuracy but also dynamic tracking capability, which was critical for real-world monitoring.

As shown in Fig. 6a, during 70 min of exposure to an O₃ atmosphere, the detected concentration obtained from the O-In₂O₃ sensor was highly consistent with the reference concentrations measured by the Dual-beam technology ozone monitor, demonstrating high agreement and minimal drift. Extended dynamic tests (Fig. S8) further reveal that the ambient O₃ concentration underwent multiple rise-fall cycles over a 200 min period. From the overall trend, both the O-In₂O₃ and In₂O₃

sensors were able to track the changes in O₃ concentration, but their response characteristics differed significantly. The O-In₂O₃ sensor showed rapid and consistent following behavior during both the concentration increase and the decrease phases, yielding detected concentrations that remained closely aligned with the reference monitor across successive cycles. In contrast, the In₂O₃ sensor showed significant deviation from the reference values, characterized by a weaker response amplitude and more obvious fluctuations during low-concentration transitions. These results directly demonstrated that the O-In₂O₃ sensor significantly outperforms the In₂O₃ sensor in real-time concentration-tracking accuracy and signal stability. This performance improvement could be attributed to abundant oxygen vacancies on the surface of O-In₂O₃, which not only enhance its adsorption capacity and reactivity toward O₃ but also optimize carrier transport kinetics, thereby triggering multi-electron migration and enabling the sensor to respond more quickly and precisely to minute changes in environmental concentration.

Selectivity was assessed by exposing the O-In₂O₃ sensor to representative interfering gases at 44°C, including benzene (C₆H₆), toluene (C₇H₈), and tetrachloroethylene (C₂Cl₄) at 110 ppm, H₂ at 100 ppm, as well as SO₂ at 1 ppm and NO₂ at 200 ppb. As summarized in Fig. 6b, under the same operating conditions, the gas sensor exhibited a significant response to O₃, but showed no obvious response to C₆H₆, C₇H₈, C₂Cl₄, H₂, and SO₂. Although the sensor responded by 43.39 toward 200 ppb of NO₂, its response to only 110 ppb of O₃ was as high as 135.4. The minimal cross-response indicated that the O-In₂O₃ sensor preferentially responds to O₃, supporting its suitability for selective O₃ monitoring in mixed-gas environments.

To comprehensively evaluate the performance advantages of this work, Fig. 6c and Fig. 6d summarize the key performance parameters of various O₃ gas sensors reported in the literature, and detailed information can be found in Table 1. The comparison showed that most of the existing MOS sensors had a relatively low response to low concentrations of O₃ (Fig. 6c). Additionally, some sensors had higher operating temperatures or higher detect concentration (Fig. 6d). In contrast, the sensor developed in this study achieved a higher response value and a lower detection limit (10 ppb) at a lower operating temperature (44°C). Therefore, this sensor not only meets the practical need for precise detection of trace O₃ but also has the potential for low power consumption due to its low-temperature operation characteristics, providing a promising solution for the practical application of MOS-based O₃ sensing technology.

3.3. O₃ sensing mechanism

To probe the surface reaction pathways underlying the enhanced O₃ sensing of O-In₂O₃, *in-situ* Fourier-transform infrared (*in-situ* FTIR) spectroscopy was performed to monitor adsorption and surface-species evolution during O₃ exposure (Fig. 7a). Before O₃ exposure (at the 0-minute time point), the O-In₂O₃ sample exhibited a largely featureless spectrum in the monitored region (Fig. 7a), indicating the absence of strongly bound infrared-active adsorbates under the baseline condition. Upon introduction of O₃, a new absorption band emerged at approximately 1050 cm⁻¹ within 1 min, which could be assigned to the characteristic vibrational modes of adsorbed O₃ molecules [95]. Notably, the intensity of this O₃-related band increased monotonically with exposure time from 1 min to 6 min, evidencing progressive accumulation of O₃-derived surface species and confirming strong adsorption of O₃ on O-In₂O₃. In contrast, In₂O₃ showed substantially weaker O₃ adsorption at the same wavenumber (Fig. 7b), and the O₃ signal was observed until after a prolonged time of 5 min. The delayed onset and reduced intensity indicated limited O₃ uptake on In₂O₃, consistent with its inferior sensing response at ppb levels.

In addition to molecular adsorption, the *in-situ* FTIR could also reflect the formation of reactive oxygen species during the O₃ action process. It was shown that during the O₃ induction process, there might exist a new

