Catalysis Letters (2024) 154:1375–1384
https://doi.org/10.1007/s10562-023-04436-6

PERSPECTIVES

A Mini Review on the Recent Progress of MoS_2-Based Gas Sensors

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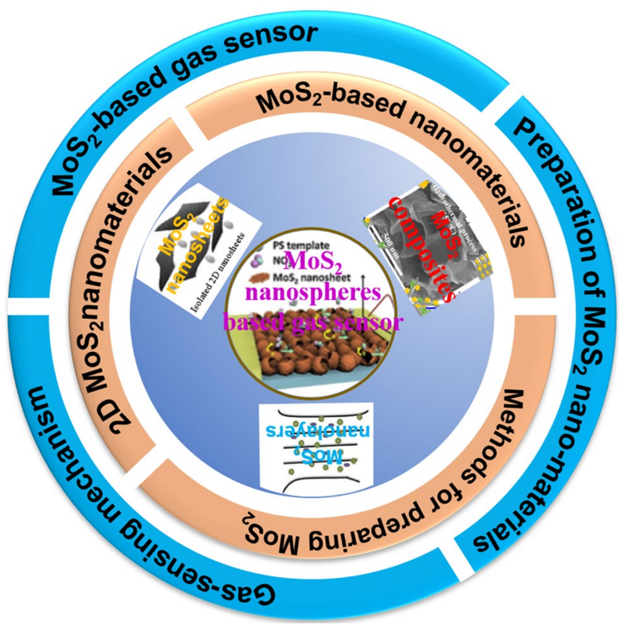
Received: 22 June 2023 / Accepted: 30 July 2023 / Published online: 28 August 2023

Abstract
Introducing nanomaterials in gas sensor applications has conspicuously improved the detection performance due to the unique nanostructures. Transition-metal dichalcogenides (TMDs) recently aroused widespread interest because of their ultrathin and layered two-dimensional nanosheet structures. The graphene-like MoS_2 has good electrical, chemical, mechanical, and optical properties, making it of great interest for developing gas sensors and an exceptionally promising building block for designing novel semiconducting nanomaterials. The content of this mini-review aspires to summarize the current progress on mono/few-layered MoS_2-based gas sensors and the influence of different components. Herein, we described the current progress on MoS_2-based gas sensors, which encompasses the preparation and application of MoS_2, and the potential improvement directions for future possibilities of expanding its applications.

Graphical Abstract



Keywords MoS_2 · TMDs · Gas sensor · Nanomaterial

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1 Introduction

The past decades' research shows that in addition to the composition and arrangement of atoms in materials, dimensionality also plays a crucial role in determining their fundamental properties. Since Professor A. K. Geim and his research team obtained monolayer graphene from graphite by mechanical tape stripping method in 2004, the existence of graphene was confirmed which set off an upsurge of research on other new two-dimensional (2D) monolayer nanomaterials. As we all know, graphene and its composites are chemically inert with lower sensitivity and thus must be activated by decoration with desired molecules before use, resulting in the loss of some singular properties [1, 2]. Besides, the lack of a band gap of graphene has inspired researchers to search for other graphene-like materials with appropriate band gap. Recently, the fabrication and application of transition metal dichalcogenides (TMDs) have become fundamentally and technologically intriguing due to the ultrathin and layered two-dimensional nanosheet structures, and have been widely used in many fields, including field-effect devices, catalysis, energy storage, chemical and biological sensors, etc.

Monolayer sheet-like TMDs can be defined as MX_2, where M covers the transition metals from the 4th to 10th group and X represents the chalcogen group (Fig. 1), and these versatile chemical properties offer fundamental and technological guidance for the various research fields. The performances of bulk TMDs are quite different from insulators like HfS_2, semiconductors like MoS_2 and WS_2, semimetals like WTe_2 and $TiSe_2$, and true metals like NbS_2 and VSe_2. Exfoliating these bulk TMD materials into single or few layers can maximize the confinement effects, thus offers powers far beyond graphene and open up new technological fields for inorganic 2D nanomaterials.

Among which, the intrinsic MoS_2 ($E_g = \sim 1.8$ eV), known for its special 2D structure similar to graphene and stacked by van der Waals force interaction with a 0.62 nm (vs. 0.34 nm of graphene) larger spacing, and good electrical, chemical, mechanical and optical properties [3], has proved to be an exceptionally promising building block for designing novel semiconducting nanomaterials. Especially, MoS_2 shows outstanding selective molecular adsorption and carrier mobility, and to some extent, it can take advantage of the performance that metal oxide semiconductors don't have, which enables MoS_2 to be a promising candidate in the field of gas sensing materials [4–6]. For this purpose, it's very important to synthesize MoS_2 nanosheets with large areas and high-quality sensing performances, like good selectivity, higher response, lower operating temperature even down to room temperature (RT), etc. [7–9].

In this short review, we highlight some interesting gas-sensing properties of mono/few-layered MoS_2 and how they are influenced by the components. Some recent progress on the preparation of intrinsic and doped MoS_2, including hydrothermal/solvothermal treatment, chemical vapor deposition (CVD), and chemical exfoliation of the bulk precursors is reviewed, as well as the implementation of the resulting MoS_2 (pristine/hybrid) sensing materials as high performance, low temperature-working and portable gas sensor devices in detail, and indicates possible future developments in MoS_2-based gas sensors.

