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Research status of gas sensing performance of Ti_3C_2Tx-based gas sensors: A mini review

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Developing efficient gas sensing materials capable of sensitive, fast, stable, and selective detection is a requisite in the field of indoor gas environment monitoring. In recent years, metal carbides/nitrides (MXenes) have attracted attention in the field of gas sensing because of their high specific surface area, good electrical conductivity, and high hydrophilicity. Ti_3C_2Tx, the first synthesised MXene material, has also become the most popular MXene material owing to its low formation energy. In this paper, the latest progress in the application of Ti_3C_2Tx-based nanomaterials in the field of gas sensors is reviewed. Some challenges currently faced by Ti_3C_2Tx gas sensors are discussed, and possible solutions are proposed, focusing on the use of composite materials and surface functionalization methods to modify Ti_3C_2Tx nanomaterials to improve their sensing performance for the detection of gaseous volatile organic compounds. This study highlights the application prospects of Ti_3C_2Tx nanomaterials in gas sensors.

KEYWORDS

Ti_3C_2Tx, volatile organic compounds (VOCs) gases, composite materials, surface functionalization, sensing performance

Introduction

In recent years, with the acceleration of urbanization, the content of volatile organic compounds (VOCs) such as toluene (C_7H_8), formaldehyde (HCHO), ethanol (C_2H_5OH), and acetone (C_3H_6O) in the air has risen rapidly. Subsidence to form ground-level ozone endangers human health (Malakar et al., 2017; Maung et al., 2022; Mozaffar et al., 2020; Yue et al., 2021); the effects and exposure limits are presented in Table 1. Therefore, all sectors of society have focused on the use of gas sensors to monitor toxic and harmful gases in indoor and outdoor environments, where gas monitoring is widely adopted in industrial manufacturing and disease diagnosis (Chaudhary et al., 2022; Chen et al., 2020a; Wang et al., 2022a). Researchers have combined metal oxides (Hu et al., 2021; Peng et al., 2022), transition metal dichalcogenides (TMDs) (Sun et al., 2022; Xin et al., 2019), carbon-based materials (Liu et al., 2021), and some emerging two-dimensional (2D) materials for application in gas sensors to develop a series of sensitive and detection-selective gas sensors. However, although gas sensor materials such as metal oxides and conductive polymers possess good electrochemical performance and gas sensitivity, their

TABLE 1 Effects of various VOCs on humans.

Harmful gases	Major sources	Harm to human	Lowest exposure range for human
C_7H_8	cigarette, paint	Headache, vomiting, confusion	300 ppm
HCHO	volcanic gases, pesticides, paints, furniture	Blurred vision, vertigo	0.1 mg/m^3
C_2H_5OH	industries	Paralysis of the nervous system, damage to the brain	3,300 ppm
C_3H_6O	petroleum refining, vehicle emissions	Difficulty breathing, corroded eyes	750 ppm for 15 min and 500 ppm for 8 h
CH_3OH	Industrial workshop, Food processing plant	Affect the nervous system and blood system of human body	50 mg/m^3
C_4H_{10}	Petroleum gas, natural gas and cracked gas	dizziness, headache, lethargy,coma	300 mg/m^3
$C_6H_{15}N$	Dyestuff, preservative, solvent	Cause pulmonary edema and even death	0.14 mg/m^3

working environment (200°C) is demanding, which exposes the defects of high power consumption and difficult application.

As a new material that was discovered only in 2011 (Naguib et al., 2011), MXene has a great potential in the sensor field owing to its unique morphology and good electrochemical properties (Zhang et al., 2018). Similar to graphene, MXene is a novel 2D-layered material composed of transition metal carbides/nitrides (Chaudhary et al., 2022). The transition metal carbide Ti_3C_2Tx, the first MXene material synthesised by etching from the MAX phase, has also become the most popular MXene material because of its relatively low formation energy (Naguib et al., 2011).

Ti_3C_2Tx has a higher specific surface area, and the contact surface with the air is larger under the same mass condition, which helps to improve the performance of the sensor (Li et al., 2021). Some experiments have demonstrated the feasibility of Ti_3C_2Tx in gas sensing (Koh et al., 2019; Lee et al., 2017). In this case, Ti_3C_2Tx is expected to prepare efficient and reliable gas sensors at room temperature. However, scholars have also found that traditional Ti_3C_2Tx materials possess a large number of -F, -OH or -O terminal groups, which make them degrade rapidly in a humid environment. This also exposes the problems of slow response, slow recovery, easy oxidation and poor stability of Ti_3C_2Tx sensors under wet conditions (Chae et al., 2019), which is also a huge challenge for Ti_3C_2Tx gas sensors at this stage.

