



Review

Ti₃C₂ MXene-Based Composites for Hydrogen and Ammonia Gas Sensing: A Review

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Abstract

The unique contributions of 2D Ti₃C₂ MXenes surface, electrical, and chemical features play a crucial role in determining toxic and flammable gas-sensing behavior. Specifically, its high electrical conductivity (metallic nature), layered nanosheet structure (nanosheets), and surface termination groups (–O, –F, and –OH) collectively contribute to excellent hydrogen (H₂) and ammonia (NH₃) gas-sensing behavior. This review systematically explores the impact of pristine and modified Ti₃C₂ MXene, including its interfaces with various metals and metal oxides for enhancing H₂ and NH₃ detection. Furthermore, the significance of room temperature operation and flexible gas sensing mechanisms is explored. Notably, integration of Ti₃C₂ MXene and sulfur nanosheets demonstrates rapid response and recovery times with detection limits at ppt level. Ti₃C₂ MXene-based interfaces also exhibit excellent long-term stability under various relative humidity conditions. The selective surface termination groups (–OH and –O) facilitate the formation of hydrogen bonds with NH₃ molecules for enhancing gas adsorption and sensing selectivity. In addition, the expansion of the interlayer spacing plays a vital role in improving the gas-sensing performance. Partial oxidation of Ti₃C₂ MXene into TiO₂ increases the interlayer distance, promoting faster diffusion of gas molecules and quicker sensor response. Overall, the intrinsic properties of Ti₃C₂ MXene and its composites significantly achieve high-performance room-temperature H₂ and NH₃ gas-sensing performance.

Keywords: Ti₃C₂ MXene; gas sensing; room temperature; flexible; long term

1. Introduction

In recent decades, rapid industrialization has led to a significant increase in release of toxic gases into the atmosphere, which results in air pollution. Interaction and exposure to these toxic gases poses serious risks to human health, particularly by causing respiratory disorders. It is to be noted that H₂ and NH₃ gases play a crucial role in advancing a sustainable and clean energy future [1]. To achieve global net-zero emissions targets, H₂ fuel is increasingly being adopted as a clean energy carrier for fuel cell vehicles and other energy applications [2]. However, the safe production, storage, and transportation of H₂ fuel remain major challenges due to high flammability. It is necessary to avoid the interaction of H₂ concentrations above the lower explosive limit of 4% with explosive materials, which makes the rapid detection of H₂ leaks essential for ensuring operational safety [3]. Similarly, NH₃ is a toxic gas and its permissible exposure limit is restricted to 25 ppm in 8 h, according to the standards of the Occupational Safety and Health Administration

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(OSHA) [4,5]. Interaction between metal and metal oxides strengthens gas-sensing behavior [6]. Therefore, the development of highly sensitive, selective, and reliable gas sensors for H_2 and NH_3 detection is of considerable importance. Semiconductor metal oxides and their heterostructures have been extensively investigated for gas sensing because of their excellent chemical stability and tunable electronic properties [7]. In particular, transition metal oxides such as ZnO , WO_3 , MoO_3 , TiO_2 , and SnO_2 (both n- and p-type) have demonstrated promising H_2 and NH_3 gas-sensing performance [8–12]. Nevertheless, conventional metal oxide sensors generally require elevated operating temperatures; they exhibit high sensitivity to ambient humidity, which decreases their H_2 gas-sensing ability. Meanwhile, decrements in the recovery process (desorption) of transition metal oxides during the NH_3 gas-sensing process have been noted. To address these limitations, forms of 2D Ti_3C_2 MXene have emerged as promising gas-sensing materials owing to their exceptional metallic conductivity, ultrathin layered structure, large specific surface area with abundant exposed active sites, and surface termination groups ($-O$, $-OH$, and $-F$), which provide favorable adsorption sites for gas molecules [13]. These unique characteristics make 2D Ti_3C_2 MXene an attractive material for room temperature H_2 and NH_3 gas sensing. Interestingly, Ti_3C_2 MXene exhibits excellent H_2 storage capability when integrated with various metal hydrides for highlighting its potential for hydrogen-related applications [14]. Its layered architecture facilitates rapid gas diffusion and high electrical conductivity (fast charge transport), which results in enhanced sensitivity, rapid response/recovery times, and improved room-temperature gas-sensing performance. Rapid charge transport kinetics also play a crucial role in determining the gas-sensing behavior of Ti_3C_2 MXene [15]. The adsorption energy of NH_3 on $Ti_3C_2O_2$ has been reported to be 0.42 eV accompanied by a charge transfer rate of 0.18 e [16], which indicates a favorable interaction between NH_3 molecules and the MXene surface. In detail, as NH_3 contains a lone electron pair, it acts as an electron donor facilitating electron transfer to $Ti_3C_2O_2$ and inducing a significant change in its electrical resistance for strengthened gas-sensing response/recovery signals. Interestingly, the surface $-OH$ termination groups on Ti_3C_2 MXene promote the formation of strong hydrogen bonds with NH_3 molecules to modulate the electrical signals [17]. In other words, the metallic or p-type semiconductor behavior in the Ti_3C_2 MXene effectively gains electrons from NH_3 and recombines with holes, which results in increase of resultant resistance [18]. In addition to H_2 and NH_3 detection, the intrinsic properties of 2D Ti_3C_2 MXene also facilitate remarkable room-temperature NO_2 gas sensing [19]. Therefore, Ti_3C_2 MXene-based composites have attracted increasing attention as promising materials for room-temperature gas-sensing applications.

This review comprehensively summarizes and evaluates the room-temperature NH_3 and H_2 gas-sensing performance of various 2D Ti_3C_2 MXene-integrated semiconductor nanostructures. Particular emphasis is placed on the remarkable improvement of the limit of detection (LOD), ranging from ppm to ppt levels. In addition, this review discusses the excellent cyclic durability and long-term stability of these composites under harsh humid environmental conditions. The influence of enlarged interlayer spacing on facilitating gas diffusion and increasing the accessibility of active adsorption sites is also highlighted. Moreover, the role of surface termination groups ($-O$, and $-OH$) in promoting hydrogen-bond formation and enhancing gas adsorption is critically examined to provide a comprehensive understanding of the improved gas-sensing performance of Ti_3C_2 MXene-based materials.

2. Importance of Ti_3C_2 MXene for Gas Sensing

As discussed above, Ti_3C_2 MXene exhibits several attractive properties, including a 2D layered structure, high specific surface area, excellent electrical conductivity, and tunable surface terminal groups. These characteristics facilitate active adsorption sites for

targeting gas molecules, which result in electrical signal variation and efficient hazardous-gas-sensing performance [20]. In particular, the layered structure promotes gas diffusion by maximizing the number of accessible active sites. The availability of a high surface-area-to-volume ratio provides abundant active edges for gas adsorption, while the surface termination groups serve as chemically active sites for strong interaction with target gas molecules. Furthermore, the high electron density of Ti_3C_2 MXene facilitates rapid charge carrier transport during gas adsorption, which leads to enhanced sensing performance. The fabrication of few-layer or monolayer Ti_3C_2 MXene nanosheets further increases the exposure of basal-plane active sites, thereby improving gas diffusion and adsorption across the nanosheet surface. Additionally, interlayer expansion achieved through the incorporation of nanoparticles or other 2D nanosheets creates additional diffusion pathways, resulting in faster response and recovery times. Collectively, these unique structural and electronic characteristics of 2D Ti_3C_2 MXene establish a highly promising material for room-temperature gas-sensing applications. Figure 1 illustrates the NH_3 and H_2 gas-sensing performance ability of Ti_3C_2 MXene integrated with various nanostructures.

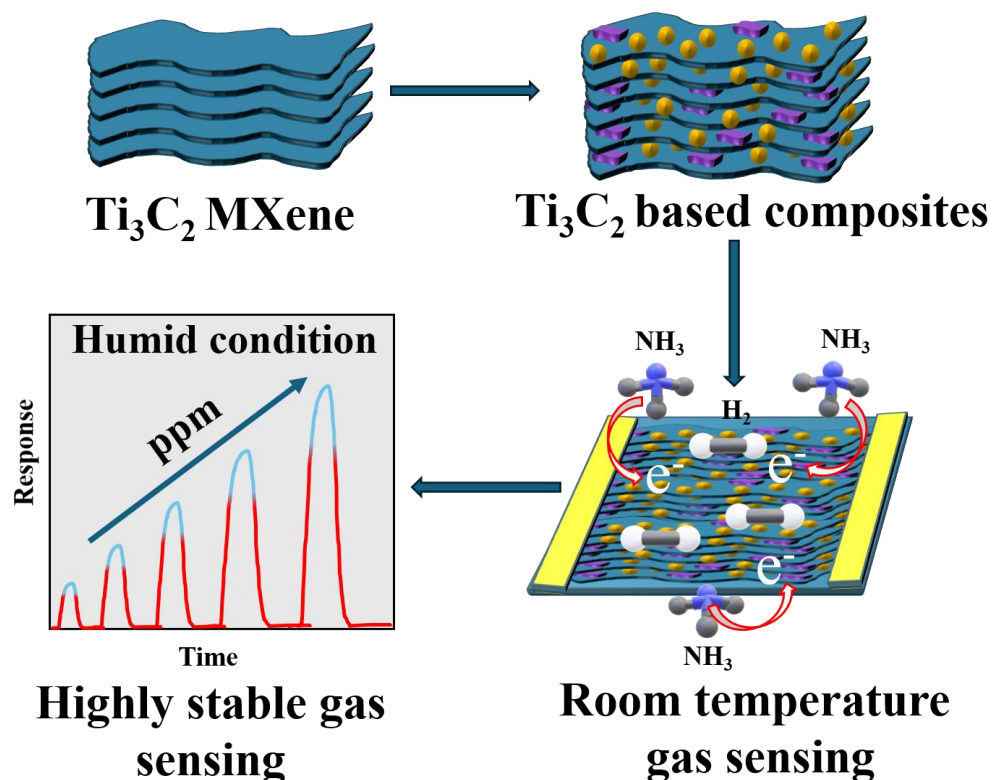


Figure 1. Room temperature NH_3 and H_2 gas-sensing performance of various Ti_3C_2 MXene nanosheet-integrated nanostructures.

3. Ti_3C_2 MXene-Based Composites for H_2 Gas Sensing

3.1. $\text{Ti}_3\text{C}_2/\text{Pd}$ Nanostructures

The effective interaction between Ti_3C_2 MXene and ultra-small Pd colloidal nanostructures (Pd CNC) (5 ± 1.9 nm) significantly enhances H_2 -sensing performance [21]. In this example, upon H_2 exposure, the formation of PdH_x altered the Pd work function (3.2 eV), facilitating electron transfer from Pd to the Ti_3C_2 MXene. Furthermore, the intercalation of Pd CNCs between Ti_3C_2 MXene nanosheets increased the interlayer spacing, resulting in a larger effective surface area for gas adsorption. The surface morphology of the Ti_3C_2 MXene@Pd CNC film is presented in Figure 2a. Accordingly, the Ti_3C_2 MXene@Pd CNC film sensor exhibited stable response and recovery characteristics during

H₂ detection. In this system, Ti₃C₂ MXene exhibited n-type semiconducting behavior and effectively accepted electrons from Pd to Ti₃C₂ MXene, which led to a decrease in electrical resistance. The sensor demonstrated response and recovery times of 32 ± 7 s and 161 ± 23 s at a low H₂ concentration of 4%. In detail, accelerated electron transfer from Pd CNC to Ti₃C₂ MXene was observed after insertion of H₂ under high H₂ adsorption. Under these conditions, the flexible paper-based Ti₃C₂@Pd CNC sensor film achieved a sensitivity of $23.0 \pm 4.0\%$ at 4% H₂, as shown in Figure 2b. In addition, the sensor maintained stable performance under bending angles of 30, 60, 90, and 120°, demonstrating excellent mechanical flexibility. For practical application, an H₂ gas leak detection system incorporating an alarm circuit and LED indicator was developed. As illustrated in Figure 2c, after exposure to 4% H₂, the LED was activated, which confirmed the sensor's capability for real-time leak detection. Overall, the flexible Ti₃C₂ MXene@Pd CNC composite demonstrated considerable potential for practical H₂ gas-sensing applications due to its high sensitivity, mechanical flexibility, and reliable detection performance.

In another study, Doan et al. [22] fabricated a room-temperature H₂ gas sensor by decorating multilayer Ti₃C₂T_x MXene with Pd nanoparticles at different loadings (30, 60, and 90 mg) on silicon substrates. The authors demonstrated that both the Ti₃C₂T_x MXene loading (60 mg) and Pd nanoparticle content significantly influenced the H₂ gas-sensing performance at 10, 50, and 100 ppm concentrations. The incorporation of Pd nanoparticles enhanced the H₂ adsorption and promoted intimate interfacial contact with Ti₃C₂T_x for facilitating the formation of efficient charge transport pathways. Among the investigated samples, the sensor containing 60 mg of Ti₃C₂T_x MXene with a lower Pd nanoparticle density exhibited highest response of 56% at 100 ppm H₂. Furthermore, the sensor showed excellent cyclic stability over five consecutive cycles and maintained a strong sensing response after approximately 90 days of storage under ambient conditions at 50 ppm H₂. The enhanced sensing performance was attributed to the formation of PdH and TiH₂ during H₂ exposure, which increased the electrical resistance of the Pd–Ti₃C₂T_x composite. Overall, the optimized combination of Ti₃C₂T_x MXene loading and Pd nanoparticle content resulted in a stable, sensitive, and reliable room-temperature H₂ gas sensor.