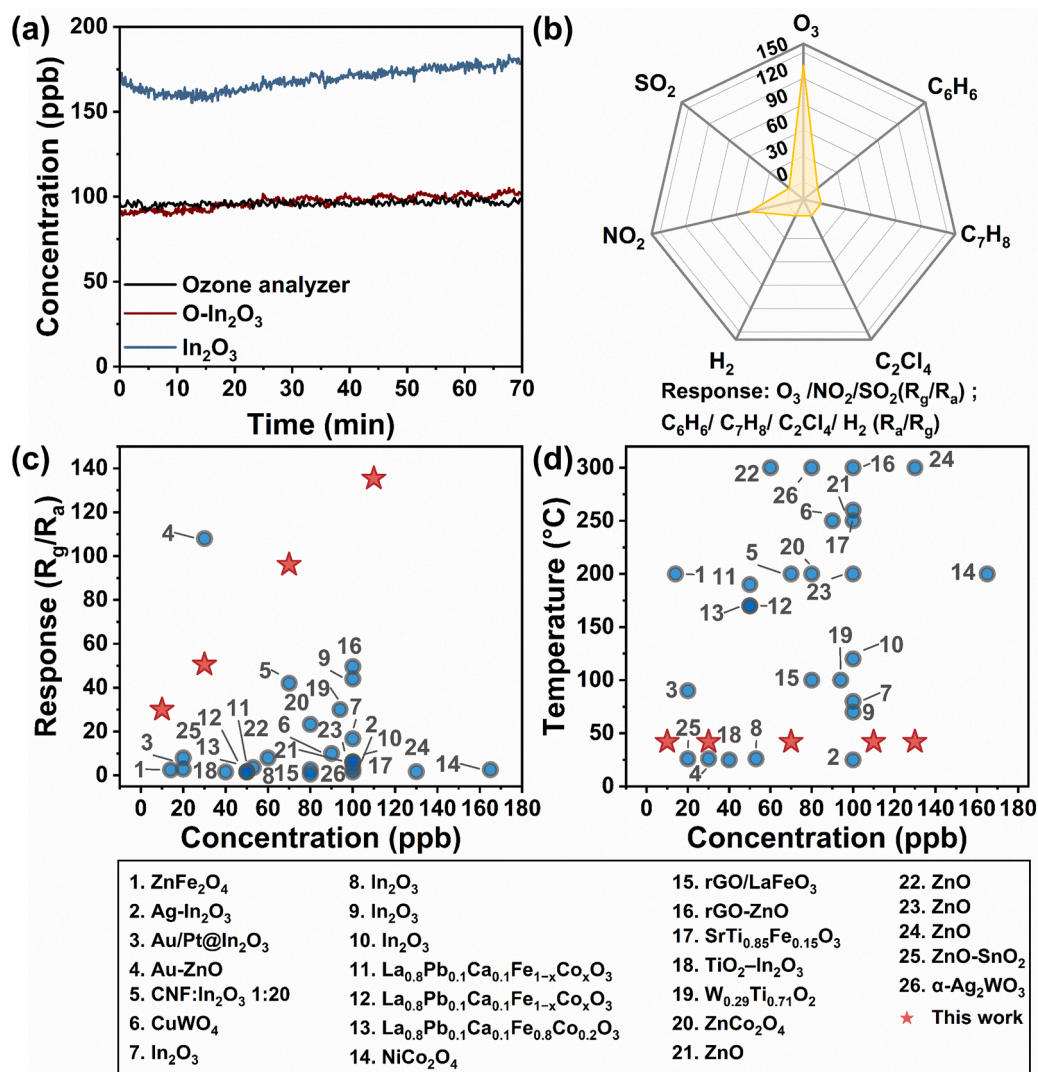


Fig. 6. (a) Under an O₃ concentration of 100 ppb, the concentrations detected using O-In₂O₃ and In₂O₃ were compared in real time with the concentrations measured by a Dual-beam technology ozone monitor; (b) Selectivity tests of O-In₂O₃ and In₂O₃ sensors for different types of gases at 44°C; Comparative analysis of (c) gas sensing response and (d) temperature response with reported O₃ sensors in the literature. The numbers in (c) and (d) are consistent with those in Table 1.

three-electron reduction pathway. At relatively low temperatures (<150°C), the conventional working mechanism of the MOS O₃ sensor was as follows: In the air without O₃, oxygen molecules in the environment adsorb on the surface of the gas-sensitive material and undergo a reduction reaction to form O₂⁻ (Step 1). When exposed to air containing O₃, due to the high electron affinity of O₃, it is superior to the oxygen molecules adsorbing on the surface of the gas-sensitive material and undergoing a reduction reaction to form O⁻ (Step 2) [93]. Therefore, during the detection process, O₂ was mainly produced through the adsorption of oxygen. Additionally, as shown in Fig. 7a and Fig. 7b, in an air environment (at the 0-minute time point), neither of these materials exhibited a significant O₂ absorption band (approximately at 1095 cm⁻¹), indicating that the content of O₂ generated by the adsorption of molecular oxygen was relatively low. However, with the introduction of O₃, the O-In₂O₃ sample significantly enhanced the O₂ generation peak. This phenomenon indicates that adsorbed O₃ may undergo reduction reactions, generating chemically adsorbed oxygen species (Step 3, the three-electron reduction pathway). In contrast, In₂O₃ displayed much weaker absorptions at the same wavenumbers (Fig. 7b and Fig. 7c), suggesting limited O₃ adsorption and fewer generated O₂ species. Additional absorption features observed between 1620 cm⁻¹ and 1365 cm⁻¹ were attributed to the stretching and

bending vibrations of -OH groups in adsorbed water [96], implying a competitive adsorption process between water and O₃ on the surface.

Step1 $O_{2(ads)} + e^- \rightarrow O_{2(ads)}^-$ $T < 150^\circ C$

Step2 $O_{3(gas)} + O_{2(ads)}^- + 2e^- \rightarrow O_{2(gas)} + 3O_{(ads)}^-$ $T < 150^\circ C$

Step3 $O_{3(gas)} + O_{(ads)}^- + 3e^- \rightarrow O_{2(gas)} + 2O_{2(ads)}^-$ $T < 150^\circ C$

where, (gas) means the gas phase, referring to the existence of oxygen in gaseous form, and (ads) means the adsorbed content, referring to the state where oxygen was adsorbed.

The O₃ sensing mechanism of O-In₂O₃ was shown in Fig. 7d. The enhanced sensing behavior can be primarily attributed to the high density of surface oxygen vacancies in O-In₂O₃. These oxygen vacancies not only provided abundant active sites for O₃ adsorption, thereby improving the adsorption capacity, but also promoted the formation of chemisorbed oxygen species (e.g., O⁻) through O₃ reduction. Furthermore, oxygen vacancies acted as electron donors, increasing the carrier concentration. This electron-rich surface facilitated efficient electron transfer to adsorbed O₃ molecules, enabling successive reduction reactions, leading to enhanced generation of reactive oxygen species and improved sensing performance.

Table 1Performance of reported sensor materials for O₃ sensors.

No.	Material	Concentration	Response (R_g / R_a)	Operating temperature (°C)	Reference
1	ZnFe ₂ O ₄	14	2.5	200	[74]
2	Ag-In ₂ O ₃	100	1.58	25	[36]
3	Au/Pt@In ₂ O ₃	20	2.9	90	[75]
4	Au-ZnO	30	108	26	[76]
5	CNF: In ₂ O ₃	70	42	200	[77]
6	CuWO ₄	90	10	250	[78]
7	In ₂ O ₃	100	16.7	80	[79]
8	In ₂ O ₃	53	3.6	26	[24]
9	In ₂ O ₃	100	44	70	[80]
10	In ₂ O ₃	100	5.7	120	[33]
11	La _{0.8} Pb _{0.1} Ca _{0.1} Fe _{1-x} Co _x O ₃	50	1.586	190	[81]
12	La _{0.8} Pb _{0.1} Ca _{0.1} Fe _{1-x} Co _x O ₃	50	1.753	170	[82]
13	La _{0.8} Pb _{0.1} Ca _{0.1} Fe _{0.8} Co _{0.2} O ₃	50	1.6	170	[83]
14	NiCo ₂ O ₄	165	2.6	200	[84]
15	rGO/LaFeO ₃	80	2.6	100	[85]
16	rGO-ZnO	100	49.6	300	[86]
17	SrTi _{0.85} Fe _{0.15} O ₃	100	3	260	[87]
18	TiO ₂ -In ₂ O ₃	40	1.6	25	[34]
19	W _{0.29} Ti _{0.71} O ₂	94	30	100	[88]
20	ZnCo ₂ O ₄	80	23.3	200	[89]
21	ZnO	100	6.2	250	[90]
22	ZnO	60	8	300	[91]
23	ZnO	100	6.2	200	[23]
24	ZnO	130	1.7	300	[92]
25	ZnO-SnO ₂	20	8	26	[93]
26	α-Ag ₂ WO ₃	80	0.6	300	[94]