2 Preparation of MoS_2-Based Gas Sensing Nano-materials

It's worth noting that monolayer MoS_2 presents only two polymorphs: trigonal prismatic and octahedral phases, and the former can be referred to as a stable monolayer 2H (or D3h) semiconductor state whereas the latter referred to the metastable 1T (or D3d) metallic state. For simplicity, they are described as monolayer 2H and 1T MoS_2, respectively. However, it is challenging to separately prepare 1T phase MoS_2 layers from bulk MoS_2 materials because of the two phases present (2H semiconducting and 1T metallic), and the prepared monolayer 1T phase of MoS_2 is unstable and tends to form the multilayer 2H phase with low conductivity over 95 °C.

As we all know, the sensing properties of the semiconductor gas sensors have been largely affected by their structure and components, since the sensing process relies on the adsorption and reaction with a target molecule on the surface of nanomaterials to account for the change in resistance [10]. For example, the layer-by-layer accumulated nano-sheet structure of MoS_2 has significant advantages in improving sensing performances because of their larger exposed area, good surface permeability, low density, and high interfacial charge-transfer efficiency [11, 12], thus will open the field of real-time and room-temperature monitoring of the toxic gas compounds [12–14]. Besides, the novel gas sensing properties of intrinsic MoS_2 are largely dependent on the number of layers. For instance, atomic-layered MoS_2 has a direct band gap (Eg) of about 1.8 eV, while multi-layered MoS_2 has an indirect band gap (Eg) of about 1.2 eV, which has been regarded as an important factor that affects electronic and optical applications.

In 2012, Gordon et al. [15] from Nanyang University of Technology fabricated 1–4 layers of MoS_2 nanosheets on Si/SiO_2 substrate by micromachined exfoliation, and fabricated MoS_2 transistor by photolithography of Ti/Au electrode to realize the detection of NO gas at room temperature, which spurred the upsurge of scientists' research on MoS_2 gas sensor. However, some defects still exist in the intrinsic