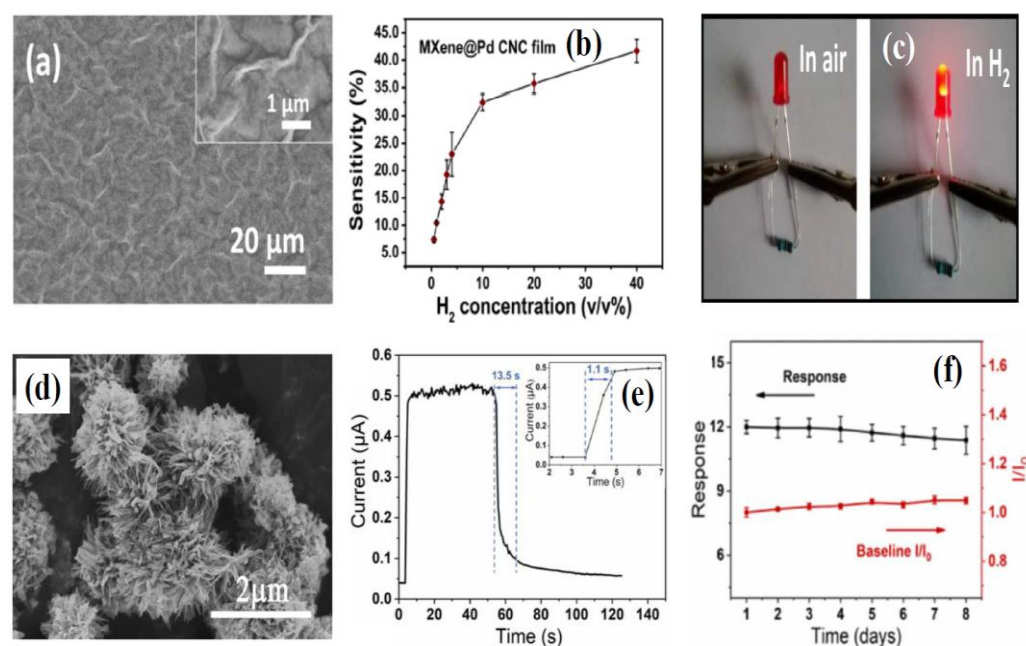


Figure 2. (a) Surface morphology of the Ti₃C₂ MXene@Pd CNC composite film, (b) H₂ gas-sensing ability of Ti₃C₂ MXene@Pd CNC at various H₂ (v/v) concentrations, (c) demonstration of the practical applicability of Ti₃C₂@Pd CNC for H₂ gas sensing using an LED indicator (Reprinted from Ref. [21],

copyright with permission from Elsevier), (d) surface morphology of Pd nanoparticles integrated Ti_3C_2 MXene-derived sodium titanate nanoribbons, (e) rapid response and recovery times of 1.1 s and 13.5 s by the Pd-NTO NRs composite, and (f) long-term stable response of the Pd-NTO NRs composite over 8 days (Reprinted from Ref. [23], copyright with permission from Elsevier).

Similarly, Wu et al. [23] combined Ti_3C_2 MXene-derived sodium titanate nanoribbons (NTO NRs) and nanotubes (NTO NTs) with Pd nanoparticles (3.5 nm) for room temperature H_2 gas sensing. Notably, the abundant oxygen vacancies in the NTO NRs facilitated rapid H_2 adsorption and dissociation, resulting in ultrafast H_2 sensing performance. The surface morphology of the Pd-NTO NRs is shown in Figure 2d. During H_2 exposure, formation of PdH_x resulted in a lower work function than n-type NTO, which created a favorable Schottky junction that promoted electron transfer from PdH_x to the NTO, which enhanced the sensing response. Furthermore, the 1D nanoribbon architecture provided a shorter charge diffusion path than the nanotube structure, which enabled more efficient charge transport under reduced scattering at multiple interconnections. XPS studies (O 1s spectrum) of the Pd-NTO NRs showed the presence of $-\text{OH}$ and oxygen vacancy peaks, which influenced the gas adsorption process. Accordingly, the Pd-NTO NRs achieved an ultrafast response time of 1.1 s (recovery-13.5 s) with a response of 12.0 toward 1% H_2 , as shown in Figure 2e. The sensor also demonstrated a wide detection range from 0.8 ppm to 10% H_2 . The enhanced sensing mechanism was mainly attributed to the catalytic activity of Pd nanoparticles, which dissociated H_2 molecules into atomic H. These H atoms spilled over onto the NTO surface, which reacted with adsorbed O_2^- ions and released the electrons, thereby increasing the sensor current. Meanwhile, the formation of $\text{O}-\text{H}$ and $\text{Ti}-\text{H}$ surface bonds further contributed to the enhanced electrical response. Moreover, the Pd-NTO NR sensor exhibited excellent long-term stability, maintaining its H_2 sensing performance even after 8 days, as illustrated Figure 2f. Overall, the synergistic interaction between Pd nanoparticles and Ti_3C_2 MXene-derived NTO nanoribbons significantly enhanced the ultrafast and highly sensitive detection of H_2 gas.

In addition to the above incorporation of Pd nanostructures, Wang et al. [24] modified the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene surface by integrating bimetallic $\text{Pd}=\text{Pt}$ nanoparticles and Pd-Pt alloy for the elevation of room-temperature H_2 gas sensing. The $\text{Pd}=\text{Pt}/\text{Ti}_3\text{C}_2\text{T}_x$ exhibited a response time of 6 s and recovery time of 8 s with a remarkable response of 24.6% towards 200 ppm H_2 . Notably, the sensor demonstrated excellent micro-leak detection capability with LOD as low as 1 ppm at an ultrafast response time of 1 s. This response time was slightly faster than that of reported Pd-NTO NRs sensor (1.1 s) at 1% H_2 [23]. The enhanced sensing performance was attributed to the modulation in the Schottky junction formed between the $\text{Pd}=\text{Pt}$ nanoparticles and $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. In air, adsorbed oxygen molecules extracted electrons from the MXene surface, leading to the formation of an electron depletion layer. Upon exposure to H_2 , the catalytic dissociation of H_2 on the $\text{Pd}-\text{Pt}$ nanoparticles promoted electron transfer back to the $\text{Ti}_3\text{C}_2\text{T}_x$ surface, altering the depletion layer and decreasing the sensor resistance. Among the two metals, Pd exhibited a higher H_2 adsorption capability than Pt, playing a dominant role in improving the sensing performance of the bimetallic composite. The $\text{Pd}=\text{Pt}/\text{Ti}_3\text{C}_2\text{T}_x$ sensor maintained stable sensing characteristics over 10 consecutive operating cycles, demonstrating excellent repeatability. Overall, the incorporation of bimetallic $\text{Pd}=\text{Pt}$ nanoparticles significantly improved the room-temperature H_2 -sensing performance, enabling highly sensitive detection of H_2 micro-leaks down to 1 ppm.

3.2. Ti_3C_2 MXene Completely Derived C/TiO_2

Ti_3C_2 MXene can be completely converted into C/TiO_2 at certain elevated temperatures, offering a promising route for developing environmental safety devices [25]. In this

context, Ti_3C_2 MXene-derived C/ TiO_2 composites prepared at 400 and 500 °C were systematically investigated for H_2 gas sensing at room temperature as well as at elevated temperatures (100, 150, 200, 250 and 300 °C) [26]. Decrease in carbon and fluorine content along with an increase in oxygen content (TiO_2 formation) was observed following increased calcination temperatures (400 and 500 °C). Here, oxygen was diffused into the Ti_3C_2 MXene, confirming the partial oxidation of Ti_3C_2 MXene into TiO_2 . The O 1s spectra revealed oxygen vacancies at 533.7 eV. In detail, H_2 interaction with lattice oxygen of C/ TiO_2 transformed into oxygen vacancy, which released electrons into the conduction band and lowered the resistance. Among the prepared samples, the C/ TiO_2 composite calcined at 500 °C exhibited the best sensing performance, delivering a response of 92.6% toward 40,000 ppm H_2 at 300 °C, with response and recovery times of 45 and 20 s, respectively. Remarkably, the same sensor also demonstrated excellent room-temperature performance by achieving a response of 62.2%, with response and recovery times of 13 and 42 s, respectively. The improved sensing performance at elevated temperatures was mainly attributed to enhanced surface reaction kinetics, reduced interference from humidity and volatile impurities, and the effective removal of reaction by-products. Overall, the controlled thermal transformation of Ti_3C_2 MXene into a C/ TiO_2 composite significantly improved the stability of H_2 sensing performance over a wide range of operating temperature.

3.3. Ti_3C_2 MXene/Organic Frameworks

In addition to noble metal-functionalized Ti_3C_2 MXene sensors, Nallamalla et al. [27] developed a flexible room-temperature H_2 gas sensor by integrating a covalent organic framework (DAAQ-COF) with Ti_3C_2 MXene on OHP sheet substrate. The resulting DAAQ-COF/ Ti_3C_2 MXene composite exhibited enhanced structural, chemical, and morphological stability owing to strong interfacial electronic modulation at the COF/MXene interface. Notably, optimizing the Ti_3C_2 MXene content to 50 wt% effectively regulated the interfacial charge transfer and H_2 adsorption behavior, leading to superior sensing performance. The adsorption strength (chemisorption) and heterointerface phenomena significantly contributed to improved room-temperature H_2 gas sensing. In this process, the flexible sensor achieved a LOD of 1 ppm with response and recovery times of 29 and 18 s, respectively, at room temperature. The response and recovery times were increased at an elevated gas-sensing temperature of 150° (74/88 s) and bending angle of 97.45° (85/87 s). Overall, the integration of DAAQ-COF with Ti_3C_2 MXene provided an effective strategy for developing flexible, highly sensitive H_2 sensors, capable of detecting H_2 at ppm-level concentrations while maintaining good operational stability under thermal and mechanical stress.

3.4. Ion-Beam Irradiated Ti_3C_2 MXene

Previously, ion-beam irradiation has been demonstrated as an effective approach for modifying the physical properties of semiconductor thin films, such as Al and Cu-doped ZnO systems [28,29]. Following this strategy, low-energy N^+ ion-beam irradiation with fluences of 1×10^{15} , 5×10^{15} , and 1×10^{16} ions cm^{-2} was employed to modify Ti_3C_2 MXene nanosheets to achieve room-temperature H_2 gas sensing [30]. The ion-beam treatment induced subtle structural modifications in the Ti_3C_2 MXene nanosheets, including reduced crystallite size, improved nanosheet ordering, and increased interlayer d-spacing. The surface morphology of Ti_3C_2 MXene irradiated with 1×10^{16} ions cm^{-2} is shown in Figure 3a. Among the different irradiation conditions, the Ti_3C_2 MXene treated at ion fluence of 1×10^{16} ions cm^{-2} exhibited higher H_2 sensing response of 2.1 toward 3000 ppm H_2 , with response and recovery times of 98 and 109 s, respectively (Figure 3b). In comparison, pure Ti_3C_2 MXene displayed a lower response of 1.37 and significantly longer response and

recovery times of 170 and 244 s, respectively. Furthermore, the ion-beam-modified Ti₃C₂ MXene demonstrated excellent cyclic stability over 10 sensing cycles and retained 94% of its initial response after 10 days (Figure 3c,d). After the interaction of Ti₃C₂ MXene with H₂, the electrons effectively transferred from H₂ to the Ti₃C₂ MXene, which increased the electron density in the sensor. Overall, ion-beam-induced structural engineering effectively optimized the surface and electronic properties of Ti₃C₂ MXene, resulting in improved room-temperature H₂-sensing performance with enhanced stability.

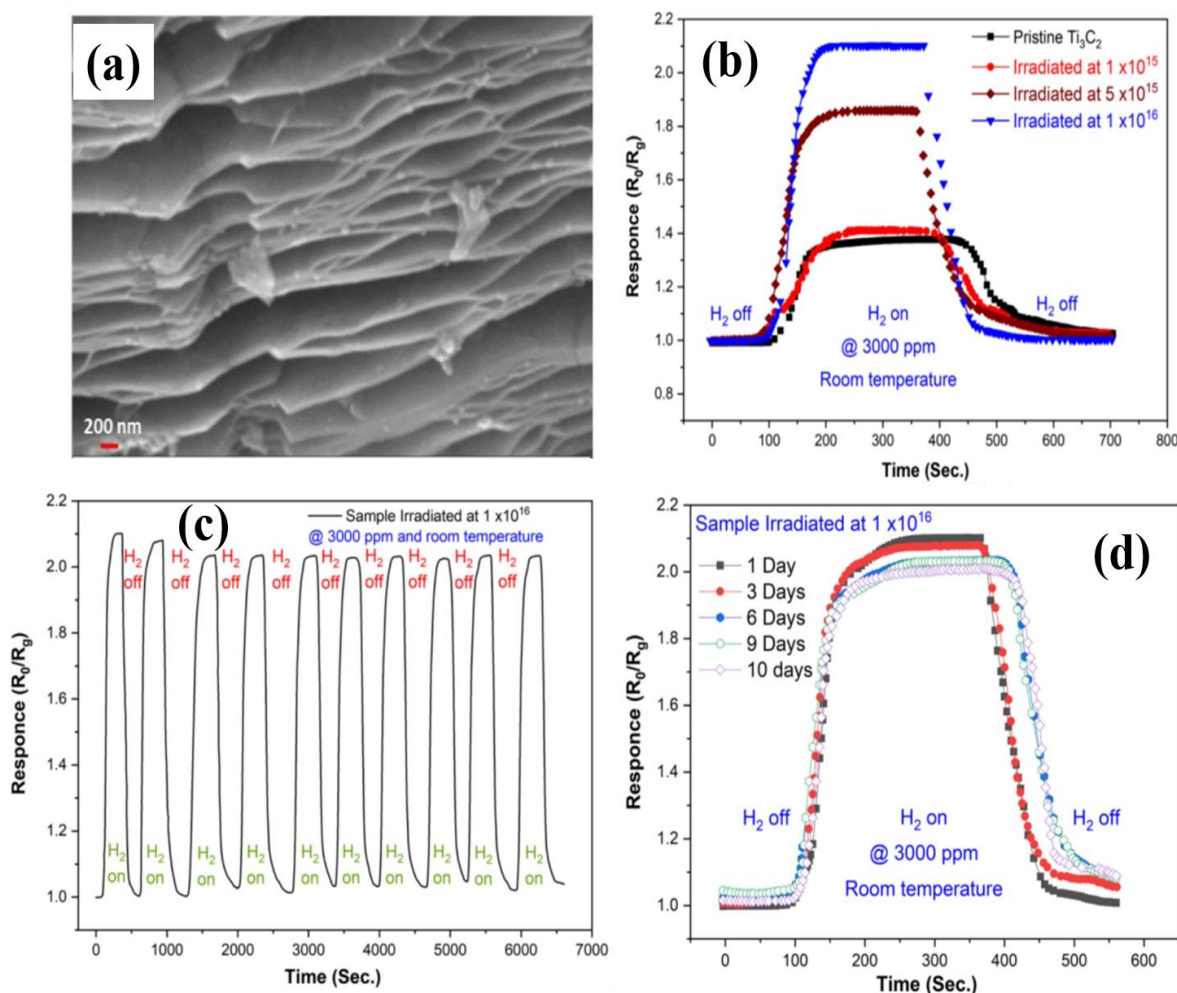


Figure 3. (a) Surface morphology of Ti₃C₂ MXene nanosheets irradiated with an N⁺ ion-beam at a fluence of 1×10^{16} ions cm⁻², (b) response and recovery characteristics of Ti₃C₂ MXene irradiated under different N⁺ ion-beam energies. (c) room temperature cyclic stability over 10 sensing cycles for Ti₃C₂ MXene irradiated at a fluence of 1×10^{16} ions cm⁻², (d) remarkable long-term stability over 1 to 10 days for Ti₃C₂ MXene irradiated at a fluence of 1×10^{16} ions cm⁻² (Reprinted from Ref. [30], copyright with permission from Elsevier).