Many review articles on Ti_3C_2Tx materials have been published, where the main focus has been the fields of biomedicine and photocatalysis. The application of Ti_3C_2Tx in gas sensors has not received much attention; in particular, the literature on the detection of VOCs gas remains very limited. In this review, the efficacy of different methods for improving the performance of sensors based on Ti_3C_2Tx materials is analysed, and the mechanisms are discussed. This study provides guidance for developing more efficient Ti_3C_2Tx-based sensors.

Pristine Ti_3C_2Tx

In 2017, Lee et al. (2017) first cast Ti_3C_2Tx on a flexible polyimide platform by solid-solution casting and applied Ti_3C_2Tx in the field of gas sensors, as shown in Figure 1A. The concentrations of ethanol, methanol, ammonia, and acetone were measured at room temperature. The efficacy for ammonia sensing was significantly higher than for the other VOCs. This is because the surface of Ti_3C_2Tx has abundant functional groups (Figure 1B) that react violently with ammonia gas to increase the resistance change by up to 20%, thus improving the sensing performance. Many factors affect the gas sensing performance of pristine Ti_3C_2Tx sensors, such as the film thickness (Kim et al., 2019), MAX phase precursor (Shuck et al., 2019), and oxidation degree (Huang Mochalin, 2020). However, despite optimization of these factors, it is difficult to efficiently and stably detect various VOC gases by relying on pure Ti_3C_2Tx. Therefore, compounding Ti_3C_2Tx with other materials and functionalizing Ti_3C_2Tx to improve the gas-sensing performance and selectivity of Ti_3C_2Tx sensors for VOC gases has also attracted increasing attention.

Ti_3C_2Tx composites

To improve the sensing performance of Ti_3C_2Tx for VOCs gases, the combination of Ti_3C_2Tx with other materials has attracted much attention. Ti_3C_2Tx has been combined with various types of materials, such as metal oxides, graphene, and polymers, as shown in Table 2.

Ti_3C_2Tx/metal oxide gas sensors

Metal oxides are sensitive and selective and can be used to prepare composite materials with high gas-sensing properties. The improved performance plausibly originates from the PN junction or PP junction formed by the combination of two different materials, Ti_3C_2Tx and a metal oxide. Many studies have been conducted on composites of Ti_3C_2Tx with metal oxides (Fe_2O_3, Co_3O_4, $ZnSnO_3$, Cu_2O, In_2O_3, and $W_{18}O_{49}$) for detecting VOCs.

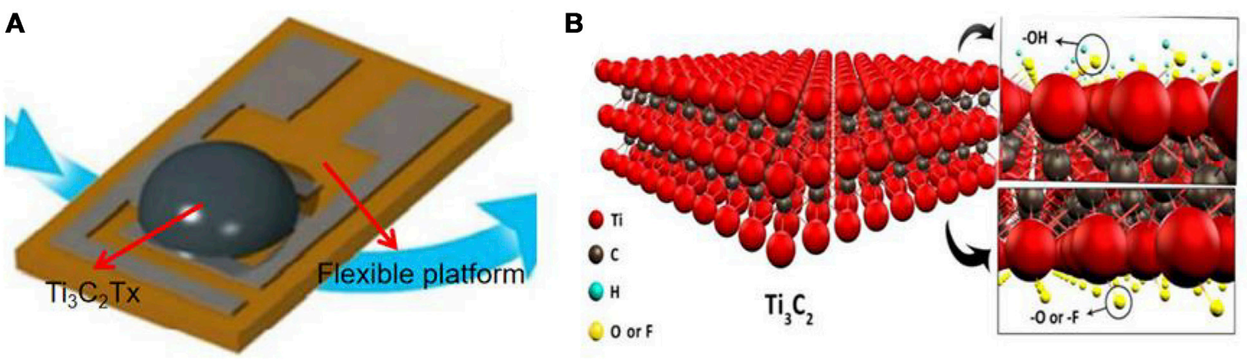

FIGURE 1
(A) Solid solution pouring method to prepare the sensor.**(B)** Ti3C2Tx structure and surface functional groups (adapted from Lee et al., 2017).

TABLE 2 Gas sensing performances of Ti3C2Tx-based gas sensors.