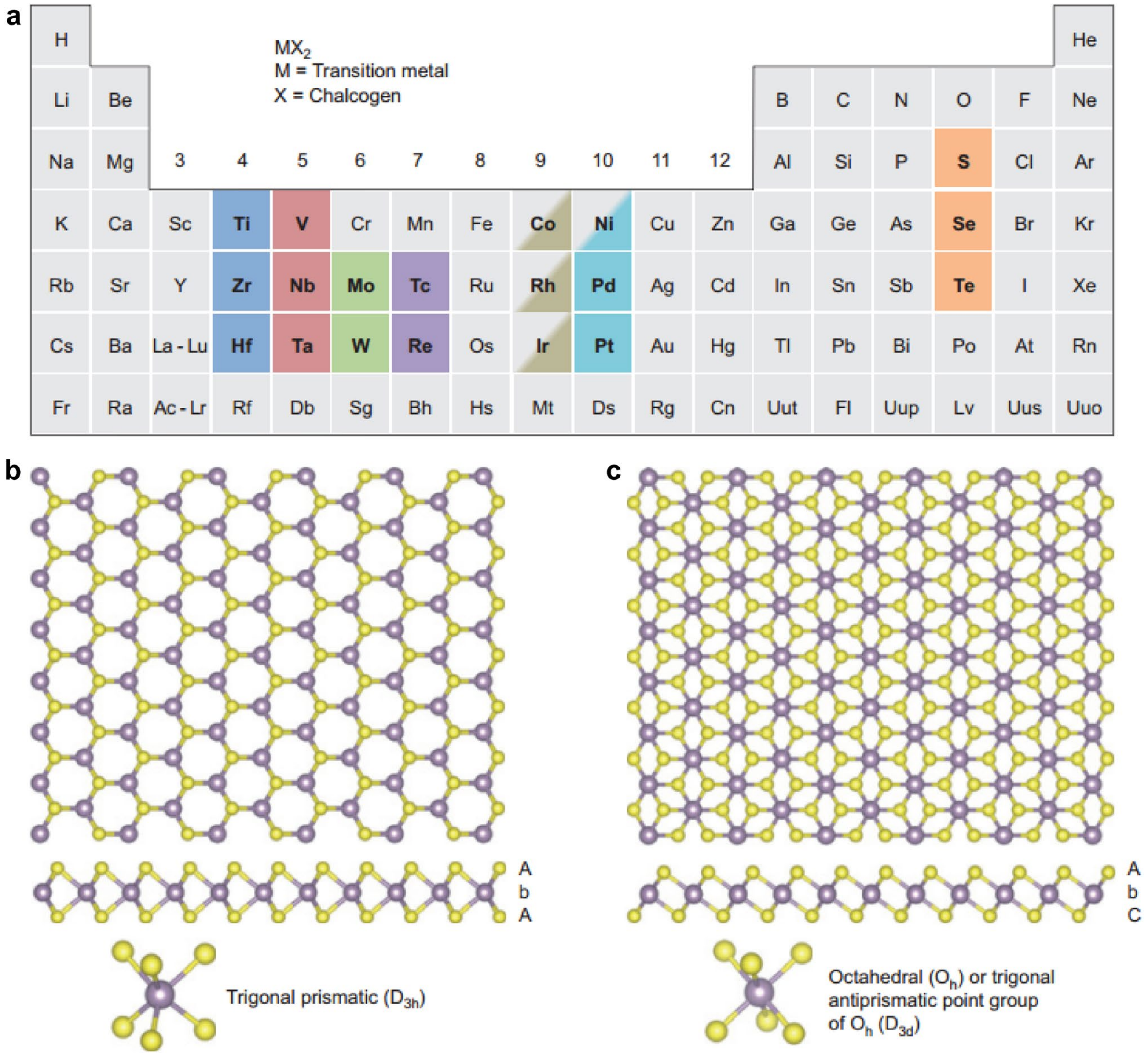

Fig. 1 Structure of monolayered TMDs: **a** The transition metals and the three chalcogen elements that predominantly crystallize in that layered structure are highlighted in the periodic table. Partial highlights for Co, Rh, Ir, and Ni indicate that only some of the dichalcogenides form layered structures. For example, NiS_2 is found to have a pyrite structure but $NiTe_2$ is a layered compound; c-Axis and section view of single-layer TMD with trigonal prismatic (**b**), and octahedral (**c**) coordinations. Images in (**a**)–(**c**) are reproduced with permission from Ref. 2

MoS_2, and oxygen in the air will affect its electrical properties and make it unstable. So people found that modifying MoS_2 with metal oxides, precious metals, or non-metallic nano-materials can make it stable in the air and improve its gas-sensing properties. In the following content, we will discuss the synthesis methods of intrinsic and doped MoS_2 gas sensing nano-materials in detail.

2.1 Intrinsic MoS_2 Gas Sensing Nano-materials

Generally speaking, there are two main methods for preparing MoS_2: top-down and bottom-up. The distinction and classification between the two methods are described in detail as follows.

Therefore, the top-down methods include the mechanical stripping method, liquid stripping method and electrochemical or chemical stripping method. Mechanical stripping is the earliest method used to prepare 2D nano-materials, and the operation process is to rub the lamellar material with other hard physical surfaces, so that a thin layer of nano-materials can be obtained. For example, Song et al. [16] fabricated MoS_2 nanosheets successfully with the size of 72.0727 m^2/g on Fe_3O_4 substrates by such a method. Although the mechanical stripping method is simple, the yield is low and the size of MoS_2 nanocrystals is limited, so it is unsuitable for large-scale production. At the same time, the liquid-phase stripping method is different from the mechanical stripping. Specifically, the MoS_2 nanosheet is floated on the surface of the solvent under ultrasonic treatment by placing the MoS_2 crystal in a suitable solvent, and finally, the supernatant is extracted to obtain the pure MoS_2 nanosheet. Accordingly, Coleman et al. [17] prepared 5–20 layers of MoS_2 nanocrystals by such a method. The liquid stripping method is simple and easy to operate and can avoid the influence of water and air, but the number of lamellae is difficult to control. Lastly, the electrochemical stripping method is usually based on the chemical method of SO_4^{2-} or Li^{2+} intercalation, as described in Fig. 2a, Zeng et al. [18] prepared a single-layered MoS_2 nanosheet on a glass substrate using an electrochemical lithium-based method. Lithiation was carried out in a set of battery test devices using the MoS_2 material and the lithium foil as the cathode and anode, respectively. The lithium process was carried out at a constant current of 0.05 mA. When the lithium-ion insertion was finished, the intercalation compounds were cleaned with acetone to remove the electrolyte, and then the MoS_2 nanosheets were stripped out in water or ethanol by

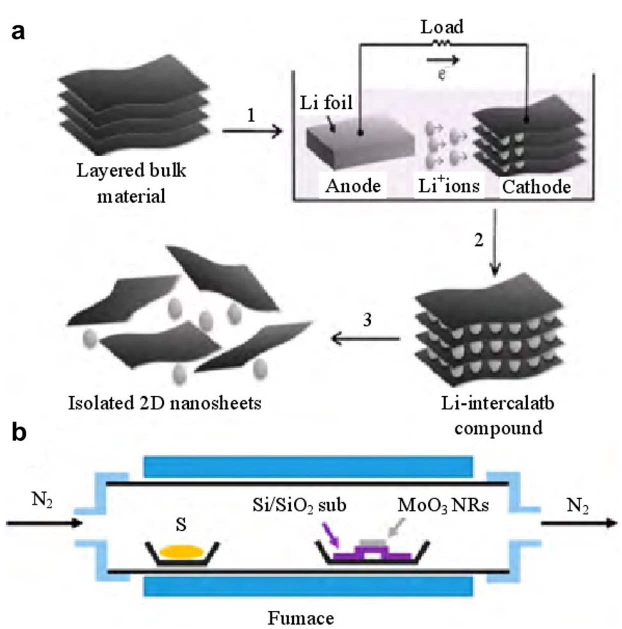

Fig. 2 MoS_2 fabrication by electrochemical (**a**) and CVD (**b**) methods. Images in (**a**) and (**b**) are reproduced with permission from Refs. [18, 20]