Overall, Ti₃C₂ MXene-based sensors have exhibited enhanced H₂ gas-sensing performance through structural modification and hybridization. Integration with Pd nanoparticles, Pd-Pt alloys, MXene-derived sodium titanate nanoribbons, COF frameworks, and ion-beam treatment features significantly improved their sensitivity, response/recovery times, stability, and LOD. Specifically, Pd facilitated H₂ dissociation and electron transfer, while engineered interfaces enhanced charge transportation and adsorption. Flexible Ti₃C₂/Pd composites detected 4% H₂ with stable operation under bending conditions. Interestingly, bi-metallic Pd-Pt/Ti₃C₂ composite achieved 1 ppm LOD, and DAAQ-COF/Ti₃C₂ also sensed 1 ppm H₂ at room temperature. On the other hand, Ti₃C₂ MXene-

derived C/TiO₂ and ion-beam-modified MXene further demonstrated improvement in H₂-sensing performance and durability. The progress in Ti₃C₂T_x MXene-based composites for room temperature H₂ gas sensing is presented in Table 1.

Table 1. Room-temperature H₂ gas-sensing ability of Ti₃C₂ MXene-based nanostructures.

Composite	Working Temperature	Response/Recovery Time (s)	Response (%)	Gas Concentration /LOD (ppm)	Gas Sensing Equation	Stability (Cycles)/Long-term Stability (Days)	Reference
<i>Ti₃C₂-MXene based composites for H₂ sensing</i>							
<i>Ti₃C₂/Pd nanostructures</i>							
Ti ₃ C ₂ @Pd CNC	Room temperature	32 ± 7/161 ± 23 s	23.0 ± 4.0 (Sensitivity)	4% H ₂	$(I_g - I_0)/I_0 \times 100$	8/—	[21]
Pd-Ti ₃ C ₂ T _x	Room temperature	—	56	100	$ R_g - R_a /R_a \times 100$	5/90 at 50 ppm	[22]
Pd-NTO NRs	Room temperature	1.1/13.5	12	1% H ₂ /0.8	$(I_{gas} - I_{air})/I_{air}$	11 at 5000 ppm/8	[23]
Pd=Pt/Ti ₃ C ₂ T _x	Room temperature	1/—	24.6	200/1	$ R_a - R_g /R_a \times 100$	10/60 at 200 ppm	[24]
<i>Ti₃C₂ MXene derived C/TiO₂</i>							
Ti ₃ C ₂ MXene derived C/TiO ₂	Room temperature	13/42	62.2	40,000/50	$ R_a - R_g /R_a \times 100$	—/30 at 300 °C	[26]
<i>Ti₃C₂ MXene/organic frameworks</i>							
DAAQ-COF/with Ti ₃ C ₂	Room temperature	29/18	—	1 ppm/—	—	5/25	[27]
<i>Ion beam irradiated Ti₃C₂ MXene</i>							
N ⁺ ion-beam induced Ti ₃ C ₂ MXene	Room temperature	98/109	2.1	3000	R_o/R_g	10/10	[30]

4. Ti₃C₂ MXene-Based Composites for NH₃ Gas Sensing

In addition to H₂ gas sensing, Ti₃C₂-based composites have been used for NH₃ gas sensing at room temperature. Specifically, ultrafast response and recovery processes were achieved in the developed composites. The dominant performance of pure Ti₃C₂ and Ti₃C₂-based composites is described below.

4.1. Pure Ti₃C₂ MXene

The room-temperature NH₃ gas-sensing performance of Ti₃C₂T_x MXene films with thickness ranging from 2.5 (0.01 mg. mL^{−1}) to 15 nm (2.56 mg. mL^{−1}) was investigated [31]. The authors reported that thinner Ti₃C₂T_x MXene films (2.5 nm) exhibited higher sensitivity toward NH₃ molecules than thicker films. The 2.5 nm Ti₃C₂T_x MXene films displayed semiconducting behavior due to the presence of surface termination groups, which induced dipole polarization. Thus, a remarkable difference in NH₃ sensing performance between the thinner and thicker films was observed. Notably, the 2.5 nm film exhibited a response of 1.22% toward 1 ppm NH₃, whereas the thicker films showed no detectable response at this concentration. Furthermore, the thinnest film achieved a maximum response of 9.4% at 100 ppm, with excellent cyclic stability over five sensing cycles. As the thickness increased from 2.5 to 15 nm, the NH₃ gas sensing rapidly decreased from 9.4 to 0.35%, respectively. These findings demonstrate that precise control of Ti₃C₂T_x MXene film

thickness plays a crucial role in enhancing room-temperature NH_3 gas-sensing performance.

Interestingly, the strategic combination of MXene and its parent MAX phase ($\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$) enabled efficient room-temperature NH_3 gas sensing [32]. The lower work function of Ti_3AlC_2 compared to $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ composite confirmed the formation of a planar heterojunction formation at the $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ interface. Furthermore, the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene surface contained higher concentrations of $-\text{OH}$ and $-\text{O}$ termination groups than $-\text{F}$ groups, which provided abundant active sites for NH_3 adsorption. According to the $\text{O} 1s$ XPS spectrum, the binding energies of adsorbed oxygen species, $\text{Ti}-\text{O}-\text{Ti}$, $\text{Ti}-\text{OH}$, and $\text{C}-\text{OH}$ were located at 529.51, 530.22, 531.95, and 532.32 eV, respectively. Upon exposure to NH_3 , these oxygen-containing functional groups facilitated electron transfer to the $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ composite, resulting in an increase in sensor resistance. Moreover, the formation of a Schottky barrier at the heterointerface promoted efficient charge carrier separation and enhanced interaction between the sensing surface and NH_3 molecules, which improved sensing performance. In this context, the $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ composite exhibited a response of 1.2% at a LOD of 50 ppb. At 200 ppm, the sensor achieved a high response of 11.0% along with rapid response and recovery times of 12 and 60 s, respectively. Furthermore, the responses towards CO_2 and ethanol were lower at about 1.5 and 2.2% compared to NH_3 (8.3%) at 100 ppm, which confirmed the high selectivity of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ heterostructure towards NH_3 . In addition, the synergistic interaction between $\text{Ti}_3\text{C}_2\text{T}_x$ and Ti_3AlC_2 contributed to excellent long-term stability with negligible degradation after 120 days. Furthermore, DFT calculations demonstrated that the $-\text{OH}$ -terminated $\text{Ti}_3\text{C}_2(\text{OH})_2/\text{Ti}_3\text{AlC}_2$ heterostructure had higher NH_3 adsorption capability compared with pristine $\text{Ti}_3\text{C}_2\text{O}_2$ and $\text{Ti}_3\text{C}_2\text{F}_2$, owing to stronger binding interactions. Among these, $\text{Ti}_3\text{C}_2(\text{OH})_2/\text{Ti}_3\text{AlC}_2$ exhibited higher NH_3 adsorption energy (-0.950 eV) than $\text{Ti}_3\text{C}_2\text{O}_2$ (-0.705 eV) and $\text{Ti}_3\text{C}_2\text{F}_2$ (-0.467 eV), which indicated superior adsorption performance and potential for improving NH_3 gas-sensing performance. Overall, the combined effects of (i) $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ heterostructure, (ii) abundant $-\text{OH}$ and $-\text{O}$ surface termination groups, and (iii) Schottky barrier formation enhanced the room-temperature NH_3 -sensing performance.

Recently, Mirzaei et al. [33] explored the NH_3 -sensing performance of pure $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (24 h etched) under self-heating conditions between 1 to 6 V applied voltages. With regard to NH_3 , acetone, methanol, ethanol, benzene, toluene, and H_2S sensing, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was highly selective towards 100 ppm NH_3 , with a response of 0.67% at 25 °C and 4 V. Partial oxidation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene into TiO_2 revealed $-\text{O}$ surface termination groups. According to the XPS $\text{O} 1s$ spectra, lattice oxygen from $\text{Ti}-\text{O}$ and adsorbed $-\text{OH}$ species at 530.1 and 532.2 eV enhanced the NH_3 adsorption. The presence of $-\text{OH}$, $-\text{O}$, and $-\text{F}$ accelerated the NH_3 adsorption and electron transfer and improved NH_3 selectivity. The response to higher humidity conditions (30 to 90%) was not much altered compared with 0% (dry air) conditions. In detail, the response at 90% relative humidity was 0.502% (22% reduction) compared with 0% humidity (0.67%) at 100 ppm NH_3 , demonstrating tolerance under harsh humid conditions. The response was unaltered at 0.613%, with no significant drift even after six cycles. Also, the sensor was sustained through 500 bending and 1000 tilting cycles, with no structural changes after mechanical testing.

4.2. Metal-Ions Intercalated Ti_3C_2 MXene

Kim et al. [34] strategically intercalated the K^+ , Na^+ , Ca^{2+} , and Mg^{2+} cations between $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets for effective room-temperature NH_3 gas sensing from 10 to 100 ppm. The Na^+ ions-intercalated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene showed a better response of about 0.36% at 100 ppm compared with the other metal cation counterparts. A signal-to-noise ratio of 531 was achieved for $\text{Na}^+-\text{Ti}_3\text{C}_2\text{T}_x$ MXene, which was higher than $\text{K}^+-\text{Ti}_3\text{C}_2\text{T}_x$ (192), Mg^{2+} -

Ti₃C₂T_x (333), and Ca²⁺-Ti₃C₂T_x (371) MXenes. The intercalation process facilitated preparation of transparent and highly conductive films for attaining stable electrical pathways during the gas-sensing process. This strategy did not lead to oxidation and TiO₂ formation, thereby preserving the pure chemical structure of Ti₃C₂T_x MXene. Overall, metal ion intercalation increased the gas-sensing performance of Ti₃C₂T_x MXene.

4.3. Alkalized Ti₃C₂ MXene

The electrical properties of Ti₃C₂T_x MXene can be effectively altered by alkalization [35]. In this context, alkalization of Ti₃C₂T_x MXene has been explored to enhance room-temperature NH₃ gas-sensing performance over a concentration range of 5 to 500 ppm [36]. In one study, Ti₃C₂T_x MXene was successfully alkalized using 2/5/8M NaOH solutions for 12 h, which significantly improved its rapid response/recovery characteristics. The alkalization process promoted the intercalation of Na⁺ ions between the Ti₃C₂T_x MXene nanosheets, facilitating the replacement of –F termination groups with more hydrophilic –OH terminations, which produced additional active sites for NH₃ adsorption. When exposed to 200 ppm NH₃, the alkalized Ti₃C₂T_x MXene exhibited faster response/recovery times (73/38 s) compared to pure Ti₃C₂T_x MXene (83/84 s) at 40% relative humidity and room temperature. The alkalized samples demonstrated excellent cyclic stability over five response/recovery cycles and long-term stability for 17 days, but pristine Ti₃C₂T_x MXene showed a gradual decline in sensing performance. As a result, the alkalized Ti₃C₂T_x MXene achieved a high response of 100.3% at 500 ppm with LOD of 5 ppm. The enhanced sensing mechanism was attributed to the interaction of NH₃ molecules with –OH and –O terminations along with H₂O-assisted electron donation towards the Ti₃C₂T_x MXene, contributing to an increase in sensor resistance. Overall, the strategic alkalization approach effectively improved the room-temperature NH₃-sensing capability of Ti₃C₂T_x MXene.