Ti_3C_2Tx composites	VOCs gas	Conc. (ppm)	Operating Temo(°C)	Response (%)	Response/Recovery time (s/s)	References
$ZnSnO_3/Ti_3C_2Tx$	HCHO	100	RT	194.7	6.2/5.1	Sima et al. (2022)
Ti_3C_2Tx/Co_3O_4	HCHO	10	RT	9.2	83/5	Zhang et al. (2021)
$rGO/N\text{-}Ti_3C_2Tx/TiO_2$	HCHO	20	RT	132	N/A	Wang et al. (2020)
$Ti_3C_2Tx/SnO\text{-}SnO_2$	C_3H_6O	100	RT	12.1	18/9	Wang et al. (2021)
$Ti_3C_2Tx/W_{18}O_{49}$	C_3H_6O	0.17	300	1.4	5.6/6	Sun et al. (2020)
$Ti_3C_2Tx/rGO/CuO$	C_3H_6O	100	RT	52.09	6.5/7.5	Liu et al. (2021a)
$\alpha\text{-}/\gamma\text{-}Fe_2O_3/ex\text{-}Ti_3C_2Tx$	C_3H_6O	100	255	215.2	13/8	Huang et al. (2022)
Ti_3C_2Tx/WSe_2	C_2H_5OH	40	RT	24	9.7/6.6	Chen et al. (2020a)
Ti_3C_2Tx/SnO_2	C_2H_5OH	10	230	5	14/26	Wang et al. (2022b)
Ti_3C_2Tx/Co_3O_4	C_2H_5OH	50	RT	190	50/45	Bu et al. (2022)
Ti_3C_2Tx/polyaniline	C_2H_5OH	200	RT	41.1	0.4/0.5	Zhao et al. (2019)
Ti_3C_2Tx/SnO_2	$C_6H_{15}N$	50	140	33.9	N/A	Liang et al. (2022)
Ti_3C_2Tx/Cu_2O	$C_6H_{15}N$	10	RT	181.6	1,062/74	Zhou et al. (2022)
Ti_3C_2Tx/In_2O_3	CH_3OH	5	RT	29.6	6.5/3.5	Liu et al. (2021b)
$S\text{-}Ti_3C_2Tx$	C_7H_8	10	RT	59.1	N/A	Shuvo et al. (2020)
$Ti_3C_2Tx/Fe_2\ (MoO_4)_3$	C_4H_{10}	100	RT	43.1	18/24	Zou et al. (2020)

Huang et al. uniformly deposited porous bi-phasic α-/γ-Fe_2O_3 nanoparticles on the surface and interlayer of Ti_3C_2Tx by solvothermal and high-temperature calcination and synthesised a stable α-/γ-Fe_2O_3/ex-Ti_3C_2Tx-X gas sensor material for acetone detection. The composite gas sensor had a good response to acetone (the response value was 215.2 for 100 ppm acetone at 255°C, and the response and recovery time were 13 and 8 s, respectively). The improved performance originates from the large number of empty cationic sites on the α-/γ-Fe_2O_3 surface, which can serve as strong adsorption sites for acetone. The α-/γ-Fe_2O_3/ex-Ti_3C_2Tx-X composites possess more surface defects, functional groups, porosity, and heterojunction interfaces than conventional Ti_3C_2Tx, which facilitates the interaction of acetone molecules with the active sites (Huang et al., 2022).

Composites of semiconductor metal oxides and Ti_3C_2Tx materials have also attracted much attention. (2022) successfully synthesised p-type semiconductor materials by combining Co_3O_4 and Ti_3C_2Tx, where Co_3O_4 was intercalated into the interlayer structure of Ti_3C_2Tx to form numerous hybrid heterojunctions. Intercalation significantly increased the specific surface area and gas adsorption sites of the material, thereby improving the gas-sensing performance. Zhang et al. (2021) also found that the ability of Ti_3C_2Tx/Co_3O_4 composite to respond and recover also improved with the increase of bending angle, which is of great significance for the study of flexible wearable sensors that can monitor human health in real time. Using facile electrostatic self-assembly and hydrothermal synthesis, Sima et al. (2022) successfully prepared $ZnSnO_3/Ti_3C_2Tx$ composites, which exhibited good gas-sensing properties for the detection of formaldehyde, because the ohmic contact between $ZnSnO_3$ and Ti_3C_2Tx formed a small Teky barrier, and the work function between Ti_3C_2Tx and -OH (3.9 eV) was lower than that of $ZnSnO_3$ (5.17 eV). According to the principle of Fermi level balance, a large number of electrons is transferred between the $ZnSnO_3$ nanotubes and Ti_3C_2Tx to reach a relatively balanced state. More electrons will be adsorbed by oxygen on the surface of the $ZnSnO_3$ nanoparticles, resulting in thickening of the electron depletion layer; thus, the resistance change will also increase, and the sensitivity of the sensor will also increase as the resistance change becomes more pronounced. Furthermore, the faster response and recovery are due to the synergistic effect between the two materials, which accelerates the separation rate of hole–electron pairs.