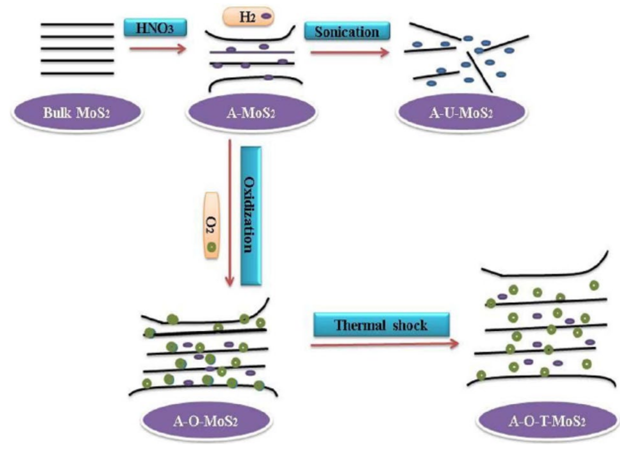

Fig. 3 Modify and intercalate stages of MoS_2 nanolayers. Image is reproduced with permission from Ref. [19]

ultrasonication. Finally, as shown in Fig. 3, Amini et al. [19] reported different methods to intercalate the layers of MoS_2 successfully, such as acid treatment, ultrasonication, oxidation, thermal shock, and so on. To summarize, this method is simple and efficient, but transferring the obtained MoS_2 nanosheets to other substrates is difficult. Besides, lithium deposition will decrease the semiconductor properties of the nanosheets, and it is hard to fabricate them with large areas.

Another method is a bottom-up approach, which includes chemical vapor deposition (CVD) and hydrothermal methods. CVD is one of the most popular methods used by researchers to prepare high-quality MoS_2 nanosheets, and the process is to make the reactive substances react in the high-temperature gas state and then form solid substances deposited on the surface of a heated solid matrix. The morphology, quality and layer number of MoS_2 nanosheets can be controlled by changing the precursor, matrix and reaction conditions during the preparation process. As shown in Fig. 2b, Liu et al. [20] added MoO_3 nanowires and sulfur powder into the reactor and filled it with N_2 gas, then heated it to 550 °C at the rate of 20 °C/min, and then heated to 850 °C at the rate of 5 °C/min and kept for 10–15 min after the sulfur powder was evaporated into steam. Finally, MoS_2 nanosheets with a thickness of 10–20 µm were deposited on the SiO_2/Si substrate after cooling, and high purity and good crystallinity of the MoS_2 product were acquired by the CVD method. However, these preparation conditions are rigorous, also the reaction temperature and the energy consumption are both very high.

Alternatively, as shown in Fig. 4, the hydrothermal method, a universal method that people are familiar with, refers to the synthesis method of chemical reaction in a sealed pressure vessel (such as an autoclave), in which water solution is used as a reaction solvent under certain high temperature and high-pressure reaction conditions.

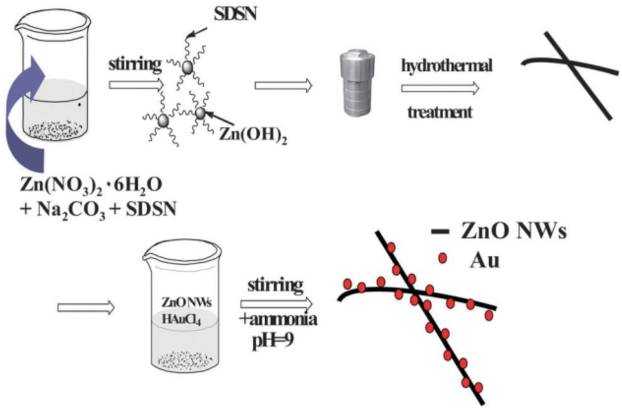

Fig. 4 A typical hydrothermal process to fabricate An-ZnO nanowires. Images are reproduced with permission from Ref. [9]

Meanwhile, if water is substituted by an organic solvent, we call it the solvothermal method. The hydrothermal method has synthesised different morphologies and structures of MoS_2 and was applied in various fields. For example, as seen in Fig. 5, Li et al. [21] prepared hierarchical and hollow MoS_2 microspheres by hydrothermal method with sodium molybdate and thioacetamide as molybdenum source and sulfur source, and polystyrene as template, respectively. In addition, Wang et al. [20] reported the use of MoS_2 nano petal arrays for supercapacitor electrode materials fabricated by a facile hydrothermal method, which showed a specific capacitance of 133 F/g at a discharge current density of 1 A/g. In Zhang's report [22], the novel 3D flower-like MoS_2 hemispheres assembled by ultrathin MoS_2 nano-sheet petals have been successfully prepared via a facile hydrothermal method using CTAB as a surfactant. Mishra et al. [23] employed a one-pot solvothermal method to synthesize metallic 1T phase MoS_2 petal-like nanostructures (MP-LNs) with large surface areas associated with densely formed petals, and so on.

Compared with the CVD method, the recently reported hydrothermal method has partly resolved the batch synthesis issue hydrothermal method needs a lower temperature and lower cost, but it's time-consuming and difficult to control the number of layers of MoS_2 nanosheets [23]. Therefore, the focus of current research will still be how to fabricate MoS_2 nanosheets with large size, good quality, and low cost.

2.2 Doped/Modified MoS_2 Gas Sensing Nano-materials

For practical application, poor intrinsic electronic conductivity still hinders the development of MoS_2. Nanocomposites formed by integration and synergetic interaction of two or three materials with different components, such as N-rich graphitic-C_3N_4 modified MoS_2 would result in heterostructures with better electrical and mechanical properties [24]. Furthermore, the fabrication of doped/modified MoS_2 nanocomposites with other dopants would be expected to effectively suppress the restacking and aggregation of MoS_2 layers, and be suitable for optical, catalytical, electric or chemical applications. Herein, we summarize the synthetic methods of doping or modifying MoS_2 compounds for the peers' review.