Following a similar strategy, Zhang et al. [37] modified the Ti₃C₂T_x MXene surface through KOH alkalization followed by annealing under nitrogen atmosphere to enhance NH₃ gas-sensing performance. These combined effects increased the surface –OH and –O termination groups and expanded the interlayer spacing from 9.1 to 12.1 Å°, which effectively facilitated the NH₃ adsorption and diffusion within the Ti₃C₂T_x MXene nanosheets. After the annealing process, the characteristic layered morphology of Ti₃C₂T_x MXene was preserved, accompanied by improved crystallinity and grain growth. As a result, the annealed Ti₃C₂T_x MXene exhibited a superior room-temperature NH₃ response of 35.7 at 200 ppm, which was higher than that of alkalized (30.1) or pure Ti₃C₂T_x MXene (18.7) with response times of 170, 300, and 200 s, respectively. Initially, alkalization improved the interlayer spacing and generated abundant reactive sites, which contributed to improved NH₃ selectivity and adsorption. The heat-treated samples achieved superior NH₃ gas sensing compared with the alkalized Ti₃C₂T_x MXene. For annealed samples, linear increment in the O/F ratio and interlayer spacing advanced the NH₃ gas-sensing performance even after 50 days, with a response of 36.11 at 5 ppm. These findings further demonstrate the significant role of alkalization and post-treatment strategies in advancing the room-temperature NH₃ gas-sensing performance of Ti₃C₂T_x MXene.

4.4. Partially Oxidized Ti₃C₂ MXene

Controlled oxidation of Ti₃C₂T_x MXene (at 280 °C) significantly enhanced room-temperature NH₃ gas-sensing performance [38]. Specifically, the improved sensing behavior was attributed to (i) enhancement of hydrogen bonding between NH₃ molecules and surface termination groups (–OH and –O) and (ii) synergistic interaction between Ti₃C₂T_x MXene and in situ formed TiO₂ (p-n junction), which promoted efficient charge transport behavior during NH₃ sensing. The abundant surface termination groups provided active

adsorption sites for NH_3 molecules, while the preserved layered structure in $\text{Ti}_3\text{C}_2\text{T}_x$ MXene facilitated rapid electron transport. The XPS O 1s spectra revealed adsorbed oxygen, $-\text{O}$, and $-\text{OH}$ termination groups located at 530.3, 532.1, and 534 eV, respectively. Notably, the oxidation process did not disrupt the intrinsic layered morphology of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, thereby retaining its excellent electrical conductivity. As a result, the oxidized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene exhibited a high response of 21.3% at 10 ppm NH_3 . At a higher concentration of 500 ppm, the sensor achieved further improvement, with a response of 147% and response/recovery times of 67/157 s. The sensing mechanism involved the reaction of NH_3 molecules with adsorbed O_2^- (in air) on the sensor surface, which released electrons towards the material, reduced the width of the electron depletion layer, and decreased the sensor resistance. The formation of TiO_2 (i) increased the charge transfer through the p-n heterojunction, (ii) provided abundant oxygen-related defects to increase NH_3 adsorption, and (iii) created active sites for the stabilization of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene for higher NH_3 -sensing capability. The oxidized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene showed a negligible response (2%) towards ethanol at 500 ppm. Responses of 138, 71, 56, 47, and 41% (at 500 ppm) were observed at various relative humidity conditions of 28, 42, 50, 62, and 70%, respectively. It should be noted that the response level was relatively stable under higher humid conditions (62 to 70%). Overall, the controlled oxidation process effectively optimized the surface chemistry and interfacial charge transportation of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, which enabled highly sensitive room-temperature NH_3 detection with LOD of 10 ppm.

4.5. Ti_3C_2 MXene/Sulfur

Shen et al. [39] demonstrated ultra-sensitive NH_3 gas sensing at the ppt level (3, 5, 7, 10, and 15) by integrating Ti_3C_2 MXene with sulfur nanosheets. The interlayer spacing of Ti_3C_2 MXene nanosheets (2–3 μm) was effectively covered by smaller sulfur nanosheets with sizes ranging from 200 to 300 nm. With an increase in NH_3 concentration from 3 to 15 ppt, the sensing response exhibited linear enhancement accompanied by rapid adsorption and desorption kinetics. The integration of sulfur nanosheets with Ti_3C_2 MXene nanosheets is shown in Figure 4a. Notably, the response/recovery times of Ti_3C_2 MXene@sulfur nanosheets (5/4 s) were significantly lower than those of pure sulfur nanosheets (60/18 s). The superior electrical conductivity of Ti_3C_2 MXene compared with sulfur nanosheets improved the charge transfer and gas-sensing performance at the ppt level. Thus, the Ti_3C_2 MXene@sulfur composite exhibited remarkable NH_3 sensing by achieving a response current of about 15 pA (sulfur nanosheets-3 pA) with ultra-rapid response and recovery times of 5 and 4 s, respectively (Figure 4b). Under these conditions, a sensing response of 375% was achieved at NH_3 concentration of 3 ppt. This structural integration again proved cyclic stability (across five cycles) and long-term stability over 20 days at 3 ppt level. The composite architecture also maintained a stable NH_3 response under various relative humidity conditions (20–70%), as shown in Figure 4c. In that study, water molecules did not interfere with NH_3 adsorption sites under relative humidity conditions between 20 to 70%. At higher conditions (>80%), excessive H_2O molecules compete with NH_3 , thereby reducing the availability of adsorption sites. In this system, NH_3 molecules acted as electron donors, which facilitated charge transfer at the Ti_3C_2 MXene@sulfur interface and resulted in improved sensing performance. The enhanced NH_3 sensing mechanism was mainly attributed to the synergistic effects of sulfur vacancies, high electrical conductivity of Ti_3C_2 MXene, and surface termination groups, which promoted efficient adsorption and desorption of NH_3 molecules even under highly humid conditions.

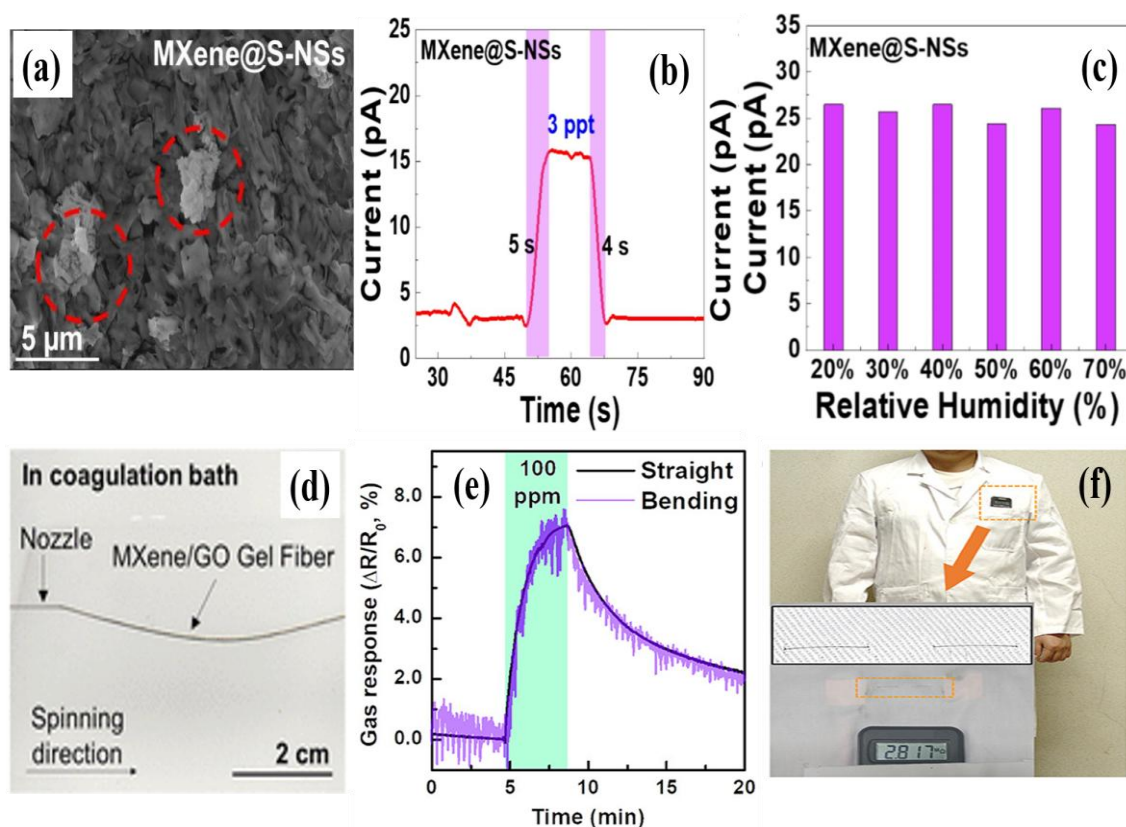


Figure 4. (a) Surface morphology of sulfur nanosheets integrated $\text{Ti}_3\text{C}_2\text{MXene}$, (b) ultrafast response and recovery times of about 5 and 4 s, (c) stable NH_3 gas sensing under relative humidity ranging from 20 to 70% (Reprinted from Ref. [39], copyright with permission from Elsevier), (d) formation of $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ flexible gel fiber, (e) unaltered NH_3 gas-sensing performance of $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ composite under straight and bent conditions, (f) flexible $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/graphene hybrid fibers woven into a laboratory coat (Reprinted from Ref. [40], copyright with permission from ACS Publication).

4.6. Ti_3C_2 MXene/Graphene

The integration of two carbon-based materials ($\text{Ti}_3\text{C}_2\text{T}_x$ MXene and graphene) into a wearable and flexible fiber architecture demonstrated efficient room-temperature NH_3 gas sensing [40]. Figure 4d shows a photograph of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{rGO}$ flexible gel fiber. The synergistic interaction between $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and rGO sheets effectively suppressed the severe aggregation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets at the molecular level under pH 6 conditions, which resulted in a well-defined hybrid structure. At selective content of about 40% $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, significant enhancement in the number of active adsorption sites for NH_3 molecules was achieved. In particular, the density of Ti-O active sites in $\text{Ti}_3\text{C}_2\text{T}_x$ MXene increased three-fold after strategic hybridization with graphene. Accordingly, the resultant composite facilitated stronger NH_3 adsorption and improving the sensing performance. Thus, the dominance of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and Ti-O active sites achieved a high response of 7.21% toward 100 ppm NH_3 , as shown in Figure 4e. The selectivity towards ethanol was very low at about 1%, which suggests preferential adsorption of NH_3 molecules by the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene//rGO hybrid fibers. In addition, the sensor achieved LOD of 10 ppm with response of 4.26%. The mechanically robust $\text{Ti}_3\text{C}_2\text{T}_x$ MXene//rGO hybrid fibers maintained consistent gas-sensing performance under repeated bending and releasing cycles. The practical demonstration of wearable $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ hybrid fiber integrated into a laboratory coat is presented in Figure 4f. Overall, the synergistic combination of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and graphene in a flexible fiber architecture provided an effective

strategy for the advancement in next-generation wearable NH_3 gas sensors operating at room temperature.

Li et al. [41] significantly improved the room-temperature NH_3 gas-sensing performance of $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ composite compared to pure $\text{Ti}_3\text{C}_2\text{T}_x$ and graphene. The authors attributed the enhanced sensing characteristics to the abundant surface termination groups on the $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ surface, which promoted the adsorption of NH_3 molecules. In particular, the $-\text{O}$ and $-\text{OH}$ termination groups effectively interacted with adsorbed NH_3 molecules, which released three electrons and one electron, respectively. The surface morphology of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ composite film is shown in Figure 5a. As a p-type sensing material, the $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ composite accepted electrons from NH_3 molecules, which led to increase in sensor resistance. The sensing response was investigated over an NH_3 concentration range of 0.5 to 100 ppm, exhibiting a linear increment from 2.0 to 25.5%, respectively, as shown in Figure 5b. The response towards NO_2 (5.4%) and H_2 (3.7%) was lower compared to NH_3 , which confirmed the developed composite's high selectivity towards NH_3 . At 100 ppm NH_3 , the composite exhibited response and recovery times of 26 and 148 s, respectively. Furthermore, the $\text{Ti}_3\text{C}_2\text{T}_x/\text{graphene}$ sensor demonstrated excellent repeatability over three consecutive sensing cycles, with a stable response of 25% and outstanding long-term stability, maintaining an average response of 24.9% after 16 days under 80% relative humidity (Figure 5c). The hydrophilic behavior favored stable NH_3 sensing at higher humidity conditions. These results successfully demonstrated that the synergistic integration between p-type $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and graphene substantially enhanced the room-temperature NH_3 -sensing performance under highly humid environmental conditions.

4.7. Ti_3C_2 MXene/Semiconductors

Furthermore, He et al. [42] enhanced the room-temperature NH_3 gas-sensing performance by decorating $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets with SnO_2 nanoparticles. The incorporation of SnO_2 nanoparticles increased the amount of surface-adsorbed oxygen species, which created additional active sites for NH_3 adsorption and facilitated improvement in gas sensing performance. Interestingly, the $\text{Ti}_3\text{C}_2\text{T}_x/\text{SnO}_2$ composite exhibited the highest sensing performance at room temperature, whereas the sensor showed almost no response at 100 °C. A linear decrease in sensor response was observed as the operating temperature increased from 25 to 100 °C. This deterioration in sensing performance at elevated temperatures was attributed to the gradual reduction in hydroxyl ($-\text{OH}$) surface terminations. The O 1s peak showed integrated lattice oxygen (530.1 eV) and adsorbed oxygen (532 eV). The improvement in surface adsorbed oxygen created more active sites, increasing sensing performance. Accordingly, the $\text{Ti}_3\text{C}_2\text{T}_x/\text{SnO}_2$ composite achieved an excellent response of 40% toward 50 ppm at room temperature under relative humidity of 46%, with response and recovery times of 36 and 44 s, respectively. The introduction of SnO_2 increased NH_3 exposure towards the interfacial regions, density of reactive oxygen species on the surface, and baseline stability. Furthermore, the response towards ethanol was very low (3.12%), which confirmed high selectivity towards NH_3 . The sensor also exhibited an ultralow LOD of 4.29 ppb, demonstrating its capability for highly sensitive NH_3 detection. In addition, the composite maintained stable sensing performance for 60 days at NH_3 concentration of 50 ppm, indicating excellent long-term stability. The electrons transfer from NH_3 to $\text{Ti}_3\text{C}_2\text{T}_x$ increased the sensor resistance and NH_3 sensing capacity. As the relative humidity increased from 25 to 85%, the response was higher at moderate conditions (45% humidity) under increased NH_3 adsorption and reaction pathways. Overall, the synergistic interaction between $\text{Ti}_3\text{C}_2\text{T}_x$ and SnO_2 nanoparticles significantly enhanced NH_3 adsorption, which enabled superior room-temperature sensing performance, high tolerance of humidity, and excellent long-term operational stability.