Ti_3C_2Tx/rGO gas sensors

Graphene and $Ti_3C_2T_x$ are both emerging two-dimensional materials with similar structures. Combining these two materials can enhance their properties through synergy. Liu et al. (2021a) fabricated a $Ti_3C_2T_x$/rGO/CuO three-dimensional aerogel sensor material by using a one-step hydrothermal method. The material showed good acetone-sensing performance (the response value to 100 ppm acetone at room temperature was 52.09, and the response and recovery times were 6.5 and 7.5 s, respectively) and stability. The good response is mainly because the 3D porous network structure of $Ti_3C_2T_x$/rGO/CuO prevents stacking of the composites, which exposes a larger surface area and provides more adsorption sites for O_2 and acetone gas. As a second factor, acetone-sensing is related to the p-p junction formed at the interface owing to the different work functions of the three materials. In addition, the large number of functional groups on the surface of $Ti_3C_2T_x$ form strong hydrogen bonds with acetone gas, the interaction force between the composite material and acetone molecules is enhanced, and the hole concentration is increased, leading to improved gas-sensing performance.

Ti_3C_2Tx/polymer gas sensors

Conductive polymers are low-cost with excellent electrical conductivity and are considered potential gas sensing materials. Polyaniline (PANI) is extensively used in polymer gas sensors, where the material itself and its mixtures show excellent NH3 gas sensing performance. At present, Zhao et al. are the only ones that have prepared Ti_3C_2Tx/polymer composites by low-temperature *in situ* polymerisation. They found that the composites have good gas sensitivity to gaseous ethanol as a VOC (response rate to 200 ppm ethanol gas at room temperature is 41.1, with response and recovery times of 0.4 and 0.5 s, respectively). The incorporation of PANI effectively inhibited the interlayer aggregation of Ti_3C_2Tx, thereby exposing a larger surface area and more functional groups (–O, –OH, and–F groups), all of which increased the resistance of the composite when exposed to ethanol. Thus, the gas-sensing performance can be improved by improving the gas adsorption ability (Zhao et al., 2019).

Functionalized Ti_3C_2Tx

In addition to compounding with other materials, methods of functionalizing Ti_3C_2Tx materials using single-atom functionalization and surface treatments are attracting increasing attention.

As shown in Figure 2A, Zong et al. modified the surface of Ti_3C_2Tx with single-atom Pt (Pt SA); the resulting sensor could detect triethylamine (TEA) at levels as low as 14 ppb. The highly catalytically active and uniformly distributed Pt SA had a chemical sensitisation effect, and the excellent adsorption of Pt SA on TEA was the main reason for the improved gas-sensing performance of the sensor. Furthermore, as shown in Figure 2B, the Pt-Ti_3C_2Tx sensor exhibited good stability in the detection of various VOC gases at room temperature. Based on density functional theory, it was proven that metal single-atom catalyst doping can improve charge transfer in VOC gases during the adsorption process in a pioneering study on the application of metal single-atom catalysts in the field of MXene nanosheet sensors (Zong et al., 2022).

Ti_3C_2Tx sensors are unstable in humid environments. To solve this problem, Chen et al. (2020b) embedded fluoroalkyl silane (FOTS) on the surface of Ti_3C_2Tx to reduce its surface energy and achieve hydrophobic effects. Ti_3C_2Tx-F exhibited good hydration stability, good tolerance in acid/base solutions, and Ti_3C_2Tx-F detects 120 ppm ethanol gas at room temperature, showing good repeatability and fast response/recovery speed (39 s/139 s). As shown in Figure 2C, the interlayer distance of the functionalized Ti_3C_2Tx is larger, which can adsorb more VOCs molecules. And it is also found that the Ti-O bond length increases from 2.26 Å to 2.57 Å due to the attractive force between the oxygen and the hydrogen atoms of the ethanol, causing the adjacent oxygen atoms of the ethanol molecule to pull outward from the layer. This indicates that the gas sensing performance of Ti_3C_2Tx-F material will be enhanced with the adsorption of ethanol molecules. In addition, the Ti_3C_2Tx-F sensor can still monitor ethanol gas well in an environment with a relative humidity of 80%. This also puts