The present paper from Zhang et al. demonstrates a simple, scalable, and economical solvent thermal method for preparing flower-shaped TiO_2/C/MoS_2 microspheres, which can be employed as an anode for LIBs. The flower-shaped TiO_2/C microspheres with flake-shaped petals acted as a backbone to provide an efficient pathway for the fast Li^+ intercalation/deintercalation of MoS_2, and to accommodate the volume changes. Compared with pure MoS_2

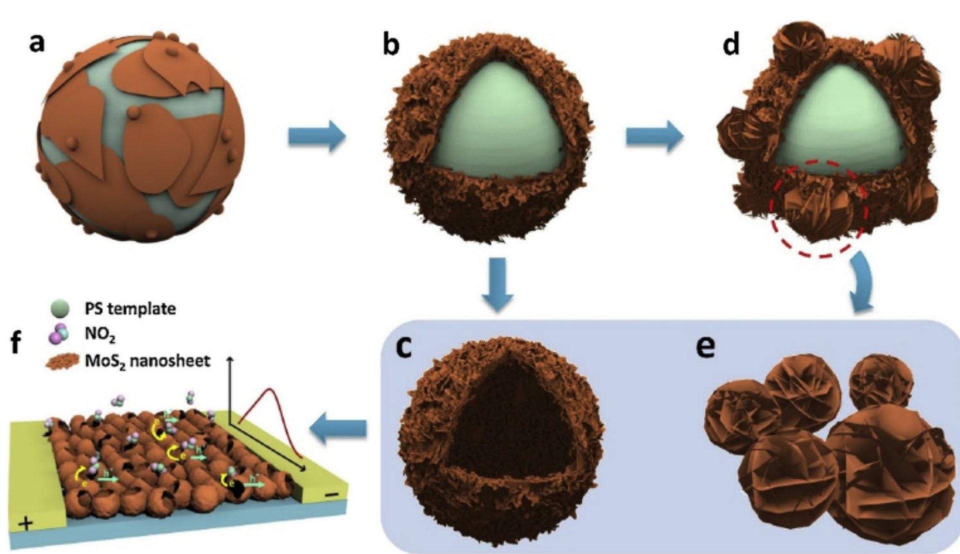

Fig. 5 Schematic depiction of the growth mechanism of hierarchical hollow and solid MoS_2 microspheres. **a** MoS_2 nanosheets nucleate on the PS template. **b** MoS_2 nanosheets nucleate and grow continually. **c** PS template was removed and the hollow sphere remain. **d** MoS_2 nucleates on the surface of MoS_2 nanosheets and grows up into little solid spheres. **e** Solid spheres fall off from hollow spheres. **f** Schematic illustration of the sensing process. Images are reproduced with permission from Ref. [21]

and TiO_2/C, TiO_2/C/MoS_2 microspheres can significantly enhance electrochemical properties, which showed a high initial discharge capacity of 1219 mA h g^{-1} and Coulombic efficiency (CE) of 70% at 100 mA g^{-1}. After 100 cycles, the TiO_2/C/MoS_2 composites discharge capacity remained at 621 mA h g^{-1} and had a CE of 98% [25]. Besides, the layered MoS_2 was also modified with nitrogen-doped carbon to improve the capacity in Li–Na psuedocapacitors [24], and lithium-ion batteries [26]. And Shi et al. [27] the positively charged ultrathin g-C_3N_4/MoS_2 composites are fabricated through a simple electrostatic adsorption and self-assembly process followed by a hydrothermal method. The superb photocatalytic performance benefits from the unique advantages, with an excellent synergistic effect toward photocatalytic degradation of organic pollutants. Senthil et al. [24] reported the synthesis of a 3D network of MoS_2 encapsulated over g-C_3N_4 nanosphere forming an inter-connected and uniform g-C_3N_4/MoS_2 scaffolds. The electrochemical properties of such scaffolds were investigated as potential anode materials for lithium-ion batteries and exhibited superior electrochemical properties, which is attributed to g-C_3N_4 support which favors better electronic conductivity, and affords more sites for Li^+ ions. Another carbon-modified composite like reduced graphene oxide-few layer MoS_2 nanocomposite for enhanced electrochemical performance in supercapacitors and water purification was also presented by Raghu et al. [28] and his group.