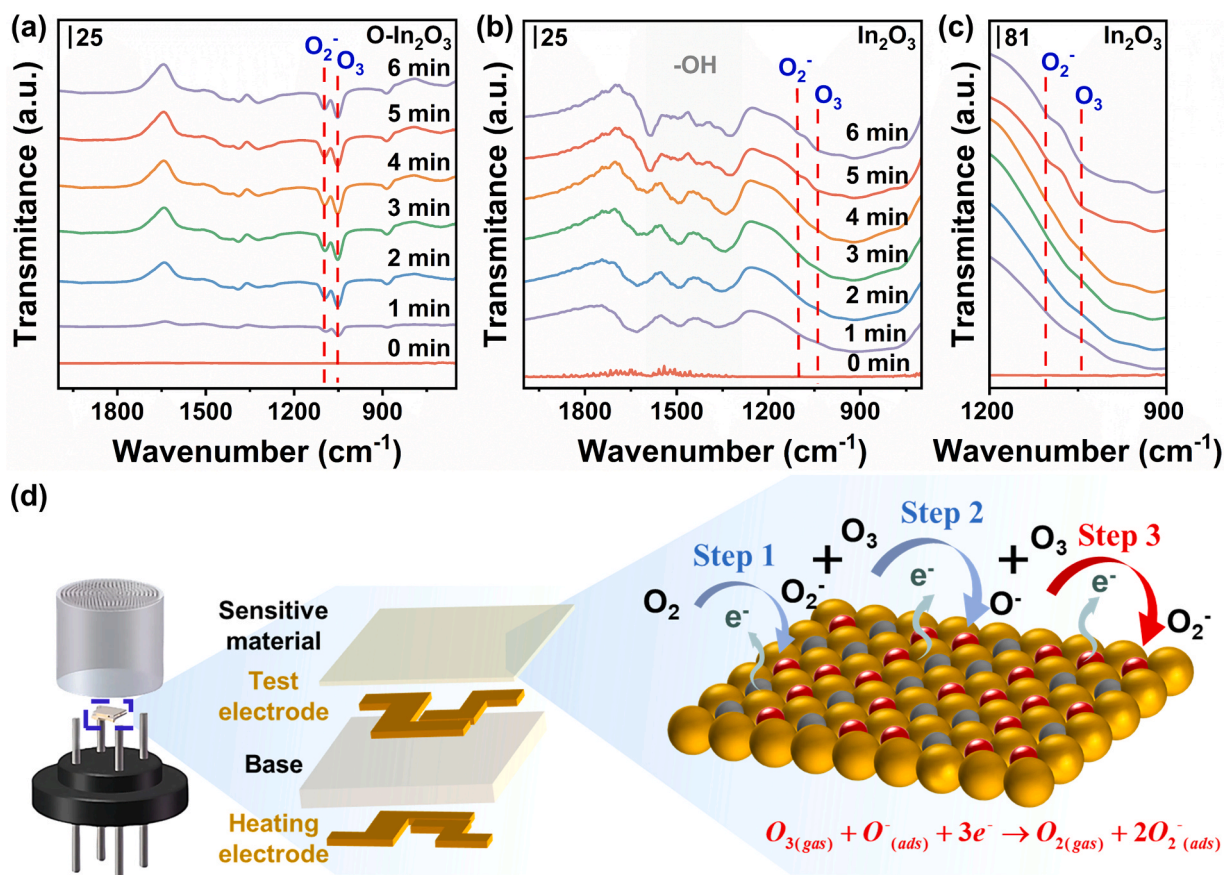


Fig. 7. *In-situ* Fourier Transform Infrared Spectroscopy (*in-situ* FTIR) analysis of (a) O-In₂O₃ and (b) In₂O₃; (c) The enlarged *in-situ* FTIR pattern at wavenumbers of 900 cm⁻¹ to 1200 cm⁻¹; (d) Schematic diagram of the gas sensing mechanism for the O-In₂O₃ sensor towards O₃ at low temperature (44°C).

4. Conclusions

In this study, O-In₂O₃ nanomaterial was prepared for the high-response detection of ppb-level O₃. The high oxygen vacancy content

on the surface of O-In₂O₃ nanomaterials provided more active sites for O₃ adsorption, acting as an electron donor and promoting the continuous transfer of electrons to the adsorbed O₃ molecules, and may introduce a new three-electron reduction pathway and achieve highly

sensitive detection. The O-In₂O₃ sensor with oxygen vacancy regulation operated at 44°C achieved a response value of up to 162.23 toward 130 ppb of O₃, which was 33.5 times higher than that of the In₂O₃ sensor. Notably, at 44°C, the detection limit of the O-In₂O₃ sensor was as low as 10 ppb, and the response value reached 29.96. In the dynamic sensing performance test, the O-In₂O₃ sensor showed greater consistency with the detected concentrations than the Dual-beam technology ozone monitor. It demonstrated better follow-up performance and lower noise during concentration changes, indicating its superior real-time monitoring accuracy. Finally, the O-In₂O₃ sensor exhibited excellent selectivity for O₃ over C₆H₆, C₇H₈, C₂Cl₄, H₂, SO₂, and NO₂.

CRedit authorship contribution statement

Ruijie Xie: Methodology. **Jinhan Mo:** Writing – review & editing. **Dongqing Pang:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Nos. 52325801 and 22306206) and Shenzhen Natural Science Foundation (Nos. JCYJ20240813143502004 and JCYJ20250604182503004).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.snb.2026.140816](https://doi.org/10.1016/j.snb.2026.140816).

Data Availability

Data will be made available on request.