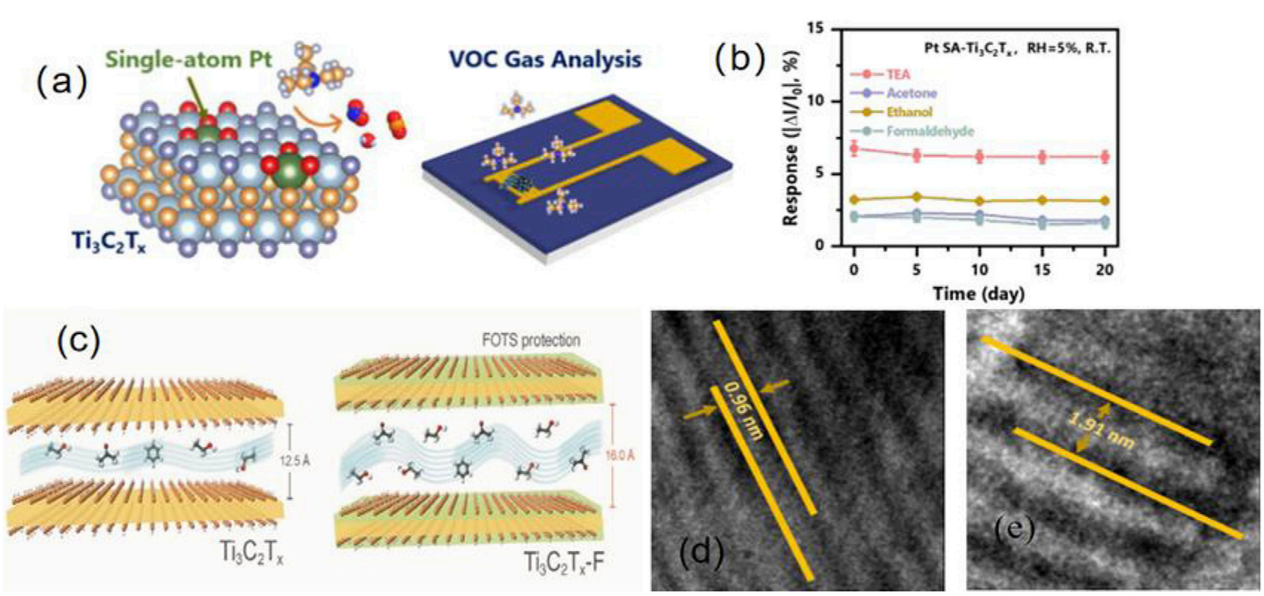

FIGURE 2
(A) Modified Pt atoms into sensors prepared in Ti3C2Tx. **(B)** Response rate of Pt-Ti3C2Tx sensors to various VOCs gases at room temperature for 20 consecutive days (adapted from Zong et al., 2022). **(C)** Interlayer distance between Ti3C2Tx materials before and after incorporation into FOTS. (adapted from Chen et al., 2020a) **(D–E)** Interlayer spacing of Ti3C2Tx materials before and after incorporation of S elements was observed under TEM (adapted from Shuvo et al., 2020).

forward a new idea to solve the shortcomings of Ti_3C_2Tx sensor, which is easy to oxidize and has poor stability in humid environment.

Shuvo et al. uniformly doped S atoms into the surface and interlayers of $Ti_3C_2T_x$, where the responses to toluene at 1 and 50 ppm were 214% and 312%, respectively, which were 2–3 times the response of conventional $Ti_3C_2T_x$. The TEM images in Figures 2D,E show that, after the incorporation of S atoms, the interlayer distance of the sensor material expanded significantly, thereby improving the gas sensing performance of the sensor. Furthermore, the S-$Ti_3C_2T_x$ sensor remained stable after 30 days of continuous exposure and exhibited good repeatability over 10 consecutive cycles (Shuvo et al., 2020).