In addition to carbon-based MoS_2 composite materials, there are also many metal oxide/MoS_2 heterojunctions, for example, Benavente et al. [29] successfully prepared a series of novel heterostructured hybrid layered ZnO and MoS_2 nanosheets composites with different MoS_2 contents. In this work, they investigated the synergetic role of MoS_2 nanosheets in enhancing the photocatalytic activity of layered hybrid ZnO (LHZnO) nanocomposites, especially in utilizing the visible light regions of the solar spectrum. Zhang et al. [30] developed a facile one-step hydrothermal method to fabricate the 3D flower-like heterostructure of MoS_2/CuS nanohybrid, and this 3D flower-like heterostructure of MoS_2/CuS nanohybrid catalyst exhibits great potential for renewable energy applications. Guo's group [31] used the first-principles calculation based on density functional theory (DFT) to explore the enhanced photocatalytic mechanism of TiO_2 by combining with both pristine and defective monolayer MoS_2. It was demonstrated that the combination of TiO_2 with MoS_2 was favorable thermodynamically. Wang's group [32] controllably synthesized the sesame ball-like CoS/MoS_2 nanospheres via a facile hydrothermal and solvothermal consecutive reaction, which then was utilized as efficient counter electrode catalysts for dye-sensitized solar cells. The hybrid interactions took place between the p orbital of I and 3d states of Co, which lead to I_3^- was activated and dissociated easily. In addition to MoS_2-based heterojunction that conforms to stoichiometric ratio, there are also some composites with non-stoichiometric ratios, and take Xie's work [33] as an example, they firstly prepared $V_{0.13}Mo_{0.87}O_{2.935}$/$MoS_2$ nanocomposites via an in-situ hydrothermal approach based on the NH_4VO_3 and MoS_2 as precursors. Furthermore, the visible-driven photocatalytic experiment results showed that the $V_{0.13}Mo_{0.87}O_{2.935}$/$MoS_2$ composites displayed better degradation ability in contrast to pure MoS_2 and other stoichiometric ratios, which could be attributed to the suppression of charge recombination by confined space effect.

Finally, there are also some synthesis methods for TMD/TMD heterojunctions. Typically, for Said Ridene's report [34], the optical gain in the new class of 2D-materials was calculated for MoS_2/WSe_2 single quantum well (QW), where a numerical solution of the ***k.p*** equation at (K^+, K^-) points of the Brillouin zone was done to obtain the energy levels and the corresponding wave functions of electrons and holes in QW. And the result turned out that MoS_2/WSe_2 QW could satisfy the lasing requirements and give interesting results about the performance of laser emitting devices.

3 Application of the MoS_2-Based Gas Sensors

Generally speaking, there are not many reports on detecting gas types by MoS2-based gas sensors, mainly about NO_x. Recently, researchers have tried to apply different techniques to synthesize a high-quality MoS_2-based gas sensor at room temperature (RT). Cui et al. [35] also pointed out that MoS_2 can be used as a promising candidate for high-performance RT sensing. However, the properties of pristine MoS_2 nanosheets are strongly influenced by the significant adsorption of oxygen in an air environment, which leads to instability of the MoS_2 sensing device, and all sensing results on MoS_2 reported to date were exclusively obtained in an inert atmosphere. To solve the problem, their lab reported a novel nanohybrid of SnO_2 nanocrystal (NC)-decorated crumpled MoS_2 nanosheets (MoS_2/SnO_2) and its exciting air-stable property for room temperature sensing of NO_2 are reported. Interestingly, the SnO_2 NCs serve as strong p-type dopants for MoS_2, leading to p-type channels in the MoS_2 nanosheets. The SnO_2 NCs also significantly enhance the stability of MoS_2 nanosheets in dry air. As a result, unlike other MoS_2 sensors operated in an inert gas (e.g. N_2), the nanohybrids exhibit high sensitivity, excellent selectivity, and repeatability to NO_2 under a practical dry air environment. This work suggests that NC decoration significantly tunes the properties of MoS_2 nanosheets for various applications.

Besides, Yong Zhou and Donarellia et al. reported different exfoliation methods of MoS_2 for use as a NO_x gas sensor [36–38]. In these reports, results were obtained in the presence of N_2 gas and showed a long response time accompanying incomplete recovery, which significantly decreases the practical application of the sensor in an open atmosphere. Consequently, it is much more meaningful to develop feasible strategies to enhance the gas sensing performance of MoS_2 NSs for operation at low temperatures in the air. Thus, functionalization is essential to sensitize the surface or to engender selectivity. Heterojunction NMs can effectively enhance the gas-sensing ability of the sensor via the synergistic effect of the constituents. To overcome the limitations and expand the application of MoS_2 NSs, research on MoS_2-based composite modified with noble metals has been reported, which improved the gas sensing and overall catalytic properties of MoS_2 NSs [39–41]. Nevertheless, more recent studies have been carried out on the decoration of MoS_2 NSs with noble metals; however, the use of expensive metal is not advantageous from an economic perspective, so it is better to functionalize MoS_2 NSs with another nanomaterial such as metal oxides (MOs). Studies relevant to Mos-modified MoS_2 NSs (MOs-MoS_2) used as a gas sensor have been seldom reported until now. Therefore, it is worth studying the gas-sensing properties of different MOS-MoS_2 composites. For this purpose, bismuth oxide (Bi_2O_3) is one of the most important semiconducting materials, which has drawn great attention due to its narrow band gap of 2.8 eV and its highly catalytic properties [42].

Li et al. [21] also have reported that the edge sites of MoS_2 are highly chemical active over the inert MoS_2 basal planes, and their hierarchical hollow MoS_2 microspheres show excellent sensing performance with 3.1 times enhancement compared with the contrast sample of a smooth solid structure. The rapid and sensitive response, decreased working temperature, as well as prominent selectivity, enable the material with attractive sensing performance for NO_2 detection. Such a study also provides new opportunities on the surface morphology control at both the micro- and nanoscale for enhancing the sensing performance of MoS_2. Ikram et al. [43] designed a facile strategy to synthesize a controllable morphology and composition for three-component heterojunctions of MoS2/Bi_2O_3/Bi_2S_3 (as can be seen in Fig. 6), which exhibited an ultra-fast response time of only 1 s at room temperature (RT) in air and the detection limit was predicted to be as low as 50 ppb.