References

- [1] J. Bao, X. Li, L. Kong, J. Li, Q. Chen, Y. Zhang, Comparative analysis of the impact of rising temperatures on ozone levels in China and the United States, *Clean. Air* 1 (1) (2025), <https://doi.org/10.1038/s44407-025-00023-8>.
- [2] A. Stenke, Natural control on ozone pollution, *Nat. Clim. Change* 10 (2) (2020) 101–102, <https://doi.org/10.1038/s41558-019-0686-3>.
- [3] Y. Li, X. Jian, Y. Guo, F. Deng, J. Zhang, Y. Li, F. Feng, Indoor ozone and ozone reaction products: an emerging health threat, *Environ. Pollut.* 389 (2026), <https://doi.org/10.1016/j.envpol.2025.127416>.
- [4] E. Tian, Q. Chen, Y. Gao, Z. Chen, Y. Wang, J. Mo, Advancing indoor air purification by mass transfer enhancement: Bridging the gap between high-performance materials and technologies, *Engineering* (2025), <https://doi.org/10.1016/j.eng.2025.07.003>.
- [5] W. Nazaroff, C. Weschler, Indoor ozone: Concentrations and influencing factors, *Indoor Air* 32 (1) (2021), <https://doi.org/10.1111/ina.12942>.
- [6] L. He, Z. Hao, C. Weschler, F. Li, Y. Zhang, J. Zhang, Indoor ozone reaction products: Contributors to the respiratory health effects associated with low-level outdoor ozone, *Atmos. Environ.* 340 (2025), <https://doi.org/10.1016/j.atmosenv.2024.120920>.
- [7] J. Ji, F. Dominici, N. Gouveia, F. Kelly, M. Neira, Air pollution interventions for health, *Nat. Med.* (2025), <https://doi.org/10.1038/s41591-025-03929-8>.
- [8] P. Ivatt, M. Evans, A. Lewis, Suppression of surface ozone by an aerosol-inhibited photochemical ozone regime, *Nat. Geosci.* 15 (7) (2022) 536–540, <https://doi.org/10.1038/s41561-022-00972-9>.
- [9] M. Cui, C. Hong, W. Liu, K. He, Q. Zhang, Future warming exacerbates heatwave-ozone compound extremes in China, *Clim. Atmos. Sci.* 8 (1) (2025), <https://doi.org/10.1038/s41612-025-01218-2>.
- [10] J. Petrucci, D. Barreto, M. Dias, E. Felix, A. Cardoso, Analytical methods applied for ozone gas detection: A review, *TRAC Trends Anal. Chem.* 149 (2022) 116552, <https://doi.org/10.1016/j.trac.2022.116552>.
- [11] J. Huang, Y. Song, M. Chu, W. Dong, M.R. Miller, M. Loh, J. Xu, D. Yang, R. Chi, X. Yang, S. Wu, X. Guo, F. Deng, Cardiorespiratory responses to low-level ozone exposure: The inDoor Ozone Study in childrEn (DOSE), *Environ. Int.* 131 (2019), <https://doi.org/10.1016/j.envint.2019.105021>.
- [12] S. Liu, Q. Huang, X. Zhang, W. Dong, W. Zhang, S. Wu, D. Yang, B. Nan, J. Zhang, H. Shen, X. Guo, F. Deng, Cardiorespiratory effects of indoor ozone exposure associated with changes in metabolic profiles among children: a repeated-measure panel study, *Partic. J.* 2 (1) (2021), <https://doi.org/10.1016/j.xinn.2021.100087>.
- [13] K. Hu, P. Guo, C. Yan, T. Deng, D. Li, C. Zhuang, Joint IT-cooling system optimization for data center energy efficiency: a critical review, *Energy Use* 1 (2) (2025), <https://doi.org/10.59717/ijp.energy-use.2025.100020>.
- [14] W. Zou, Y. Wang, E. Tian, J. Wei, J. Peng, J. Mo, A new dynamic and vertical photovoltaic integrated building envelope for high-rise glaze-facade buildings, *Engineering* 39 (2024) 194–203, <https://doi.org/10.1016/j.eng.2024.01.014>.
- [15] A. Kumar, J. Mazumder, K. Joyen, F. Favier, A. Mirzaei, J. Kim, M. Kwoka, M. Bechelany, R. Jha, M. Kumar, H. Kim, S. Kim, Defect engineering approaches for metal oxide semiconductor-based chemiresistive gas sensing, *Coord. Chem. Rev.* 541 (2025), <https://doi.org/10.1016/j.ccr.2025.216836>.
- [16] J. Hu, Y. Zou, Y. Deng, H. Li, H. Xu, D. Wang, L. Wu, Y. Deng, G. Li, Recent advances in non-ionic surfactant templated synthesis of porous metal oxide semiconductors for gas sensing applications, *Progress. Mater. Sci.* 150 (2025), <https://doi.org/10.1016/j.pmatsci.2024.101409>.
- [17] H. Long, Y. Li, K. Chai, W. Zeng, Metal oxide semiconductor-based core-shell nanostructures for chemiresistive gas sensing: a review, *Sens. Actuators B Chem.* 417 (2024) 136183, <https://doi.org/10.1016/j.snb.2024.136183>.
- [18] D. Pang, E. Tian, R. Xie, Z. Yin, J. Chen, J. Deng, J. Mo, Advances and challenges in metal oxide semiconductor-based sensors for indoor ozone detection, *Build. Environ.* 285 (2025), <https://doi.org/10.1016/j.buildenv.2025.113596>.