Modification mechanism

In summary, the composite and functional methods are used to improve the gas-sensing performance of Ti_3C_2Tx sensor materials to VOCs gas. It is not difficult to find that although the methods are different, the modification mechanism is roughly the same. After summarizing, the author found that the modification mechanism is mainly as follows: ① Inhibiting the aggregation of Ti_3C_2Tx materials resulting in obtaining more surface area and more abundant functional groups; ② Improving the interaction force between the sensor material and gas molecules, and so accelerating the air The separation rate of the hole-electron pair; ③ increasing the thickness of the electron depletion layer, causing the larger channel for electron flow and thereby improving the sensitivity of the resistance change; ④ compounding with the n-type material to form a non-uniform p-n junction, making the two materials with different work functions connect together (since the Fermi level needs to be kept at the same level, electron transfer will occur between them, thereby a built-in electric field and a Schottky barrier will be formed). ⑤ Introducing other atoms to improve the charge transfer during the adsorption process. All of these reasons can effectively improve the sensing performance of the sensor, which also provides ideas for the discovery of new sensor materials in the future.

Conclusion

The research status of gas sensors based on Ti_3C_2Tx in recent years was reviewed, demonstrating that the modification of Ti_3C_2Tx by compounding with other materials, surface modification, and single-atom doping can effectively improve the gas-sensing performance of Ti_3C_2Tx-based gas sensors. Combining other materials into the surface and interlayer structure of Ti_3C_2Tx can increase the interlayer spacing of the structure to expose a larger specific surface area, provide more active sites for target gas molecules, enhance the adsorption capacity of the sensor, and improve the sensitivity. Using density functional theory, it has been proven that metal single-atom catalyst doping can improve charge transfer in VOC gases during the adsorption process, which provides insight for developing high-performance Ti_3C_2Tx-based gas sensors. We hope that our work will provide guidance for the development of new Ti_3C_2Tx-based gas-sensor materials in the future.

Author contributions

BP conceived and designed the experiment. BP analyzed the data. BP and XH wrote the manuscript with input from all authors. All authors read and approved the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Bu, X. R., Ma, F., Wu, Q., Wu, H. Y., Yuan, Y. B., Hu, L., et al. (2022). Metal-organic frameworks-derived Co3O4/Ti3C2Tx Mxene nanocomposites for high performance ethanol sensing. *Sensors Actuators B Chem.* 369, 132232. doi:10.1016/j.snb.2022.132232

Chae, Y., Kim, S. J., Cho, S. Y., Choi, J., Maleski, K., Lee, B. J., et al. (2019). An investigation into the factors governing the oxidation of two-dimensional Ti3C2 MXene. *NANOSCALE* 11 (17), 8387–8393. doi:10.1039/c9nr00084d

Chaudhary, V., Ashraf, N., Khalid, M., Walvekar, R., Yang, Y., Kaushik, A., et al. (2022). Emergence of MXene–polymer hybrid nanocomposites as high-performance next-generation chemiresistors for efficient air quality monitoring. *Adv. Funct. Mat.* 32 (33), 2112913. doi:10.1002/adfm.202112913

Chen, W. Y., Jiang, X., Lai, S.-N., Peroulis, D., and Stanciu, L. (2020a). Nanohybrids of a MXene and transition metal dichalcogenide for selective detection of volatile organic compounds. *Nat. Commun.* 11 (1), 1302. doi:10.1038/s41467-020-15092-4

Chen, W. Y., Lai, S. N., Yen, C. C., Jiang, X., Peroulis, D., and Stanciu, L. A. (2020b). Surface functionalization of $Ti_3C_2T_x$ MXene with highly reliable superhydrophobic protection for volatile organic compounds sensing. *ACS Nano* 14 (9), 11490–11501. doi:10.1021/acsnano.0c03896

Hu, J., Chen, X., and Zhang, Y. (2021). Batch fabrication of formaldehyde sensors based on LaFeO3 thin film with ppb-level detection limit. *Sensors Actuators B Chem.* 349, 130738. doi:10.1016/j.snb.2021.130738

Huang, D., Li, H., Wang, Y., Wang, X., Cai, L., Fan, W., et al. (2022). Assembling a high-performance acetone sensor based on MOFs-derived porous bi-phase α-/γ-Fe2O3 nanoparticles combined with Ti3C2Tx nanosheets. *Chem. Eng. J.* 428, 131377. doi:10.1016/j.cej.2021.131377

Huang, S., and Mochalin, V. N. (2020). Understanding Chemistry of two-dimensional transition metal carbides and carbonitrides (MXenes) with gas analysis. *ACS Nano* 14 (8), 10251–10257. doi:10.1021/acsnano.0c03602

Kim, S. J., Choi, J., Maleski, K., Hantanasirisakul, K., Jung, H.-T., Gogotsi, Y., et al. (2019). Interfacial assembly of ultrathin, functional MXene films. *ACS Appl. Mat. Interfaces* 11 (35), 32320–32327. doi:10.1021/acsami.9b12539