Besides, according to Li's report [41], the reduced graphene oxide/MoS_2 composite sensitive films were prepared by layer-by-layer self-assembly method, as can be seen in Fig. 7a. The sensitivity to the formaldehyde gas was measured at room temperature, as present in Fig. 7b, where the

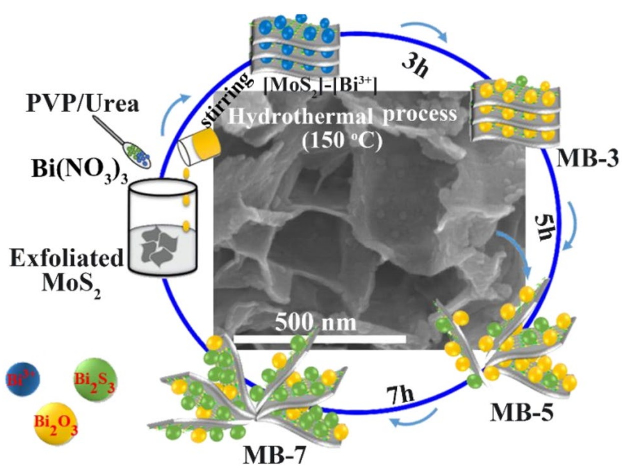

Fig. 6 Preparation process of three component heterojunctions of $MoS_2/Bi_2O_3/Bi_2S_3$. Images are reproduced with permission from Ref. [43]

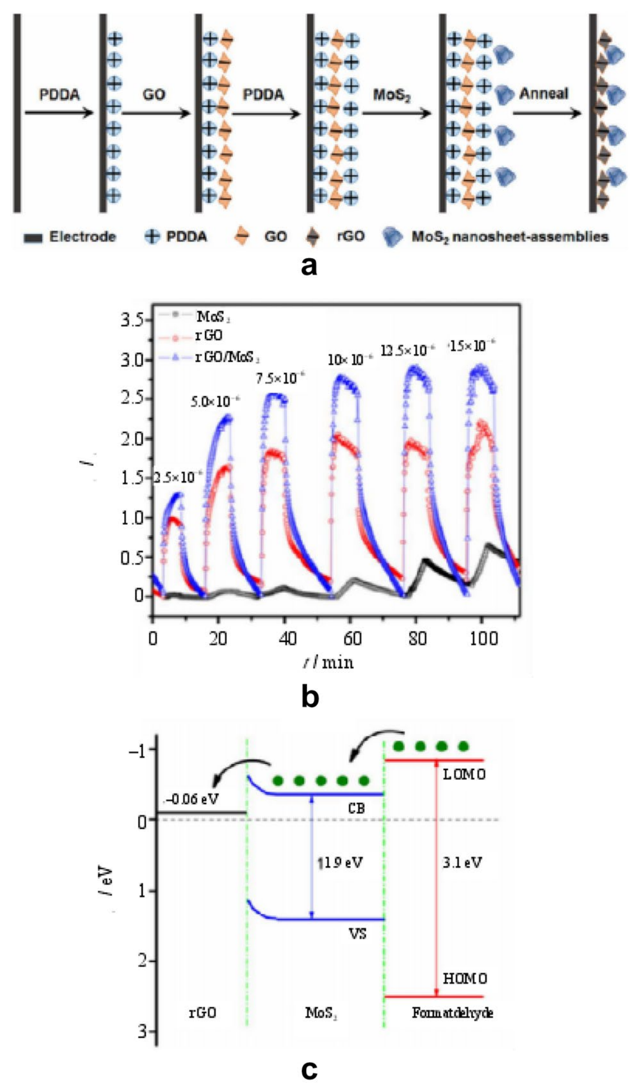

Fig. 7 Fabrication of rGO/MoS_2 film (**a**), the response of MoS_2, rGO, and rGO/ MoS_2 film to HCHO at RT (**b**), and potential and energy diagram (**c**). Images are reproduced with permission from Ref. [41]

rGO/MoS_2 composite films showed obviously higher current values than rGO when exposed to the formaldehyde, and even tens of times higher than that of the MoS_2, indicating the rGO/MoS_2 composite films presented improved sensitivity after doping rGO onto MoS_2 films. The barrier and electron band of rGO/MoS_2 composite film are shown in Fig. 7c, and the electrons released from formaldehyde are first transferred to the surface of MoS_2, adsorbed by oxygen molecules on its conduction band, and then further transferred to rGO, which makes the conductivity of the mixed thin film change dramatically.

Furthermore, Zhang et al. [44] successfully prepared Pd-SnO_2/MoS_2 composite sensitive thin films by hydrothermal synthesis, as shown in Fig. 8a. The sensitivity of Pd-SnO_2/MoS_2 to H_2 was studied at room temperature with the results shown in Fig. 8b and c. It was found that the gas-sensing properties of the modified MoS_2 were greatly improved, and the selectivity of H_2 was obviously enhanced. So the doping and modifying of the noble metal and the metal oxide can form the catalytic activity of gas adsorption, reduce the activation energy of interface reaction between the gas and the MoS_2, expand the gas detection range, and enhance the response sensitivity and selectivity of the MoS_2 sensor to the specific gas.