- [19] C. Zhang, G. Liu, X. Geng, K. Wu, M. Debligny, Metal oxide semiconductors with highly concentrated oxygen vacancies for gas sensing materials: A review, *Sens. Actuators A Phys.* 309 (2020) 112026, <https://doi.org/10.1016/j.sna.2020.112026>.
- [20] C. Fan, Y. Lei, M. Piscitelli, J. Mo, Generalizable data-driven building operation control methods for scalable cross-building applications, *Energy Use* 1 (1) (2025), <https://doi.org/10.59717/ijp.energy-use.2025.100008>.
- [21] A. Dey, Semiconductor metal oxide gas sensors: A review, *Materials Science Engineering B* 229 (2018) 206–217, <https://doi.org/10.1016/j.mseb.2017.12.036>.
- [22] A. Gaddari, F. Berger, M. Amjoud, J. Sanchez, M. Lahcini, B. Rhouta, D. Mezzane, C. Mavon, E. Beche, V. Flaud, A novel way for the synthesis of tin dioxide sol-gel derived thin films: Application to O₃ detection at ambient temperature, *Sens. Actuators B Chem.* 176 (2013) 811–817, <https://doi.org/10.1016/j.snb.2012.10.049>.
- [23] M. Acuatla, S. Bernardini, L. Gallais, T. Florido, L. Patout, M. Bendahan, Ozone flexible sensors fabricated by photolithography and laser ablation processes based on ZnO nanoparticles, *Sens. Actuators B Chem.* 203 (2014) 602–611, <https://doi.org/10.1016/j.snb.2014.07.010>.
- [24] T. Wagner, J. Hennemann, C. Kohl, M. Tiemann, Photocatalytic ozone sensor based on mesoporous indium oxide: influence of the relative humidity on the sensing performance, *Thin Solid. Films* 520 (3) (2011) 918–921, <https://doi.org/10.1016/j.tsf.2011.04.181>.
- [25] J. Huang, X. Wang, Y. Gong, Y. Liu, P. Zhou, X. Suo, D. Zeng, H. Li, Construction of WO₃ coatings with micro-nano hybrid structures by liquid precursor flame spray for enhanced sensing performances to sub-ppm ozone, *Mater. Lett.* 205 (2017) 106–109, <https://doi.org/10.1016/j.matlet.2017.06.076>.
- [26] L. Liu, T. Li, Z. Yi, F. Chi, Z. Lin, X. Zhang, K. Xu, Conductometric ozone sensor based on mesoporous ultrafine Co₃O₄ nanobricks, *Sens. Actuators B Chem.* 297 (2019) 126815, <https://doi.org/10.1016/j.snb.2019.126815>.
- [27] Z. Tseng, Y. Jiang, C. Lin, J. Do, T. Hsu, C. Shih, Y. Chang, S. Liao, C. Huang, Highly stable flexible ozone gas sensors using Mn₃O₄ nanoparticles-decorated IGZO thin films through the SILAR method, *Ceram. Int.* 50 (16) (2024) 28584–28592, <https://doi.org/10.1016/j.ceramint.2024.05.168>.
- [28] Q. Huang, Z. Deng, R. Zhang, A. Klamchuen, M. Horprathum, S. Wang, X. Fang, L. You, S. Huang, G. Meng, Highly sensitive and selective ppb-level ozone sensor based on porous CuO nanoparticles, *Sens. Actuators B Chem.* 406 (2024) 135434, <https://doi.org/10.1016/j.snb.2024.135434>.
- [29] N. Kaur, Nickel oxide nanostructures for gas sensing: Recent advances, challenges, and future perspectives, *ACS Sens.* 10 (3) (2025) 1641–1674, <https://doi.org/10.1021/acssensors.4c02946>.
- [30] Z. Liu, J. Jia, G. Zhao, Recent advances in modified In₂O₃-based gas sensors for ultra-sensitive formaldehyde detection, *Talanta* 299 (2026), <https://doi.org/10.1016/j.talanta.2025.129102>.
- [31] L. Liu, C. He, J. Zeng, Y. Peng, W. Chen, Y. Zhao, X. Yang, Theoretical study of oxygen-vacancy distribution in In₂O₃, *J. Phys. Chem. C.* 125 (13) (2021) 7077–7085, <https://doi.org/10.1021/acs.jpcc.1c01462>.
- [32] S. Shah, S. Hussain, S. Din, A. Shahid, J. Amu-Darko, M. Wang, Y. Tianyan, G. Liu, G. Qiao, A review on In₂O₃ nanostructures for gas sensing applications, *J. Environ. Chem. Eng.* 12 (3) (2024), <https://doi.org/10.1016/j.jece.2024.112538>.
- [33] N. Sui, S. Cao, P. Zhang, T. Zhou, T. Zhang, The effect of different crystalline phases of In₂O₃ on the ozone sensing performance, *J. Hazard. Mater.* 418 (2021) 126290, <https://doi.org/10.1016/j.jhazmat.2021.126290>.
- [34] C. Wu, T. Chou, R. Wu, Rapid detection of trace ozone in TiO₂-In₂O₃ materials by using the differential method, *Sens. Actuators B Chem.* 255 (2018) 117–124, <https://doi.org/10.1016/j.snb.2017.08.055>.
- [35] D. Klaus, D. Klawinski, S. Amrehn, M. Tiemann, T. Wagner, Light-activated resistive ozone sensing at room temperature utilizing nanoporous In₂O₃ particles: Influence of particle size, *Sens. Actuators B Chem.* 217 (2015) 181–185, <https://doi.org/10.1016/j.snb.2014.09.021>.