Koh, H.-J., Kim, S. J., Maleski, K., Cho, S.-Y., Kim, Y.-J., Ahn, C. W., et al. (2019). Enhanced selectivity of MXene gas sensors through metal ion intercalation: *In situ* X-ray diffraction study. *ACS Sens.* 4 (5), 1365–1372. doi:10.1021/acssensors.9b00310

Lee, E., VahidMohammadi, A., Prorok, B. C., Yoon, Y. S., Beidaghi, M., and Kim, D.-J. (2017). Room temperature gas sensing of two-dimensional titanium carbide (MXene). *ACS Appl. Mat. Interfaces* 9 (42), 37184–37190. doi:10.1021/acsami.7b11055

Li, Q., Li, Y., and Zeng, W. (2021). Preparation and application of 2D MXene-based gas sensors: A review. *Chemosensors* 9 (8), 225. doi:10.3390/chemosensors9080225

Liang, D., Song, P., Liu, M., and Wang, Q. (2022). 2D/2D SnO2 nanosheets/Ti3C2Tx MXene nanocomposites for detection of triethylamine at low temperature. *Ceram. Int.* 48 (7), 9059–9066. doi:10.1016/j.ceramint.2021.12.089

Liu, C., Hu, J., Wu, G., Cao, J., Zhang, Z., and Zhang, Y. (2021). Carbon nanotube-based field-effect transistor-type sensor with a sensing gate for ppb-level formaldehyde detection. *ACS Appl. Mat. Interfaces* 13 (47), 56309–56319. doi:10.1021/acsami.1c17044

Liu, M., Wang, Z., Song, P., Yang, Z., and Wang, Q. (2021a). Flexible MXene/rGO/CuO hybrid aerogels for high performance acetone sensing at room temperature. *Sensors Actuators B Chem.* 340, 129946. doi:10.1016/j.snb.2021.129946

Liu, M., Wang, Z., Song, P., Yang, Z., and Wang, Q. (2021b). In2O3 nanocubes/Ti3C2Tx MXene composites for enhanced methanol gas sensing properties at room temperature. *Ceram. Int.* 47 (16), 23028–23037. doi:10.1016/j.ceramint.2021.05.016

Malakar, S., Saha, P. D., Baskaran, D., and Rajamanickam, R. (2017). Comparative study of biofiltration process for treatment of VOCs emission from petroleum refinery wastewater-A review. *Environ. Technol. INNOVATION* 8, 441–461. doi:10.1016/j.eti.2017.09.007

Maung, T. Z., Bishop, J. E., Holt, E., Turner, A. M., and Pfrang, C. (2022). Indoor air pollution and the health of vulnerable groups: A systematic review focused on particulate matter (pm), volatile organic compounds (VOCs) and their effects on children and people with pre-existing lung disease. *Int. J. Environ. Res. Public Health* 19 (14), 8752. doi:10.3390/ijerph19148752

Mozaffar, A., and Zhang, Y. L. (2020). Atmospheric volatile organic compounds (VOCs) in China: A review. *Curr. Pollut. Rep.* 6 (3), 250–263. doi:10.1007/s40726-020-00149-1

Naguib, M., Kurtoglu, M., Presser, V., Lu, J., Niu, J. J., Heon, M., et al. (2011). Two-dimensional nanocrystals produced by exfoliation of Ti3AlC2. *Adv. Mat.* 23 (37), 4248–4253. doi:10.1002/adma.201102306

Peng, X., Liu, J., Tan, Y., Mo, R., and Zhang, Y. (2022). A CuO thin film type sensor via inkjet printing technology with high reproducibility for ppb-level formaldehyde detection. *Sensors Actuators B Chem.* 362, 131775. doi:10.1016/j.snb.2022.131775

Shuck, C. E., Han, M., Maleski, K., Hantanasirisakul, K., Kim, S. J., Choi, J., et al. (2019). Effect of Ti_3AlC_2 MAX phase on structure and properties of resultant $Ti_3C_2T_x$ MXene. *ACS Appl. Nano Mat.* 2 (6), 3368–3376. doi:10.1021/acsanm.9b00286

Shuvo, S. N., Ulloa Gomez, A. M., Mishra, A., Chen, W. Y., Dongare, A. M., and Stanciu, L. A. (2020). Sulfur-doped titanium carbide MXenes for room-temperature gas sensing. *ACS Sens.* 5 (9), 2915–2924. doi:10.1021/acssensors.0c01287