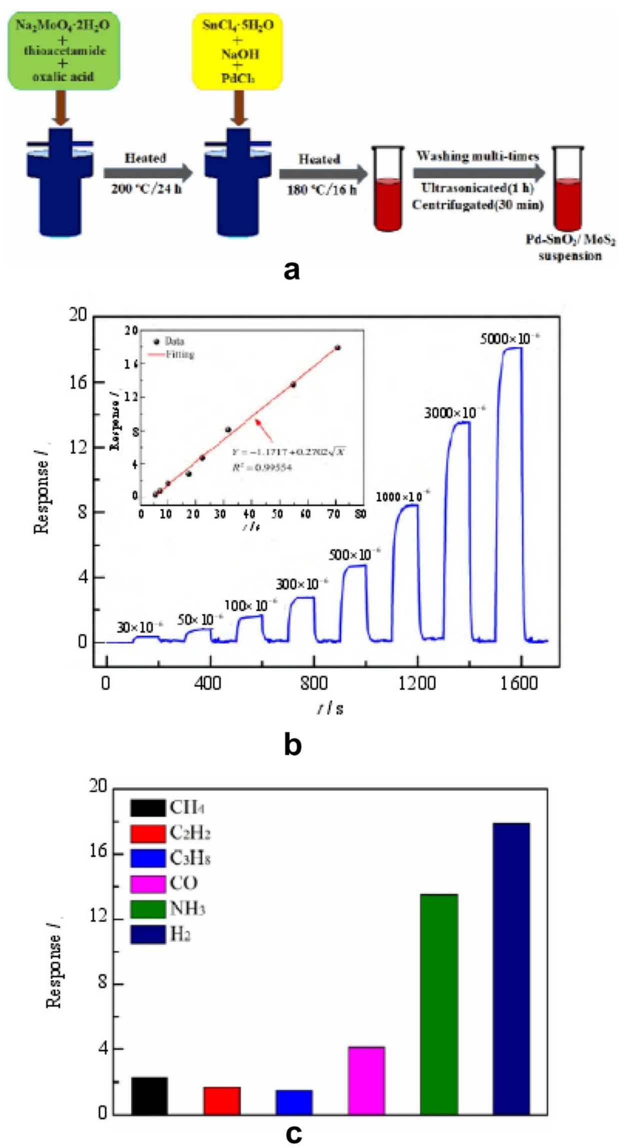

Fig. 8 Preparation (**a**), H_2 response (**b**), and selectivity (**c**) of Pd-SnO_2/MoS_2. Images are reproduced with permission from Ref. [44]

4 Conclusion

This short review enhanced our understanding of the research progress and recent development of MoS_2-based gas sensors, summarized the preparations of intrinsic and modified MoS_2 gas-sensing nano-materials, and summed up their application in gas sensing detection. The following summarization highlights the tangible advantages:

(1) The MoS_2 modified with rGO, nitrogen-doped carbon, metal oxide, or noble metal particles can significantly improve the detection sensitivity and selectivity of gas sensors, and enlarge the gas species.
(2) Advanced modification methods, different fabrication processes, and various functional gas sensing nanomaterials make MoS_2-based nanocomposites promising candidates for high-performance, low-power micro-nano gas sensor materials.
(3) The 2D layer MoS_2-based heterojunction structure is a promising approach to maximize the interfacial heterojunction area and enable electronic interactions at the interface to enhance sensing response.

However, despite the significant progress made in MoS_2-based sensors there are still some problems with gas sensors based on MoS_2:

(1) When the adsorption between MoS_2-based nanomaterial and gas molecules is strong, the desorption process will be relatively slow. Presently, the common desorption methods are heating and ultraviolet irradiation, hence causing more energy consumption and indistinctive effects. Therefore, a new desorption technique needs to be developed.
(2) Although modified by the functionalization, the MoS_2 can be only selective for certain gases, but the selective detection of the specific gas in the complex gas environment is difficult to be realized.
(3) So far, the MoS_2-based gas sensor is still in the laboratory research stage. Realizing the industrialization of MoS_2-based electronic devices is still facing many challenges.

The following countermeasures are proposed to improve the property of the MoS_2-based sensors:

a. The structural guide agents or template agents should be applied to the synthesis of MoS_2 for unique shapes and morphologies, enabling discrimination of VOC gases that are typically demanding to detect due to different exposure surfaces and oxygen vacancies.
b. The chemical simulation software, such as VASP, Materials Studio, and Gaussian could be employed to calculate electronic structures, energy levels of diverse molecular conformations, and other essential mechanisms to provide a deeper understanding of mechanisms for improving performance.
c. Wearable electronic devices in environmental monitoring, disease diagnosis, the food industry, and other fields pose significant challenges requiring researchers' further consideration and exploration.

Acknowledgements This work was funded by the Key Projects of Guangxi Natural Science Foundation (No. 2020GXNSFDA297015), China; Natural Science Foundation of Guangxi Province (No. 2022GXNSFAA035565), China; Innovation Project of Guangxi Graduate Education (No. YCSW2022101).

Declarations

Competing interests The authors declare no competing financial interests.

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