Yao et al. [43] synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ SnO nanocomposite by integrating ultrathin SnO nanoflakes with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene through a one-step hydrothermal method, for room-temperature NH_3 vapor response over a wide range of 1 to 1000 ppm concentrations. The formation of p-n heterojunctions improved the charge carrier concentration, which led to superior NH_3 -sensing performance compared to individual p-type or n-type components. Moreover, the matrix effectively suppressed the oxidation of SnO into SnO_2 , preserving the structural and chemical stability of the composite. Furthermore, the conductive $\text{Ti}_3\text{C}_2\text{T}_x$ skeleton increased the surface area of the composite ($14.27 \text{ m}^2/\text{g}$), which generated abundant oxygen adsorption sites and active reaction centers for NH_3 molecules. In addition to lattice oxygen (530.3 eV), formation of surface adsorbed oxygen species at 531.8 eV was noticed. Here, the adsorbed oxygen species mainly contributed to the improved gas-sensing performance. In addition, the ultrathin SnO nanoflakes with a thickness of 9 nm facilitated rapid electron transportation and accelerated the sensing kinetics. The synergistic interaction between $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and SnO effectively modulated the electrical conductivity of the p-n heterojunctions, which resulted enhanced response and recovery characteristics. Furthermore, SnO greatly contributed to increased surface reactions through adsorbed oxygen, charge transfer through heterostructure, and abundant surface-active sites to achieve long-term sensing stability. The nanocomposite exhibited a response of 7.8 for 200 ppm (35.49 for 1000 ppm), with response and recovery times of 61 and 119 s, respectively. The response of about 1.59 towards ethanol was very low compared to NH_3 , which confirmed high selectivity towards NH_3 . Furthermore, the sensor achieved LOD of 1 ppm and demonstrated excellent repeatability over four sensing cycles and stable long-term performance for 22 days. The interaction of NH_3 with adsorbed oxygen transferred the electrons towards the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ SnO , improving the NH_3 sensing performance. According to the gas-sensing signal direction, SnO behaved like an n-type semiconductor, which created p-n junction at the interface of p-type $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. Overall, the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ SnO heterostructure exhibited a broad NH_3 -detection range (1–1000 ppm), high sensitivity, rapid sensing kinetics, and excellent long-term stability for advancing the room-temperature NH_3 sensing applications.

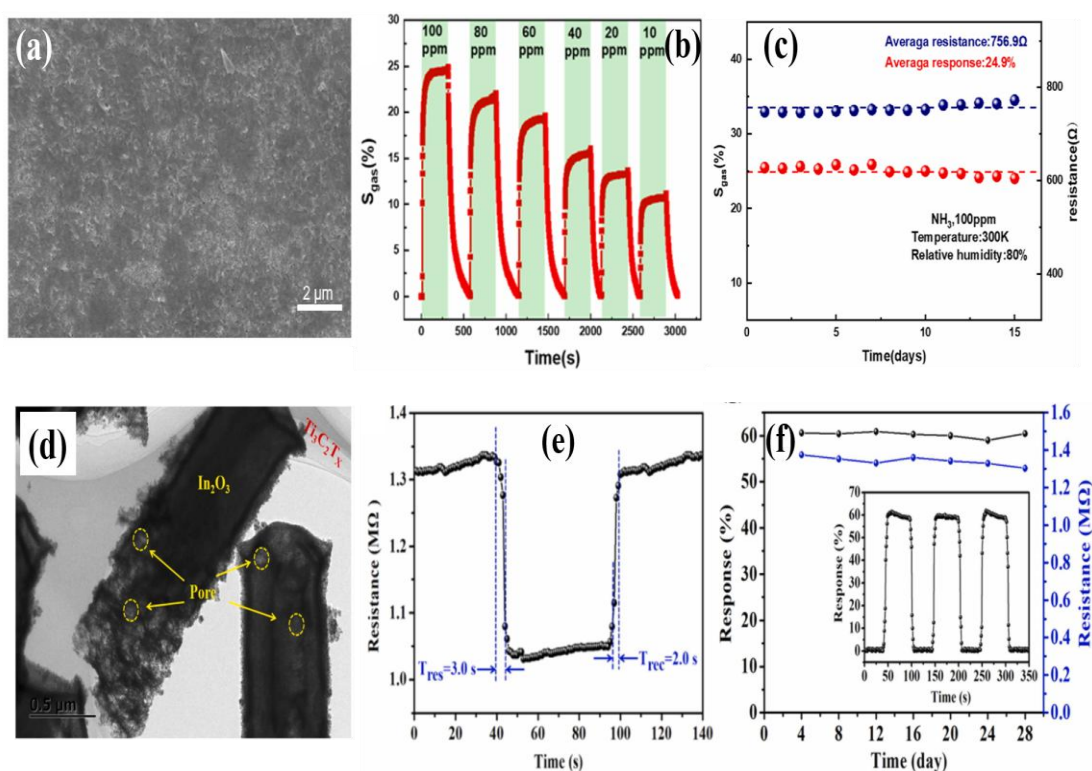


Figure 5. (a) Surface morphology of the $\text{Ti}_3\text{C}_2\text{T}_x$ /graphene composite film, (b) NH_3 gas response over a concentration range of 10–100 ppm, (c) remarkable long-term stability of the $\text{In}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite with a stable response over 16 days at 80% relative humidity, (Reprinted from Ref. [41], copyright with permission from Elsevier), (d) TEM image of In_2O_3 microtubes interfaced with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, (e) ultrafast response and recovery times of 3 s and 2 s for the $\text{In}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite, (f) excellent cyclic and long-term stability of the $\text{In}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite, (Reprinted from Ref. [44], copyright with permission from Elsevier).

Achieving ultrafast response and recovery is crucial for realizing high-performance gas sensors with rapid adsorption and desorption kinetics. In this context, Liu et al. [44] developed a metal–organic frameworks (MOFs)-derived In_2O_3 microtube (2–5 μm)/ $\text{Ti}_3\text{C}_2\text{T}_x$ MXene heterostructure for room-temperature NH_3 gas sensing. The TEM image of the MOFs-derived In_2O_3 microtubes/ $\text{Ti}_3\text{C}_2\text{T}_x$ MXene heterostructure is shown in Figure 5d. The composite exhibited a highly mesoporous architecture with a large specific surface area of 446.63 m^2/g and pore size distribution of 5–10 nm, which provided abundant active sites for NH_3 adsorption. The O 1s spectrum revealed lattice oxygen, oxygen defects, and chemisorbed oxygen at 528.9, 530.5, and 532.0 eV, respectively. These features created more gas-sensing capability. As shown in Figure 5e, the heterostructure achieved ultrafast response and recovery times of 3 and 2 s toward 5 ppm NH_3 at room temperature, whereas the corresponding values increased to 28 and 65 s at 200 °C. The significantly shortened response time at room temperature indicated the enhancement in NH_3 adsorption kinetics and efficient electron transfer within the heterostructure. However, at 100 °C, the response/recovery time slightly increased to 5/3 s due to the partial oxidation of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, which reduced the electrical conductivity of the composite. The NH_3 molecules interacted with adsorbed oxygen and released electrons to the $\text{In}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ heterostructure, reducing the sensor resistance. Introduced In_2O_3 behaved like an active sensing component for the detection of NH_3 through surface adsorption. Due to its mesoporous architecture, In_2O_3 provided numerous active sites at the interface of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, leading to enhancement in charge transfer and sensor response at room temperature. Thus, the MOFs-derived $\text{In}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite exhibited outstanding room-temperature NH_3 gas sensing of 60.6% with ultra-fast response and recovery characteristics (Figure 5f). The response towards NH_3 was significantly higher than ethanol, CO, and NO_2 , which suggests high selectivity towards NH_3 . Furthermore, the sensor retained a stable NH_3 response up to relative humidity of 60%, demonstrating excellent humidity tolerance. At higher relative humidity conditions (>60%), decreases in response were noticed due to the interference of water molecules. The work function of p-type $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (4.28 eV) was higher than n-type In_2O_3 (4.28 eV). Thus, electrons transferred from In_2O_3 to the surface functional groups modulated the p-type $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. Overall, the formation of p–n heterojunctions between In_2O_3 and $\text{Ti}_3\text{C}_2\text{T}_x$ MXene significantly enhanced charge transfer and gas-adsorption features for exceptional room-temperature NH_3 -sensing performance.

The interaction of NiO with a Ni_2P nanosheet heterostructure enhanced H_2S gas sensing [45]. In this context, Yang et al. [46] highlighted the incorporation of NiO nanoparticles into $\text{Ti}_3\text{C}_2\text{T}_x$ MXene ($\text{NiO}/\text{Ti}_3\text{C}_2\text{T}_x$) for room-temperature NH_3 gas sensing. The $\text{NiO}/\text{Ti}_3\text{C}_2\text{T}_x$ heterostructure exhibited faster recovery than response over an NH_3 concentration range of 10–50 ppm. More importantly, the sensing response of $\text{NiO}/\text{Ti}_3\text{C}_2\text{T}_x$ composite was 1.18 and 1.38 times higher than those of pristine $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and NiO, respectively. This enhanced sensing performance was attributed to the increased density of active adsorption sites and improved electron transport across the $\text{NiO}/\text{Ti}_3\text{C}_2\text{T}_x$ heterojunction. Furthermore, pristine $\text{Ti}_3\text{C}_2\text{T}_x$ MXene exhibited a higher response than pure NiO owing to its abundant surface termination groups (–O, –OH, and –F), which provided

favorable adsorption sites for NH_3 molecules. According to the O 1s spectra, Ni-O and -OH groups on the NiO corresponded to lattice oxygen and adsorbed oxygen, respectively. The effectively adsorbed NH_3 molecules interacted with adsorbed oxygen and transferred electrons towards the sensor, increasing the sensor resistance. Specifically, NiO increased the NH_3 adsorbed oxygen species, surface area, and Schottky heterojunction, increasing the adsorption sites for room-temperature NH_3 gas sensing. Upon forming the heterostructure, the NiO/ $\text{Ti}_3\text{C}_2\text{T}_x$ composite achieved a response of 6.13% toward 50 ppm NH_3 with rapid response and recovery times of 60 and 19 s, respectively. Responses towards ethanol and IPA were observed to be 2.26 and 0.53%, respectively, which suggests high selectivity towards NH_3 (6.13%). The sensor was also capable of detecting NH_3 concentrations as low as 10 ppm and demonstrated excellent repeatability over 15 sensing cycles at 50 ppm (long-term stability for 15 days). In addition, the NiO nanoparticles increased the specific surface area and number of active sites available for oxygen and NH_3 adsorption. The NH_3 response was highest at 10% humidity, gradually decreasing at 30 to 50%, with a significant reduction between 70 to 90% relative humidity conditions. Combined with the abundant surface termination groups (-O, -OH, and -F) and high charge-carrier mobility in $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, enhanced room-temperature NH_3 -sensing performance was achieved in the NiO/ $\text{Ti}_3\text{C}_2\text{T}_x$ heterostructure.

In addition to previously reported SnO_2 [42], SnO [43], and NiO [46] semiconductor nanostructures, Pasupuleti et al. [47] demonstrated sub-ppb-level NH_3 detection at room temperature under UV illumination using a $\text{ZnO}@\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite. In this composite, ZnO nanoparticles were uniformly anchored onto $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets, which resulted in a larger specific surface area ($47.55 \text{ m}^2/\text{g}$) than that of pristine ZnO ($23.61 \text{ m}^2/\text{g}$) and $\text{Ti}_3\text{C}_2\text{T}_x$ ($13.86 \text{ m}^2/\text{g}$). The increased surface area provided abundant active sites for NH_3 adsorption, which facilitated both sensitivity and selectivity. Key features such as lattice oxygen, oxygen vacancy, and chemisorbed oxygen were observed in the O 1s spectrum, and these promoted NH_3 adsorption. Furthermore, the Schottky junction formed at the $\text{ZnO}/\text{Ti}_3\text{C}_2\text{T}_x$ interface reduced the electron depletion layer upon NH_3 exposure, which played a crucial role in enhancing the sensing performance. Introduction of ZnO nanoparticles created oxygen vacancies (active adsorption sites), Schottky junctions (charge transfer), and suppressed $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheet restacking (high surface area), increasing the long-term stability of NH_3 gas sensing. Under UV illumination, photogenerated holes promoted the neutralization of adsorbed O_2^- ions, promoting the desorption of NH_3 molecules and accelerating the recovery process. As a result, the $\text{ZnO}@\text{Ti}_3\text{C}_2\text{T}_x$ exhibited response and recovery times of 92 and 104 s, respectively, with an impressive LOD of 89.41 ppb. At an NH_3 concentration of 20 ppm, the sensor achieved a remarkable response of 39.16%, higher than for CO (6.415) and NO_2 (16.25%) gases. These findings demonstrated that ZnO nanoparticles effectively modulated the interfacial electronic structure of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene for efficient photo-assisted room-temperature NH_3 gas sensing.