- [36] Z. Zhu, J. Chang, C. Wu, T. Chou, R. Wu, Promotion effect of silver on Indium(III) oxide for detecting trace amounts of ozone, *Sens. Actuators B Chem.* 232 (2016) 442–447, <https://doi.org/10.1016/j.snb.2016.03.088>.
- [37] F. Liu, J. Zhao, S. Li, Z. Lv, Y. Zhang, J. Liu, L. Wu, Z. Wang, F. Wang, Strategic engineering of D-band center and oxygen vacancy in $\text{In}_6\text{WO}_{12-x}\text{S}_x$ for ultrahigh signal-to-noise ratio gas sensing at parts-per-billion level NO_2 , *J. Hazard. Mater.* 504 (2026), <https://doi.org/10.1016/j.jhazmat.2026.141365>.
- [38] F. Liu, J. Liu, J. Zhao, Z. Jin, S. Li, L. Liu, Z. Wang, L. Wu, Au atomic clusters engineered on sea urchin-like $\text{In}_6\text{WO}_{12}$ nanospheres for high-performance ppb-level NO_2 sensing at room temperature, *Sens. Actuators B Chem.* 435 (2025), <https://doi.org/10.1016/j.snb.2025.137653>.
- [39] F. Liu, J. Liu, J. Zhao, S. Li, Z. Lv, L. Liu, W. Du, Z. Wang, L. Wu, Synergistic effects of electron scattering and space charge transfer in mesoporous $\text{In}_6\text{WO}_{12}/\text{Pr}_2\text{O}_3$ heterojunction for enhanced NO_2 detection at room temperature, *J. Mater. Sci. & Technol.* 246 (2026) 290–298, <https://doi.org/10.1016/j.jmst.2025.03.083>.
- [40] F. Liu, J. Liu, J. Zhao, S. Li, Z. Lv, Y. Zhang, L. Wu, Unraveling NO_2 sensing Anomalies: Dual-reaction pathway governed by active oxygen anions and D-band center in Hierarchical $\text{In}_6\text{WO}_{12}$ nanospheres, *Sens. Actuators B Chem.* 446 (2026), <https://doi.org/10.1016/j.snb.2025.138665>.
- [41] D. Zhang, Z. Yang, P. Li, X. Zhou, Ozone gas sensing properties of metal-organic frameworks-derived In_2O_3 hollow microtubes decorated with ZnO nanoparticles, *Sens. Actuators B Chem.* 301 (2019) 127081, <https://doi.org/10.1016/j.snb.2019.127081>.
- [42] J. Deng, X. Yu, D. Pang, B. Fei, J. Mo, Cutting-edge gas sensor design for monitoring thermal runaway in lithium-ion batteries: A critical review, *J. Energy Chem.* 109 (2025) 769–785, <https://doi.org/10.1016/j.jechem.2025.06.025>.
- [43] J. Bai, L. Xie, C. Chen, W. Yang, Z. Wei, Q. Zhang, situ PL tracking the evolution and functionality of oxygen defects in the In_2O_3 -based NO_2 gas sensor, *ACS Sens.* (2025), <https://doi.org/10.1021/acssensors.5c01682>.
- [44] J. Deng, J. Chen, J. Mo, Powering humanoid robots: The central role of battery technology, *Energy Use 2* (1) (2026), <https://doi.org/10.59717/ijp.energy-use.2026.100032>.
- [45] S. Wang, R. Gao, Y. Wu, T. Li, M. Zheng, X. Zhang, Y. Xu, S. Gao, X. Zhou, L. Huo, Oxygen defect-rich In_2O_3 thin film sensor via in-situ controllable assembly for enhanced detection of Cl_2 under low power consumption, *Sens. Actuators B Chem.* 443 (2025), <https://doi.org/10.1016/j.snb.2025.138185>.
- [46] Q. Chen, R. Xiao, X. Lei, T. Yu, J. Mo, Experimental and modeling investigations on the adsorption behaviors of indoor volatile organic compounds in an in-situ thermally regenerated adsorption-board module, *Build. Environ.* 203 (2021), <https://doi.org/10.1016/j.buildenv.2021.108065>.
- [47] J. Zhao, Y. Guo, Z. Zhang, X. Zhang, Q. Ji, H. Zhang, Z. Song, D. Liu, J. Zeng, C. Chuang, E. Zhang, Y. Wang, G. Hu, M.A. Mushtaq, W. Raza, X. Cai, F. Ciucci, Out-of-plane coordination of iridium single atoms with organic molecules and cobalt-iron hydroxides to boost oxygen evolution reaction, *Nat. Nanotechnol.* 20 (1) (2025) 57–66, <https://doi.org/10.1038/s41565-024-01807-x>.
- [48] T. Bi, Z. Du, S. Chen, H. He, X. Shen, Y. Fu, Preparation of flower-like ZnO photocatalyst with oxygen vacancy to enhance the photocatalytic degradation of methyl orange, *Appl. Surf. Sci.* 614 (2023), <https://doi.org/10.1016/j.apsusc.2022.156240>.
- [49] X. Bi, G. Du, A. Kalam, D. Sun, Y. Yu, Q. Su, B. Xu, A.G. Al-Sehemi, Tuning oxygen vacancy content in TiO_2 nanoparticles to enhance the photocatalytic performance, *Chem. Eng. Sci.* 234 (2021), <https://doi.org/10.1016/j.ces.2021.116440>.
- [50] L. Liu, Y. Jiang, H. Zhao, J. Chen, J. Cheng, K. Yang, Y. Li, Engineering coexposed {001} and {101} facets in oxygen-deficient TiO_2 nanocrystals for enhanced CO_2 photoreduction under visible light, *ACS Catal.* 6 (2) (2016) 1097–1108, <https://doi.org/10.1021/acscatal.5b02098>.
- [51] Y. Jian, Y. Meng, J. Li, H. Wu, S. Saravanamurugan, H. Li, Engineering oxygen vacancy and crystal surfaces for TiO_2 -based photocatalysts for enhanced photocatalytic hydrogenation of bio-based carbonyls to biofuels, *J. Environ. Chem. Eng.* 10 (6) (2022), <https://doi.org/10.1016/j.jece.2022.108837>.
- [52] S. Lin, X. Guo, W. Cai, Y. Wang, Binder-free defective bimetallic metal-organic framework nanostructures with lattice distortion as hybrid supercapacitor electrodes, *ACS Appl. Mater. Interfaces* 7 (1) (2024) 1078–1088, <https://doi.org/10.1021/acsnanm.3c05037>.
- [53] Y. Xu, L. Zheng, C. Yang, W. Zheng, X. Liu, J. Zhang, Oxygen vacancies enabled porous SnO_2 thin films for highly sensitive detection of triethylamine at room temperature, *ACS Appl. Mater. Interfaces* 12 (18) (2020) 20704–20713, <https://doi.org/10.1021/acsnanm.3c05037>.
- [54] Y. Zhai, R. Yang, J. Wu, J. Li, K. Xiang, N. Hu, M. Zeng, J. Yang, Z. Yang, Nitrogen plasma-driven oxygen vacancy modulation in tin dioxide nanosheets enables Sub-Parts-per-Billion nitrogen dioxide detection at low operating temperature, *ACS Sens.* 10 (6) (2025) 4184–4193, <https://doi.org/10.1021/acssensors.5c00298>.
- [55] C. Shen, K. Sun, Z. Zhang, N. Rui, X. Jia, D. Mei, C.-j. Liu, Highly active $\text{Ir}/\text{In}_2\text{O}_3$ catalysts for selective hydrogenation of CO_2 to methanol: experimental and theoretical studies, *ACS Catal.* 11 (7) (2021) 4036–4046, <https://doi.org/10.1021/acscatal.0c05628>.
- [56] R. Cuscó, A. Taguchi, T. Yamaguchi, Phonon anharmonicity in $\alpha\text{-In}_2\text{O}_3$: A Raman scattering study of the A_{1g} modes, *J. Alloy. Compd.* 1020 (2025), <https://doi.org/10.1016/j.jallcom.2025.179350>.
- [57] W. Wang, Z. Qu, L. Song, Q. Fu, An investigation of Zr/Ce ratio influencing the catalytic performance of $\text{CuO}/\text{Ce}_{1-x}\text{Zr}_x\text{O}_2$ catalyst for CO_2 hydrogenation to CH_3OH , *J. Energy Chem.* 47 (2020) 18–28, <https://doi.org/10.1016/j.jechem.2019.11.021>.