Sima, Z., Song, P., Ding, Y., Lu, Z., and Wang, Q. (2022). ZnSnO3 nanocubes/Ti3C2Tx MXene composites for enhanced formaldehyde gas sensing properties at room temperature. *Appl. Surf. Sci.* 598, 153861. doi:10.1016/j.apsusc.2022.153861

Sun, S., Wang, M., Chang, X., Jiang, Y., Zhang, D., Wang, D., et al. (2020). W18O49/Ti3C2Tx Mxene nanocomposites for highly sensitive acetone gas sensor with low detection limit. *Sensors Actuators B Chem.* 304, 127274. doi:10.1016/j.snb.2019.127274

Sun, Y., Hu, J. Y., and Zhang, Y. (2022). Visible light assisted trace gaseous NO2 sensor with anti-humidity ability via LSPR enhancement effect. *Sensors Actuators B Chem.* 367, 132032. doi:10.1016/j.snb.2022.132032

Wang, C., Li, R., Feng, L., and Xu, J. (2022a). The SnO2/MXene composite ethanol sensor based on MEMS platform. *Chemosensors* 10 (3), 109. doi:10.3390/chemosensors10030109

Wang, J., Yang, Y., and Xia, Y. (2022b). Mesoporous MXene/ZnO nanorod hybrids of high surface area for UV-activated NO2 gas sensing in ppb-level. *Sensors Actuators B Chem.* 353, 131087. doi:10.1016/j.snb.2021.131087

Wang, Y., Zhou, Y., and Wang, Y. (2020). Humidity activated ionic-conduction formaldehyde sensing of reduced graphene oxide decorated nitrogen-doped MXene/titanium dioxide composite film. *Sensors Actuators B Chem.* 323, 128695. doi:10.1016/j.snb.2020.128695

Wang, Z., Wang, F., Hermawan, A., Asakura, Y., Hasegawa, T., Kumagai, H., et al. (2021). SnO-SnO2 modified two-dimensional MXene Ti3C2T for acetone gas sensor working at room temperature. *J. Mater. Sci. Technol.* 73, 128–138. doi:10.1016/j.jmst.2020.07.040

Xin, X., Zhang, Y., Guan, X., Cao, J., Li, W., Long, X., et al. (2019). Enhanced performances of PbS quantum-dots-modified MoS2 composite for NO2 detection at room temperature. *ACS Appl. Mat. Interfaces* 11 (9), 9438–9447. doi:10.1021/acsami.8b20984

Yue, X. C., Ma, N. L., Sonne, C., Guan, R. R., Lam, S. S., Le, Q. V., et al. (2021). Mitigation of indoor air pollution: A review of recent advances in adsorption materials and catalytic oxidation. *J. Hazard. Mater.* 405, 124138. doi:10.1016/j.jhazmat.2020.124138

Zhang, D., Mi, Q., Wang, D., and Li, T. (2021). MXene/Co3O4 composite based formaldehyde sensor driven by ZnO/MXene nanowire arrays piezoelectric nanogenerator. *Sensors Actuators B Chem.* 339, 129923. doi:10.1016/j.snb.2021.129923

Zhang, Y. J., Wang, L., Zhang, N. N., and Zhou, Z. J. (2018). Adsorptive environmental applications of MXene nanomaterials: A review. *RSC Adv.* 8 (36), 19895–19905. doi:10.1039/c8ra03077d

Zhao, L., Wang, K., Wei, W., Wang, L., and Han, W. (2019). High-performance flexible sensing devices based on polyaniline/MXene nanocomposites. *InfoMat* 1 (3), 407–416. doi:10.1002/inf2.12032

Zhou, M., Yao, Y., Han, Y. T., Xie, L. L., and Zhu, Z. G. (2022). Cu2O/Ti3C2T (x) nanocomposites for detection of triethylamine gas at room temperature. *NANOTECHNOLOGY* 33 (41), 415501. doi:10.1088/1361-6528/ac7dec

Zong, B., Xu, Q., and Mao, S. (2022). Single-atom Pt-functionalized $Ti_3C_2T_x$ field-effect transistor for volatile organic compound gas detection. *ACS Sens.* 7 (7), 1874–1882. doi:10.1021/acssensors.2c00475

Zou, S., Gao, J., Liu, L., Lin, Z., Fu, P., Wang, S., et al. (2020). Enhanced gas sensing properties at low working temperature of iron molybdate/MXene composite. *J. Alloys Compd.* 817, 152785. doi:10.1016/j.jallcom.2019.152785