In another study, Lu et al. [48] successively fabricated a $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ MoS_2 /PPy ternary composite for efficient room-temperature NH_3 gas sensing. In this hybrid structure, PPy provided abundant hydrogen-bonding active sites for enhanced NH_3 adsorption, while MoS_2 nanosheets increased the interlayer spacing of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets for effective exposure of additional active sites and gas adsorption. The surface morphology of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{MoS}_2$ /PPy is shown in Figure 6a. Owing to the p-type semiconducting behavior of $\text{Ti}_3\text{C}_2\text{T}_x$, electron donation from NH_3 molecules resulted in increased sensor resistance. The composite exhibited a detectable response of 2.31% at 10 ppm NH_3 and a high response of 21% at 100 ppm with rapid response/recovery times of 43.6/40.8 s at room temperature under 45% relative humidity (Figure 6b). The response decreased from 23 to 4.7% (at 100 ppm) by increasing the relative humidity from 30 to 90%, respectively. Adsorption of water molecules on active sensing sites prevented the NH_3 molecules from

reaching the sensor surface. The response towards ethanol and NO₂ was 5.4 and 2.5%, respectively. This suggests that the Ti₃C₂T_x MXene/MoS₂/PPy composite was highly selective towards NH₃ compared with ethanol and NO₂. In addition, the sensor displayed excellent repeatability over five sensing cycles and maintained stable long-term performance for 7 days under the same humidity conditions (Figure 6c). Overall, the synergistic effects of Ti₃C₂T_x MXene, MoS₂ nanosheets, and PPy significantly improved NH₃ sensing performance in harsh humid environments.

In another study, Bi₂O₃ was integrated with Ti₃C₂T_x (Bi₂O₃/Ti₃C₂T_x) for room-temperature NH₃ gas sensing [49]. This composite was highly selective to NH₃ with a response of 61% at 100 ppm, compared with ethanol (10%), methanol (3%), and acetic acid (4%). High surface area, electrical conductivity, interfacial charge transfer, and surface functional groups (–O, –OH, and –F) accelerated the NH₃ adsorption and interaction. Response and recovery times of 61 and 164 s were observed for the Bi₂O₃/Ti₃C₂T_x composite at 100 ppm. Notably, the response linearly increased from 61 to 124% with an increase in relative humidity from 50 to 90%, which suggested high humidity tolerance. Identical response signals were achieved after six cycles and 20 days (five cycles each day), showing long-term stability. Thus, the developed Bi₂O₃/Ti₃C₂T_x composite provided remarkable adsorption/desorption kinetics at the interface with minimal degradation of active sensing sites.

Seekaew et al. [50] developed a Ti₃C₂T_x MXene/GO/CuO/ZnO (9:1:5:5 wt%) heterojunction composite by hydrothermal process, for room-temperature NH₃ gas sensing in the range of 25 to 200 ppm. This combination included p-n junctions. The intimate contact between various semiconductors achieved abundant adsorption sites, charge transfer, and oxygen vacancies, thereby enhancing NH₃ gas sensing. Notably, stable response and complete recovery were achieved with response time and recovery of 26 and 26 s, respectively, at 100 ppm. The LOD was about 4.1 ppm. The presence of –OH and –O groups accelerated the NH₃ adsorption. Thus, an NH₃ response of 96.3% was achieved at 200 ppm (25 ppm–30.7%). The response towards NH₃ was significantly higher than ethanol, methanol, and acetone. No response towards NO₂ was achieved by the selective composite. These results suggest that the surface chemistry favored NH₃ selectivity compared with other volatile organic compounds. At 80 to 90% relative humidity, the sensor showed a highly stable response with slight decrease in resistance. At 200 ppm, this composite achieved stable response and recovery curves after six repeated cycles and long-term stability after 45 days. Overall, the formation of multiple-semiconductor-heterojunction-integrated Ti₃C₂T_x MXene contributed to excellent response and recovery in the detection of NH₃ at room temperature.

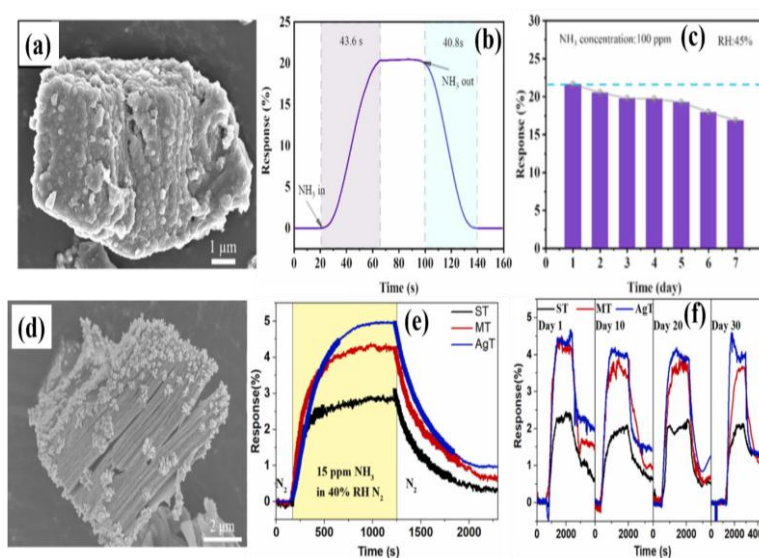


Figure 6. (a) Surface morphology of the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ MoS_2 /PPy composite, (b) response and recovery times of 43.6 and 40.8 s with a response of 21% under 100 ppm NH_3 , (c) long-term stability over 7 days at 45% relative humidity (Reprinted from Ref. [48], copyright with permission from Elsevier), (d) surface morphology of Ag nanoparticle-integrated oxygen-rich p-type $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, (e) enhanced response toward 15 ppm NH_3 under 40% relative humidity, and (f) remarkable long-term cyclic stability and NH_3 sensing performance over 30 days (Reprinted from Ref. [51], copyright with permission from Elsevier).

4.8. Ti_3C_2 MXene/Ag and Au Metals

The incorporation of Ag nanoparticles into oxygen-rich p-type $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (AgT) significantly enhanced room-temperature NH_3 gas-sensing performance [51]. The surface morphology of an AgT composite is presented in Figure 6d. During the sensing process, NH_3 gas molecules were initially adsorbed onto the Ag nanoparticles, followed by their diffusion into the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene layers, resulting in an increment in the sensor resistance. Interestingly, the rapid recovery behavior was attributed to the abundant surface termination groups, where the $-\text{O}$ terminations exhibited weaker adsorption energy and $-\text{OH}$ groups facilitated faster NH_3 desorption. XPS studies showed that lattice oxygen and adsorbed oxygen were observed through Ti-O-Ti formation at 530.0 eV. Furthermore, $-\text{O}$ and $-\text{OH}$ termination groups were observed through C-Ti-OH formation at 531.9 eV. Accordingly, the AgT composite exhibited enhanced NH_3 gas-sensing performance up to 10 ppm (stable at 15 and 20 ppm). In this process, the AgT sensor achieved responses of 4.35% and 4.96% toward 10 and 15 ppm NH_3 , respectively, which outperformed pristine single-layer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (2.93%) and multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (4.30%), as shown in Figure 6e. In addition, the AgT composite achieved LOD of 0.5 ppm. At a relative humidity of 40%, the AgT sensor exhibited response and recovery times of 511 and 605 s, respectively, compared to 319/578 s for single-layer and 446/659 s for multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. Moreover, the synergistic effects of the multilayer architecture, Ag nanoparticles, and abundant surface termination groups enabled excellent long-term stability over 30 days, even under 40% relative humidity (Figure 6f). DFT studies highlighted the superior NH_3 adsorption of Ag- $\text{Ti}_3\text{C}_2\text{O}_2$ ($-\text{O}$ termination groups), with adsorption energy of -0.445 eV (dry) and -0.490 eV (pre-adsorbed H_2O) at adsorption distances of 2.494 and 2.269 Å, respectively. Pre-adsorbed H_2O increased the charge transfer to 0.08 e, which confirmed enhanced NH_3 adsorption and sensing performance compared with pristine $\text{Ti}_3\text{C}_2\text{O}_2$. Overall, defect engineering combined with surface functionalization through Ag nanoparticles effectively improved the room-temperature NH_3 -sensing performance of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene.

Interestingly, the selective interaction of noble Au (1.92 at%) and Pt (0.83%) metallic nanoparticles with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets for NH_3 gas-sensing applications was investigated [52]. The sensor thickness was maintained within the range of 10 to 20 μm . Among the two-metal nanoparticle-decorated composites, Au-modified $\text{Ti}_3\text{C}_2\text{T}_x$ MXene exhibited superior NH_3 response and selectivity compared to Pt-modified $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. The surface morphology of the Au nanoparticle-interfaced $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets is presented in Figure 7a. Ohmic contact between sensors and electrodes with negligible polarization did not influence the sensing signal. Accordingly, Au (1.92 at%) and Pt (0.83%)-decorated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene sensors demonstrated room-temperature NH_3 responses (100 ppm) of 16 and 9%, respectively. The response/recovery times for Au- and Pt-decorated sensors were recorded as 87/217 s and 77/248 s, respectively, over six consecutive sensing cycles. Furthermore, the flexibility of the sensors was evaluated under 0 to 120° bending conditions. Remarkably, after bending at 120° , the flexible NH_3 gas sensors retained responses of 9.9% and 6% for Au (1.92 at%) and Pt (0.83 at%) nanoparticle-decorated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, respectively (Figure 7b). These composite sensors also demonstrated stable NH_3 -sensing performance under highly humid conditions. As an electron-donating gas, NH_3

molecules effectively transferred electrons towards the sensor, which altered the sensor resistance. The proposed charge transfer mechanism and interaction between NH_3 molecules and the sensor surface is illustrated in Figure 7c. Overall, the incorporation of noble metal nanoparticles into $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets enhanced the sensing characteristics and enabled flexible, room-temperature NH_3 gas detection.

4.9. Ti_3C_2 MXene/Polymers

Qiu et al. [53] enhanced room-temperature NH_3 gas sensing by developing an organic–inorganic p–n heterojunction based on PEDOT:PSS/nitrogen-doped $\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite film. A selective mass ratio of 1:0.5 (N-MXene:PEDOT:PSS) maintained stable NH_3 gas-sensing performance owing to the dominant electron extraction by the PEDOT matrix compared to N-MXene. The incorporated N-atoms acted as electron donors, which increased the density of active adsorption sites within the PEDOT:PSS matrix. Furthermore, the formation of TiO_2 nanoparticles between the N-MXene layers enlarged the interlayer space and suppressed the retacking of MXene nanosheets, which facilitated efficient NH_3 diffusion and improved response and recovery characteristics. Consequently, the well-defined layered architecture promoted rapid gas transportation, resulting in response and recovery times of 280 and 393.6 s, respectively. Under these optimized conditions, the PEDOT:PSS/N-MXene composite exhibited a response of about 13% toward 10 ppm at 20 °C and 36%RH. The NO_2 and CO response was negligible compared to NH_3 , which suggests PEDOT:PSS/N-MXene's high selectivity towards NH_3 gas. In addition, the sensor demonstrated excellent repeatability over four sensing cycles and maintained stable performance up to 17 days. These results confirmed that the synergistic integration between PEDOT:PSS and N-doped $\text{Ti}_3\text{C}_2\text{T}_x$ MXene significantly improved the room-temperature NH_3 -sensing performance.

Arkoti et al. [54] reported improvement in NH_3 gas-sensing performance by developing $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-based sensors with and without a mixed-matrix membrane (MMM) filter composed of PVDF-ZIF-67. The authors demonstrated that the incorporation of the MMM filter improved the long-term stability of the sensor. In comparison, pure $\text{Ti}_3\text{C}_2\text{T}_x$ MXene dominated the sensor behavior than with the MMM filter. Interestingly, strong hydrogen-bonding interactions between NH_3 gas molecules and –OH termination groups influenced the gas-sensing behavior. The minimum detectable NH_3 concentrations were 9 ppt and 1 ppb for sensors without and with the MMM filter. At 5 ppm NH_3 concentration, the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene sensor exhibited response/recovery times of 37.8/34.5 s and 49.5/51.2 s without and with MMM filter, respectively. Furthermore, at 35% relative humidity, the NH_3 -sensing responses of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene with and without the MMM filter were about 10.6% and 11.86%, respectively. Responses towards ethanol and NO_2 were observed to be 2.8 and 1.2% without the MMM filter, confirming high selectivity towards NH_3 . The MMM filter facilitated controlled diffusion of NH_3 molecules toward the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene layer, resulting in improved long-term stability over 35 days. Overall, the introduction of the MMM filter effectively reduced interference from water molecules and suppressed the oxidation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene for enhancing the durability of NH_3 gas-sensing devices.

Room-temperature NH_3 gas sensing using PANI/ $\text{Ti}_3\text{C}_2\text{T}_x$ was studied [55]. The formation of –OH and –O functional groups led to effective interaction with NH_3 . The constructive interface between conductive $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and semiconducting PANI created a potential Schottky barrier, which enhanced the NH_3 adsorption properties under altered sensor resistance. According to DFT studies, the adsorption energy of NH_3 (−5.351 eV) was lower than CO (0.057), NO_2 (−4.498 eV), and ethanol (0.127 eV), which confirmed the remarkable adsorption capacity of NH_3 on the PANI/ $\text{Ti}_3\text{C}_2\text{T}_x$ surface. Under these conditions, the flexible PANI/ $\text{Ti}_3\text{C}_2\text{T}_x$ composite achieved a room-temperature NH_3 response of 55.90% at 20 ppm (pure PANI-24.20%). Interestingly, the response increased from 52.32 to

58.54% under relative humidity conditions of 25 and 68%, respectively. This organized flexible PANI/Ti₃C₂T_x composite achieved excellent cyclic repeatability without decaying even after five cycles. Moreover, long-term stability over 21 days was maintained without altering the response. Overall, remarkable NH₃ adsorption capacity in the flexible PANI/Ti₃C₂T_x composite was achieved.