- [58] D. Wang, C. Han, C. Zheng, H. Fang, D. Xu, H. Zhao, Fabrication of a ppb-level NO_2 gas sensor by sensitizing nanobundles assembled by In_2O_3 nanotubes with TiO_2 quantum dots, *Sens. Actuators B Chem.* 387 (2023), <https://doi.org/10.1016/j.snb.2023.133833>.
- [59] W. Yang, L. Feng, S. He, L. Liu, S. Liu, Density gradient strategy for preparation of broken In_2O_3 microtubes with remarkably selective detection of triethylamine vapor, *ACS Appl. Mater. Interfaces* 10 (32) (2018) 27131–27140, <https://doi.org/10.1021/acsnanm.3c05037>.
- [60] Z. Jin, J. Zhao, L. Liu, F. Liu, Z. Wang, F. Wang, J. Liu, Y. Mou, L. Wu, X. Wu, Humidity-independent gas sensors in the detection of hydrogen sulfide based on Nd_2O_3 -loaded In_2O_3 porous nanorods, *Sens. Actuators B Chem.* 403 (2024) 135237, <https://doi.org/10.1016/j.snb.2023.135237>.
- [61] B. Wang, Y. Sun, Y. Dong, Y. Hou, Z. Lu, Z. Wei, W. Zhang, K. Suematsu, J. Hu, Chemiresistive flexible gas sensor for NO_2 sensing at room-temperature using in situ constructed $\text{Au}/\text{In}_2\text{S}_3/\text{In}_2\text{O}_3$ hybrid microflowers, *Sens. Actuators B Chem.* 422 (2025), <https://doi.org/10.1016/j.snb.2024.136666>.
- [62] X. Yang, H. Fu, Y. Tian, Q. Xie, S. Xiong, D. Han, H. Zhang, X. An, Au decorated In_2O_3 hollow nanospheres: A novel sensing material toward amine, *Sens. Actuators B Chem.* 296 (2019), <https://doi.org/10.1016/j.snb.2019.126696>.
- [63] S. Zhao, Y. Shen, X. Yan, P. Zhou, Y. Yin, R. Lu, C. Han, B. Cui, D. Wei, Complex-surfactant-assisted hydrothermal synthesis of one-dimensional ZnO nanorods for high-performance ethanol gas sensor, *Sens. Actuators B Chem.* 286 (2019) 501–511, <https://doi.org/10.1016/j.snb.2019.01.127>.
- [64] S. Kucharski, P. Ferrer, F. Venturini, G. Held, A.S. Walton, C. Byrne, J. A. Covington, S.K. Ayyala, A.M. Beale, C. Blackman, Direct in situ spectroscopic evidence of the crucial role played by surface oxygen vacancies in the O_2 sensing mechanism of SnO_2 , *Chem. Sci.* 13 (20) (2022) 6089–6097, <https://doi.org/10.1039/d2sc01738e>.
- [65] C. Yuan, J. Ma, Y. Zou, G. Li, H. Xu, V.V. Sysoev, X. Cheng, Y. Deng, Modeling Interfacial Interaction between Gas Molecules and Semiconductor Metal Oxides: A New View Angle on Gas Sensing, *Adv. Sci. N.* 9 (33) (2022) e2203594, <https://doi.org/10.1002/adv.202203594>.
- [66] Y. Xia, S. Guo, L. Yang, S. He, L. Zhou, M. Wang, J. Gao, M. Hou, J. Wang, S. Komarneni, Enhanced free-radical generation on MoS_2/Pt by light and water vapor Co-activation for selective CO detection with high sensitivity, *Adv. Mater.* 35 (30) (2023), <https://doi.org/10.1002/adma.202303523>.
- [67] Y. Huang, Z. Zeng, T. Liang, J. Li, Z. Liao, J. Li, T. Yang, An encapsulation strategy of graphene humidity sensor for enhanced anti-interference ability, *Sens. Actuators B Chem.* 396 (2023), <https://doi.org/10.1016/j.snb.2023.134517>.
- [68] H. Bai, C. Feng, R. Guo, Y. Chen, W. Yuan, Y. Du, Y. Feng, W. Liu, K. Liu, F. Guo, J. Wang, D. Chen, R. Zhang, Wireless gas sensor based on monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ -modified GaN/CuO heterostructures for ultrafast and trace detection of NO_2 gas, *Chem. Eng. J.* 524 (2025), <https://doi.org/10.1016/j.cej.2025.169751>.
- [69] Z. Gao, G. Song, X. Zhang, Q. Li, S. Yang, T. Wang, Y. Li, L. Zhang, L. Guo, Y. Fu, A facile PDMS coating approach to room-temperature gas sensors with high humidity resistance and long-term stability, *Sens. Actuators B Chem.* 325 (2020), <https://doi.org/10.1016/j.snb.2020.128810>.
- [70] K.-I. Choi, H.-J. Kim, Y.-C. Kang, J.-H. Lee, Ultrasensitive and ultrasensitive detection of H_2S in highly humid atmosphere using CuO -loaded SnO_2 hollow spheres for real-time diagnosis of halitosis, *Sens. Actuators B Chem.* 194 (2014) 371–376, <https://doi.org/10.1016/j.snb.2013.12.111>.
- [71] W. Gao, X. Chang, O. Ola, Z. Wang, Q. Liao, X. Zhu, J. Li, Y. Jiang, D. Wang, S. Sun, Humidity-tolerant ammonia gas sensors based on $\text{PrO}_x/\text{In}_2\text{O}_3/\text{WO}_3$ heterostructure films, *Chem. Eng. J.* 509 (2025), <https://doi.org/10.1016/j.cej.2025.161482>.
- [72] Z. Jin, Y. Mou, J. Zhao, F. Liu, L. Liu, J. Liu, S. Li, F. Wang, Z. Wang, L. Wu, F-dopants blocking hydroxyl interference: A facile solution for realizing humidity-resistive, selectivity adjustable, highly sensitive In_2O_3 -based gas sensors, *Chem. Eng. J.* 512 (2025), <https://doi.org/10.1016/j.cej.2025.162338>.
- [73] S. Zhang, M. King, Y. Zheng, B. Zhang, N. Luo, Y. Wang, Z. Zhang, Humidity-independent gas sensor based on $\text{Pt}/\text{SnO}_2/\text{NiO}$ with advanced CO sensing capabilities, *J. Alloy. Compd.* 1010 (2025), <https://doi.org/10.1016/j.jallcom.2024.177712>.
- [74] R. de Oliveira, R. Pontes Ribeiro, G. Cruvinel, R. Ciola Amoresi, M. Carvalho, A. de Oliveira, M. de Oliveira, S. de Lazaro, L. da Silva, A. Catto, A. Simões, J. Sambrano, E. Longo, Role of surfaces in the magnetic and ozone gas-sensing properties of ZnFe_2O_4 nanoparticles: Theoretical and experimental insights, *ACS Appl. Mater. & Interfaces* 13 (3) (2021) 4605–4617, <https://doi.org/10.1021/acsnanm.3c05037>.
- [75] N. Sui, X. Wei, S. Cao, P. Zhang, T. Zhou, T. Zhang, Nanoscale bimetallic AuPt-functionalized metal oxide chemiresistors: Ppb-level and selective detection for ozone and acetone, *ACS Sens.* 7 (8) (2022) 2178–2187, <https://doi.org/10.1021/acssensors.2c00214>.
- [76] N. Joshi, L. da Silva, F. Shimizu, V. Mastelaro, J.-C. M'Peko, L. Lin, O. Oliveira, UV-assisted chemiresistors made with gold-modified ZnO nanorods to detect ozone gas at room temperature, *Microchim. Acta* 186 (7) (2019), <https://doi.org/10.1007/s00604-019-3532-4>.
- [77] L. Resende, A. Amanda, I. Maria, J. Antonio, R. Valmor, Environmentally friendly synthesis of In_2O_3 nano octahedrons by cellulose nanofiber template-assisted route and their potential application for O_3 gas sensing, *Ceram. Int.* 50 (7) (2024) 10192–10202, <https://doi.org/10.1016/j.ceramint.2023.12.329>.
- [78] A. Catto, T. Fiorido, É. Souza, W. Avansi, J. Andres, K. Aguir, E. Longo, L. Cavalcante, L. da Silva, Improving the ozone gas-sensing properties of CuWO_4 nanoparticles, *J. Alloy. Compd.* 748 (2018) 411–417, <https://doi.org/10.1016/j.jallcom.2018.03.104>.
- [79] N. Sui, P. Zhang, S. Cao, T. Zhou, T. Zhang, Nanosheet-assembled In_2O_3 for sensitive and selective ozone detection at low temperature, *J. Alloy. Compd.* 888 (2021) 161430, <https://doi.org/10.1016/j.jallcom.2021.161430>.

- [80] N. Sui, P. Zhang, T. Zhou, T. Zhang, Selective ppb-level ozone gas sensor based on hierarchical branch-like In_2O_3 nanostructure, *Sens. Actuators B Chem.* 336 (2021) 129612, <https://doi.org/10.1016/j.snb.2021.129612>.
- [81] S. Smiy, M. Bejar, E. Dhahri, T. Florido, K. Aguir, V. Laithier, M. Bendahan, Film-thickness influence on ozone detection of perovskite $\text{La}_{0.8}\text{Pb}_{0.1}\text{Ca}_{0.1}\text{Fe}_{1-x}\text{Co}_x\text{O}_3$ based sensors, *New. J. Chem.* 45 (26) (2021) 1162611635.
- [82] S. Smiy, M. Bejar, E. Dhahri, T. Florido, K. Aguir, M. Bendahan, $\text{La}_{0.8}\text{Pb}_{0.1}\text{Ca}_{0.1}\text{Fe}_{1-x}\text{Co}_x\text{O}_3$ thin films as ozone-sensitive layers, *J. Mater. Sci. Mater. Electron.* 32 (19) (2021) 23983–23998, <https://doi.org/10.1007/s10854-021-06862-x>.
- [83] S. Smiy, M. Bejar, E. Dhahri, T. Florido, M. Bendahan, K. Aguir, Ozone detection based on nanostructured $\text{La}_{0.8}\text{Pb}_{0.1}\text{Ca}_{0.1}\text{Fe}_{0.8}\text{Co}_{0.2}\text{O}_3$ thin films, *J. Alloy. Compd.* 829 (2020), <https://doi.org/10.1016/j.jallcom.2020.154596>.
- [84] N. Joshi, L. da Silva, H. Jadhav, J.-C. M'Peko, B. Millan Torres, K. Aguir, V. Mastelaro, O. Oliveira, One-step approach for preparing ozone gas sensors based on hierarchical NiCo_2O_4 structures, *RSC Adv.* 6 (95) (2016) 92655–92662, <https://doi.org/10.1039/c6ra18384k>.
- [85] S. Thirumalairajan, K. Girija, V. Mastelaro, K.S. Subramanian, Enhanced ultrasensitive detection of ozone gas using reduced graphene oxide-incorporated LaFeO_3 nanospheres for environmental remediation process, *Journal Materials Science Materials Electronics* 31 (11) (2020) 8933–8945, <https://doi.org/10.1007/s10854-020-03428-1>.
- [86] B. de Lima, A. Komorizono, W. Silva, A. Ndiaye, J. Brunet, M. Bernardi, V. Mastelaro, Ozone detection in the ppt-level with rGO-ZnO based sensor, *Sens. Actuators B Chem.* 338 (2021) 129779, <https://doi.org/10.1016/j.snb.2021.129779>.
- [87] L. da Silva, V. Mastelaro, A. Catto, C. Escanhoela, S. Bernardini, S. Zilio, E. Longo, K. Aguir, Ozone and nitrogen dioxide gas sensor based on a nanostructured $\text{SrTi}_{0.85}\text{Fe}_{0.15}\text{O}_3$ thin film, *J. Alloy. Compd.* 638 (2015) 374–379, <https://doi.org/10.1016/j.jallcom.2015.03.089>.
- [88] E. Santos, A. Catto, A. Peterline, W. Avansi Jr, Transition metal (Nb and W) doped TiO_2 nanostructures: The role of metal doping in their photocatalytic activity and ozone gas-sensing performance, *Appl. Surf. Sci.* 579 (2022) 152146, <https://doi.org/10.1016/j.apsusc.2021.152146>.
- [89] N. Joshi, L. da Silva, H. Jadhav, F. Shimizu, P. Suman, J.-C. M'Peko, M. Orlandi, J. Seo, V. Mastelaro, O. Oliveira, Yolk-shelled ZnCo_2O_4 microspheres: Surface properties and gas sensing application, *Sens. Actuators B Chem.* 257 (2018) 906–915, <https://doi.org/10.1016/j.snb.2017.11.041>.
- [90] A. Catto, L. da Silva, C. Ribeiro, S. Bernardini, K. Aguir, E. Longo, V. Mastelaro, An easy method of preparing ozone gas sensors based on ZnO nanorods, *RSC Adv.* 5 (25) (2015) 19528–19533, <https://doi.org/10.1039/c5ra00581g>.
- [91] W. dos Santos Silva, B. de Lima, M. Bernardi, V. Mastelaro, Enhancement of the ozone-sensing properties of ZnO through chemical-etched surface texturing, *J. Nanopart. Res.* 24 (5) (2022) 96, <https://doi.org/10.1007/s11051-022-05479-3>.
- [92] Y. Colmenares, W. Correr, B. Lima, V. Mastelaro, The effect of morphology on the ozone-gas sensing properties of zinc oxide sputtered films, *Thin Solid. Films* 703 (2020) 137975, <https://doi.org/10.1016/j.tsf.2020.137975>.
- [93] L. da Silva, J. M'Peko, A. Catto, S. Bernardini, V. Mastelaro, K. Aguir, C. Ribeiro, E. Longo, UV-enhanced ozone gas sensing response of ZnO-SnO₂ heterojunctions at room temperature, *Sens. Actuators B Chem.* 240 (2017) 573–579, <https://doi.org/10.1016/j.snb.2016.08.158>.
- [94] L. da Silva, A. Catto, W. Avansi, L. Cavalcante, J. Andrés, K. Aguir, V. Mastelaro, E. Longo, A novel ozone gas sensor based on one-dimensional (1D) $\alpha\text{-Ag}_2\text{WO}_4$ nanostructures, *Nanoscale* 6 (8) (2014) 4058–4062, <https://doi.org/10.1039/c3nr05837a>.
- [95] Y. Cheng, J. Kang, P. Yan, J. Shen, Z. Chen, X. Zhu, Q. Tan, L. Shen, S. Wang, S. Wang, Surface oxygen vacancies prompted the formation of hydrated hydroxyl groups on ZnO in enhancing interfacial catalytic ozonation, *Appl. Catal. B Environ.* 341 (2024), <https://doi.org/10.1016/j.apcatb.2023.123325>.
- [96] K. Chakarova, I. Strauss, M. Mihaylov, N. Drenchev, K. Hadjiivanov, Evolution of acid and basic sites in UiO-66 and UiO-66-NH₂ metal-organic frameworks: FTIR study by probe molecules, *Microporous Mesoporous Mater.* 281 (2019) 110–122, <https://doi.org/10.1016/j.micromeso.2019.03.006>.

Dongqing Pang is now a doctoral student majoring in Civil and Hydraulic Engineering at Shenzhen University. Her current research interest is in gas sensor technology.

Ruijie Xie received his Ph.D. from Sun Yat-Sen University. He is now an Associate Professor at the College of Civil and Transportation Engineering, Shenzhen University. His research topics are air and water treatment and environmental chemistry.

Jinhan Mo received his Ph.D. from Tsinghua University and did Postdoctoral research in Inorganic Chemistry at Tsinghua University. He is now a distinguished Professor at the College of Civil and Transportation Engineering, Shenzhen University. His research interests include component transportation and separation at interfaces (including mass transfer of gaseous or solid-phase contaminants on indoor surfaces, advanced indoor air separation/purification technologies, air pollution sampling and analysis).