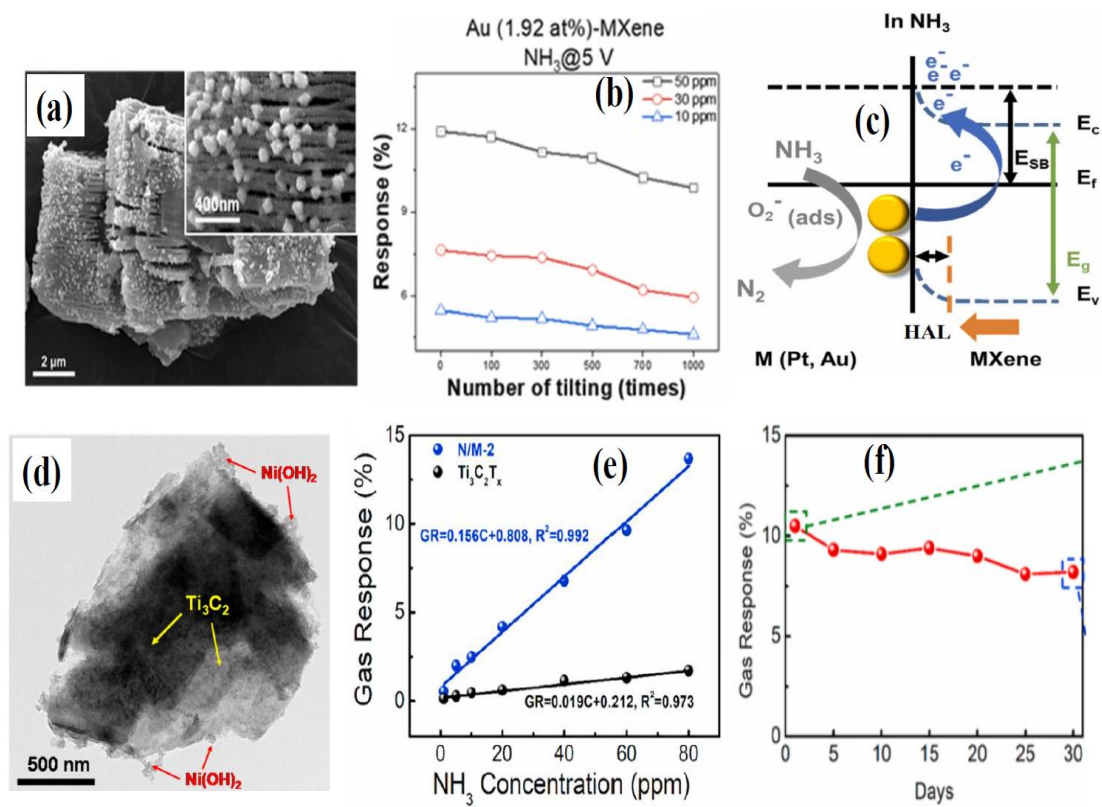


Figure 7. (a) Surface morphology of Au nanoparticle-decorated Ti₃C₂T_x MXene nanosheets, (b) NH₃ gas response over the concentration range of 10–50 ppm at an Au concentration of 1.92%, (c) charge transfer mechanism and NH₃ gas sensing mechanism of the Au/Ti₃C₂T_x MXene composite, (Reprinted from Ref. [52], copyright with permission from Elsevier), (d) TEM image of Ni(OH)₂ nanoparticles interfaced with Ti₃C₂T_x MXene nanosheets, (e) enhanced gas-sensing response of the Ni(OH)₂ nanoparticles interfaced with Ti₃C₂T_x compared with pure Ti₃C₂T_x MXene, and (f) stable long-term response over 30 days at 50 ppm NH₃ for the Ni(OH)₂ nanoparticle-interfaced Ti₃C₂T_x MXene composite (Reprinted from Ref. [56], copyright with permission from Elsevier).

4.10. Ti₃C₂ MXene/Metal Hydroxides

The incorporation of Ni(OH)₂ nanoparticles onto Ti₃C₂T_x MXene nanosheets significantly enhanced room-temperature NH₃ gas-sensing performance [56]. The introduction of optimized Ni(OH)₂ loading (7.8 wt.%) increased the interlayer spacing of Ti₃C₂T_x MXene nanosheets, which provided additional diffusion pathways and abundant adsorption sites for NH₃ molecules. Consequently, the composite exhibited a high specific surface area of 53.0591 m² g^{−1}, which further promoted gas adsorption. The TEM image of the Ni(OH)₂/Ti₃C₂T_x MXene composite is presented in Figure 7d. During the hybridization process, some of the –OH surface termination groups were replaced through the incorporation of Ni ions (XPS studies), which modified the surface chemistry of the MXene. Owing to the dominant Ti₃C₂T_x MXene content relative to low Ni(OH)₂ loading (7.8 wt.%), electrical resistance of the composite remained primarily governed by the conductive MXene network and enhanced the surface reactivity introduced by Ni(OH)₂. Thus, the Ni(OH)₂/Ti₃C₂T_x composite exhibited a room-temperature NH₃ response of 13.69% at 80

ppm, as shown in Figure 7e. Furthermore, the sensor demonstrated stable response and recovery times of 78 and 108 s, with a response of 10.3% after five consecutive sensing cycles and excellent long-term stability over 30 days at 50 ppm, as shown in Figure 7f. The response value towards 70 ppm NO (2.4%) was lower than towards NH₃ (11.6%), which suggests that the Ni(OH)₂/Ti₃C₂T_x composite was highly selective towards NH₃. Notably, the sensor maintained excellent sensing performance under humid conditions, exhibiting responses of 5.1 and 6.2% toward 10 ppm NH₃ at relative humidities of 40 and 60%, respectively. At higher humidity of 80%, the response decreased to 3.9% due to the excessive water molecules blocking the NH₃ adsorption sites. The adsorbed NH₃ transferred electrons to the Ni(OH)₂ and Ti₃C₂T_x, leading to a decrease in the concentration of holes, which increased the sensor resistance and increased the NH₃ sensing capacity. Overall, the synergistic integration of Ni(OH)₂ nanoparticles with Ti₃C₂T_x MXene effectively enhanced the NH₃ adsorption, gas diffusion, and humidity tolerance.

Similarly, Huang et al. [57] developed a Co(OH)₂/Ti₃C₂T_x nanocomposite for room-temperature NH₃ gas sensing. The incorporation of optimized Co(OH)₂ content (2.13%) along with NaOH interaction (alkalization) altered the characteristic (002) diffraction peak position of Ti₃C₂T_x MXene towards lower diffraction angles, which indicated an increase in the interlayer spacing [35]. This structural modification promoted the diffusion of NH₃ molecules into the enlarged interlayer channels. In addition, the specific surface area of the Co(OH)₂/Ti₃C₂T_x nanocomposite (19.0984 m²/g) was substantially higher than that of pure MXene (3.9900 m²/g), providing a greater number of active adsorption sites for NH₃ molecules. Lattice oxygen in the Co(OH)₂/Ti₃C₂T_x nanocomposite was observed, with O-H and Ti-O bonds at 529.8 and 531.1 eV, respectively. As a result, the nanocomposite containing 2.13% Co(OH)₂ exhibited NH₃ gas response of 14.7% at 100 ppm, with response and recovery times of 39 and 49 s, respectively. The response towards ethanol was negligible at 0.7%, which confirmed the potential response and selectivity of Co(OH)₂/Ti₃C₂T_x composite towards NH₃. Furthermore, the sensor demonstrated excellent repeatability over five sensing cycles and maintained stable sensing performance up to 30 days. The synergistic interaction between Co(OH)₂ and Ti₃C₂T_x also enhanced the NH₃ sensing performance under humid conditions of 30% (high response), 40–60% (decreasing), and 70% (increase again). At higher humidity conditions of 70%, NH₃ interacted with water molecules and formed hydrated NH₃ molecules, which increased the Ti₃C₂T_x nanosheets' interlayer spacing and sensing ability. The adsorbed NH₃ transferred the electrons to the Co(OH)₂ and Ti₃C₂T_x, which reduced the concentration of holes. Overall, the surface modification of Ti₃C₂T_x MXene with Co(OH)₂ effectively enhanced the selectivity and room-temperature NH₃ sensing performance.

4.11. Ti₃C₂ MXene/MOFs

Very recently, Qiu et al. [58] successfully demonstrated ppb level NH₃ gas sensing at room temperature by integrating Ni₃(HITP)₂ MOF and Ti₃C₂ MXene. In this hybrid structure, Ni₃(HITP)₂ MOF crystals were directly grown on the Ti₃C₂ MXene surface, enabling intimate interfacial contact between two components. The resulting Ni₃(HITP)₂/Ti₃C₂ composite exhibited a high specific surface area of 431.2 m²/g, which provided abundant active sites for NH₃ adsorption, diffusion, and transportation. This unique architecture significantly advanced the molecular capture capability of the sensing platform. Furthermore, the formation of Ti-O-Ni and/or Ti-F-Ni bonds at the Ni₃(HITP)₂ MOF/Ti₃C₂ MXene interface facilitated interfacial charge transfer, improving the gas-sensing performance. This structural integration enhanced the NH₃ gas-sensing response to 33% at 30 ppm, with rapid response/recovery times of 9/13 s, which demonstrated efficient and reversible NH₃ adsorption and desorption processes. Also, composite sensors demonstrated excellent cyclic stability over five cycles under NH₃ concentrations of 1, 5, and 15 ppm, along with

long-term stability for more than 50 days at 15 ppm at 30% relative humidity. A remarkably LOD of 100 ppb at room temperature was achieved. After NH_3 exposure, NH_3 gas molecules behaved like electron donors and experienced potential redox reaction with adsorbed oxygen ions. Overall, the integration of MOF and Ti_3C_2 MXene provided a promising strategy for developing highly sensitive, stable, and room-temperature NH_3 gas sensors with ppb-level detection capability.

4.12. Ti_3C_2 MXene/Single Atoms

In addition to the above studies, Ni single-atom active sites coordinated with N and C (Ni–N–C) on $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$) have been studied with regard to room-temperature NH_3 gas sensing [59]. A composite integrated with a gold electrode (AuE–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$) exhibited a response of 20.1% toward 5 ppm, with LOD of 29.3 ppb. Furthermore, $\text{Ti}_3\text{C}_2\text{T}_x$ -MXene (ME) and $\text{Ti}_3\text{C}_2\text{T}_x$ -MXene/NMP/PEDOT:PSS (MNPE) electrode inks were employed to fabricate ME–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$ and MNPE–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$ sensors, which achieved responses of 33.2 and 27.3% at 5 ppm, respectively. The ME–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$ and MNPE–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$ composites exhibited response/recovery times of 30/80 s and 30/150 s with LOD of 27.0 and 12.1 ppb, respectively. This improved NH_3 sensing performance was attributed to the oxygen-enriched groups in the MNPE and ME electrodes, which facilitated higher density of surface-active sites than the AuE–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$. Moreover, the ME–Ni–N–C/ $\text{Ti}_3\text{C}_2\text{T}_x$ sensor demonstrated superior long-term stability by retaining 35.8% of its sensing response after 4 weeks. These findings highlight the effectiveness of ME and MNPE electrode inks for developing flexible and high-performance NH_3 gas sensors.

4.13. Ti_3C_2 MXene/Cationic Polyacrylamide

Rapid NH_3 gas response/recovery process was achieved by developing flexible cationic polyacrylamide (CPAM)-interfaced $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets (CPAM/ $\text{Ti}_3\text{C}_2\text{T}_x$) [60]. The structural defects and surface termination groups (–OH, –O, and – NH_2) in the CPAM/ $\text{Ti}_3\text{C}_2\text{T}_x$ composite played a crucial role in enhancing the adsorption of NH_3 gas molecules. Among these functional groups, the bond length ($1.89 \text{ \AA}$) between the NH_3 and –OH terminations at adsorption energy of -0.515 eV contributed to $\text{Ti}_3\text{C}_2\text{T}_x$ MXene's role in the NH_3 sensing mechanism. The strong hydrogen bonding between the –OH termination groups and NH_3 molecules facilitated electron transfer from NH_3 to CPAM/ $\text{Ti}_3\text{C}_2\text{T}_x$. In this context, the sensor exhibited rapid response/recovery time of 12.7/14.6 s and response of 3.1% at 150 ppm, which further increased to 4.7% at 200 ppm. The presence of abundant functional groups also enabled stable NH_3 -sensing performance at 200 ppm at a relative humidity of 35%. The sensor achieved high tolerance at relative humidity of under 45%, with negligible changes, and 50% decreased response at relative humidity of 95%. Furthermore, CPAM acted as an effective interfacial binder, which promoted strong adhesion between the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets and mechanical stability, ensuing a stable response at 60°C over 140 operating cycles. Overall, the synergistic effect of surface termination groups and the CPAM interface significantly enhanced the flexibility, stability, and rapid room-temperature NH_3 -sensing performance of the CPAM/ $\text{Ti}_3\text{C}_2\text{T}_x$ composite.

Overall, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-based composites exhibited remarkable room-temperature NH_3 gas sensing, with abundant surface terminations (–OH, –O, and –F), enlarged inter-layer spacing, gas diffusion, and adsorption. Functionalization with polymers, graphene, metal oxides, MOFs, noble metals, sulfur nanosheets, and hydroxides greatly enhanced the key features such as adsorption, charge transfer, selectivity, and stability by suppressing oxidation. Results revealed NH_3 responses up to 147%, ultrafast response/recovery as low as 3/2 s, LOD from ppm to ppt levels, stable operation under humid conditions,

bending, and long-term stability. Interestingly, strategies such as oxidation, alkalization, thickness control, and defect engineering further optimized the active sites, enabling highly sensitive, flexible, and wearable NH₃ gas-sensing platforms at room temperature. Developments in Ti₃C₂T_x MXene-based composites for room-temperature NH₃ gas sensing are presented in Table 2.

Table 2. Room-temperature NH₃ gas-sensing ability of Ti₃C₂ MXene-based nanostructures.

Composite	Working Temperature	Response/Recovery Time (s)	Response (%)	Gas Concentration /LOD (ppm)	Gas Sensing Equation	Stability (Cycles)/Long-term Stability (Days)	Reference
<i>Ti₃C₂ MXene based composites for NH₃ sensing</i>							
<i>Pure Ti₃C₂-MXene</i>							
Ti ₃ C ₂ T _x	Room temperature	—	1.22	1/—	$ R_g - R_a /R_a \times 100$	5 at 100 ppm	[31]
Ti ₃ C ₂ T _x /Ti ₃ AlC ₂	Room temperature	12/60	11	200/50 ppb	$ R_g - R_a /R_a \times 100$	—/120	[32]
Ti ₃ C ₂ T _x	Room temperature	—	0.67	100/—	$\Delta R/R_a \times 100$	6/—	[33]
<i>Metal ions intercalated Ti₃C₂ MXene</i>							
K ⁺ , Na ⁺ , Ca ²⁺ and Mg ²⁺ cations intercalated Ti ₃ C ₂ T _x MXene	Room temperature	—	0.36	100/10	$\Delta R/R_0 \times 100$	—	[34]
<i>Alkalized Ti₃C₂ MXene</i>							
NaOH alkalized Ti ₃ C ₂ T _x	Room temperature	73/38 (200 ppm)	100.3	500/5	$ R_g - R_a /R_a \times 100$	5/17	[36]
KOH alkalized Ti ₃ C ₂ T _x	Room temperature	170/— at 100 ppm	35.7	200/	—	8/50	[37]
<i>Partially alkalized Ti₃C₂ MXene</i>							
Partially oxidized Ti ₃ C ₂ T _x	Room temperature	67/157	21.3	10/—	$\Delta R/R_g$	4/21 at 500 ppm	[38]
<i>Ti₃C₂ MXene/sulfur</i>							
Ti ₃ C ₂ @Sulfur	Room temperature	5/4	375	3 ppt/—	—	5/20	[39]
<i>Ti₃C₂ MXene/Graphene</i>							
Ti ₃ C ₂ T _x MXene/graphene	Room temperature	—	7.21	100/10	$\Delta R/R_0$	2000 (bending)	[40]
Ti ₃ C ₂ T _x /graphene	Room temperature	26/148	25.5	100/0.5	$r_m - r_g/r_g \times 100$	3/16	[41]
<i>Ti₃C₂ MXene/semiconductors</i>							
Ti ₃ C ₂ T _x /SnO ₂	Room temperature	36/44	40 at 46% RH	50/4.29 ppb	$ R_a - R_g /R_a \times 100$	5 at 30 ppm/60 at 50 ppm	[42]
Ti ₃ C ₂ T _x /SnO	Room temperature	61/119	7.8	200/1	R_a/R_g	4/22	[43]
In ₂ O ₃ /Ti ₃ C ₂ T _x	Room temperature	3/2	60.6	5/—	$ R_a - R_g /R_a \times 100$	3/30	[44]
NiO/Ti ₃ C ₂ T _x	Room temperature	60/19	6.13	50/10	$ R_g - R_a /R_a \times 100$	15/15	[46]

ZnO@Ti ₃ C ₂ T _x	Room temperature	92/104	39.16	20/89.1 ppb	$ R_a - R_g /R_a \times 100$	10/—	[47]
Ti ₃ C ₂ T _x /MoS ₂ /PPy	Room temperature	43.6/40.8	23.1	10/—	$ R_g - R_a /R_a \times 100$	5/7	[48]
Bi ₂ O ₃ /Ti ₃ C ₂ T _x	Room temperature	61/164	61	100/5	$ R_g - R_a /R_a \times 100$	6/20	[49]
Ti ₃ C ₂ T _x /GO/CuO/ZnO	Room temperature	26/25	96.3	200/4.1	$ R_a - R_g /R_a \times 100$	6/45	[50]
<i>Ti₃C₂ MXene/Ag and Au metals</i>							
Ag-loaded Ti ₃ C ₂ T _x	Room temperature	511/605	4.96	10/0.5	$ R_g - R_a /R_a \times 100$	—/30	[51]
Au/Ti ₃ C ₂ T _x	Room temperature	87/217	16	100/—	$ R_g - R_a /R_a \times 100$	6/—	[52]
<i>Ti₃C₂ MXene/polymers</i>							
PEDOT:PSS/nitrogen doped Ti ₃ C ₂ T _x	Room temperature	280/393.6	13 at 36% RH	10/—	$ R_g - R_0 /R_0 \times 100$	4/17	[53]
PVDF-ZIF-67/Ti ₃ C ₂ T _x	Room temperature	37.8/34.5	10.56	5/(9 ppt and 1 ppb)	$ R_g - R_a /R_a \times 100$	5/35	[54]
PANI/Ti ₃ C ₂ T _x	Room temperature	—	55.90	20/5	$ R_g - R_a /R_a \times 100$	6/21	[55]
<i>Ti₃C₂ MXene/metal hydroxides</i>							
Ni(OH) ₂ /Ti ₃ C ₂ T _x	Room temperature	78/108 s	13.69	80/1	$ R_g - R_a /R_a \times 100$	5/30 at 50 ppm	[56]
Co(OH) ₂ /Ti ₃ C ₂ T _x	Room temperature	39/49	14.7	100/5	$ R_a - R_g /R_a \times 100$	5/30	[57]
<i>Ti₃C₂ MXene/MOFs</i>							
Ni ₃ (HITP) ₂ /Ti ₃ C ₂	Room temperature	9/13	33	30/0.1	$ R - R_0 /R_0$	5/50	[58]
<i>Ti₃C₂ MXene/single atoms</i>							
ME-Ni-N-C/Ti ₃ C ₂ T _x	Room temperature	30/80 s	33.2	5/27.0 ppb	$ R_a - R_g /R_a \times 100$	5/24	[59]
<i>Ti₃C₂ MXene/cationic polyacrylamide</i>							
CPAM/Ti ₃ C ₂ T _x	Room temperature	12.7/14.6	3.1	150	$(I_g - I_0)/I_0$	2 at 200 ppm/10	[60]

5. Stability of Ti₃C₂ MXene-Based Composites Under Humid Conditions

Achieving a stable composite with rapid adsorption/desorption kinetics for target molecules is highly desirable for practical detection of toxic gas at room temperature. The unique advantages of Ti₃C₂ MXene, including its layer structure, tunable surface termination groups, and excellent electrical conductivity have significantly progressed the use of Ti₃C₂ MXene-based composites for NH₃ gas sensing across a range of ppm to ppt levels. More importantly, these composites have demonstrated reliable room-temperature NH₃ sensing performance under harsh environmental conditions, particularly in humid atmospheres. The coordination of Ni(OH)₂/Ti₃C₂T_x composite exhibited enhanced NH₃ responses of 5.1 and 6.2% at 10 ppm under humidity levels of 40 and 60%, respectively [56]. Similarly, a Ti₃C₂T_x/SnO₂ composite achieved room-temperature NH₃ response of 40% towards 50 ppm NH₃ at 46% relative humidity with response and recovery times of 36 and 44 s, respectively [42]. Furthermore, a p-n heterojunction-based MOFs-derived In₂O₃/Ti₃C₂T_x MXene composite demonstrated an unaltered NH₃ response of 60.6% with ultra-fast response/recovery times of 5/3 s [44]. Additionally, Ag nanoparticle-decorated

oxygen-rich $\text{Ti}_3\text{C}_2\text{T}_x$ MXene maintained long-term NH_3 sensing stability over 30 days even under 40% relative humidity conditions [51]. A p-type $\text{Ti}_3\text{C}_2\text{T}_x$ /graphene composite achieved NH_3 response of 24.9% under an elevated humidity level of 80% [41]. Interestingly, alkalization treatment of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene improved the response/recovery characteristics, achieving 73/38 s at 200 ppm NH_3 under 40% relative humidity [36]. Compared with pristine $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, the alkalized samples exhibited excellent cyclic stability over five sensing cycles and long-term stability for 17 days without significant response degradation. Furthermore, a Ti_3C_2 MXene@sulfur composite demonstrated stable NH_3 sensing performance over a broad humidity range of 20–70% with ultrafast response and recovery times of 5 and 4 s, respectively [39]. Meanwhile, Ti_3C_2 MXene-based sensors demonstrated lower responses towards ethanol (0.7–5.4%), NO_2 (1.2–5.4%), CO_2 (1.5%), H_2 (3.7%), IPA (0.53%), and NO (2.4%) compared to NH_3 response behavior. These results confirm the excellent selectivity and durability of Ti_3C_2 MXene-based composites for reliable NH_3 detection at room temperature. These advancements in the NH_3 gas-sensing abilities of Ti_3C_2 MXene-based composites are summarized in Figure 8.

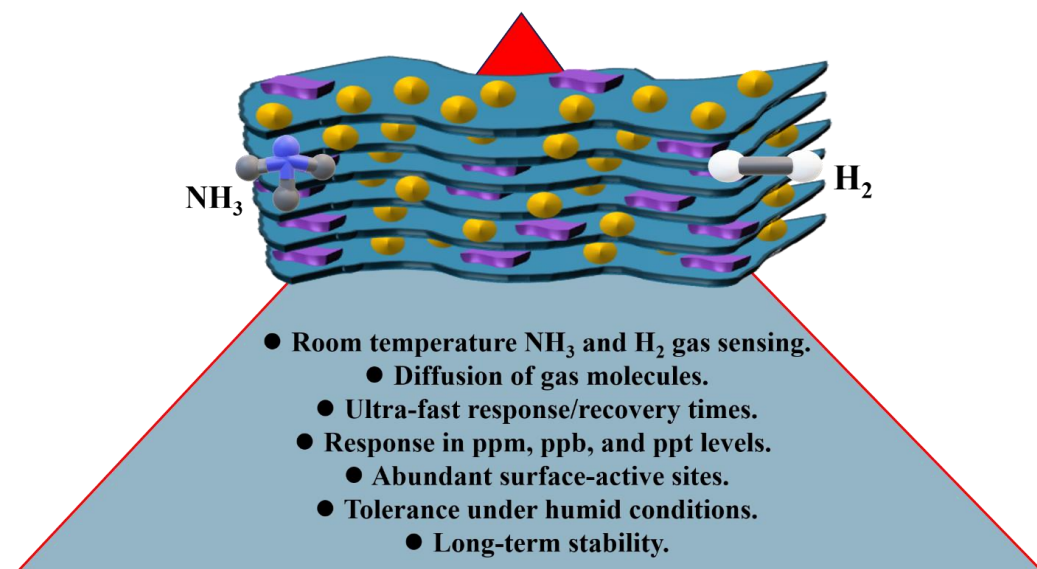


Figure 8. Key features contributing to the enhanced room-temperature NH_3 and H_2 gas-sensing performance of $\text{Ti}_3\text{C}_2\text{MXene}$ -based nanostructures.

6. Conclusions

The incorporation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene into various nanostructured interfaces has successfully contributed to room-temperature NH_3 and H_2 gas-sensing applications. The intrinsic properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, including high electrical conductivity (facilitating charge transfer), surface termination groups (promoting hydrogen bonding and molecular interaction), and layered architecture (enhancing gas diffusion), play crucial roles in improving sensing performance at room temperature. The structural and chemical features have enabled development of robust gas sensors with high sensitivity ranging from ppm to ppt concentrations and ultrafast response characteristics. As a proof of concept, Ti_3C_2 MXene@sulfur nanosheets achieved exceptional response/recovery times of 5/4 s under ppt-level of NH_3 [39]. Moreover, the Ti_3C_2 MXene-based composites maintained stable sensing performance under humid environments and exhibited long-term stability exceeding 50 days. For practical H_2 leak detection, the integration of Ti_3C_2 MXene-based sensors with an alarm circuit and LED indicator was successfully demonstrated, where the LED was activated upon exposure to 4% H_2 gas [21]. Additionally, flexible $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/graphene hybrid fibers woven into laboratory coats have demonstrated the

potential for wearable room-temperature NH_3 sensing applications [40]. Overall, the synergistic coupling of 2D Ti_3C_2 MXene with diverse semiconductor nanostructures has significantly enhanced the selectivity and sensing capability of H_2 and NH_3 gas sensors at room temperature.

7. Future Perspectives

Although $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-based composites have demonstrated outstanding room-temperature H_2 and NH_3 -sensing performance, the following key strategies can further strengthen their H_2 and NH_3 -sensing capabilities.

1. The anchoring of isolated single metal atoms onto Ti_3C_2 MXene surfaces can accelerate gas molecule dissociation and activation through tunable adsorption energies. Highly dispersed metallic centers act as adsorption intermediates, which modify electrical properties through enhanced electron transfer and improved sensitivity.

2. Controlled engineering of selective surface termination groups can promote selective gas adsorption and facilitate charge transfer between gas molecules and sensing materials to improve sensing performance.

3. Advanced in situ characterization techniques, including in-situ X-ray absorption spectroscopy, Raman spectroscopy, and FTIR are essential for understanding gas adsorption mechanisms and identifying intermediate species formed during room-temperature gas sensing.

4. Theoretical investigations into Ti_3C_2 MXene-based H_2 and NH_3 gas sensors remain relatively limited. Therefore, comprehensive DFT studies are required in order to understand the adsorption behavior of gas molecules on different surface terminations, including $-\text{OH}$, $-\text{O}$, and $-\text{F}$ -functionalized Ti_3C_2 MXenes.

5. Further modification of the Ti_3C_2 MXene structure (into a monolayer or few layers) can enable ultrafast response and recovery kinetics for ppb-level detection through improved gas adsorption, charge trapping, and charge transport mechanisms. Also, intercalation of various nanostructures between Ti_3C_2 MXene nanosheets expands the interlayer spacing and increases the accessible surface area, thereby enhancing the gas-sensing performance.

Overall, Ti_3C_2 MXene-based composites provide a promising platform for advancing room-temperature H_2 and NH_3 gas sensing from ppm to ppb detection regimes.

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