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## Synthesis of $\text{MoS}_2$ -based nanostructures and their applications in rechargeable ion batteries, catalysts and gas sensors: a review

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Molybdenum disulfide ( $\text{MoS}_2$ ) is a two-dimensional (2D) layered material with a graphene-like structure that has attracted attention because of its large specific surface area and abundant active sites. In addition, the compounding of  $\text{MoS}_2$  with other materials can enhance the performance in applications such as batteries, catalysts, and optoelectronic devices, etc.  $\text{MoS}_2$  is prepared by various methods, among which chemical deposition and hydrothermal methods are widely used. In this review, we focus on summarizing the applications of  $\text{MoS}_2$  and  $\text{MoS}_2$  composite nanomaterials in rechargeable ion batteries, catalysts for water splitting and gas sensors, and briefly outline the preparation methods.

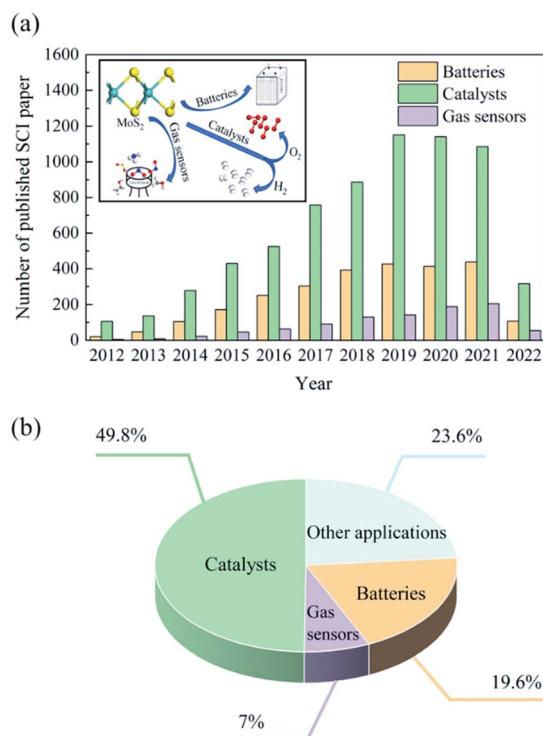
### 1. Introduction

Nanomaterials have attracted increasing research interest as a result of its fascinating physicochemical properties, such as the nano-size effect and large specific surface area. In 2005, the emergence of monolayer graphene set off a research boom in 2D materials.<sup>1–3</sup> Many novel 2D materials have also been developed, such as hexagonal boron nitride (hBN) and transition metal dichalcogenides (TMDs). They are widely used in energy, sensing and other applications due to their excellent physical and chemical properties.<sup>4–9</sup> Notably,  $\text{MoS}_2$ , a member of TMDs, is a promising 2D material among compounds with graphene-like structures.

It is well known that  $\text{MoS}_2$  materials have a wide range of applications, and we found that it has a high proportion of catalysts, batteries and gas sensors applications by searching the Web of Science for articles related to the applications of  $\text{MoS}_2$  in the last decade (Fig. 1b). Fig. 1a summarizes the number of published SCI papers on  $\text{MoS}_2$  over the last decade (up to May 2022) in the batteries, catalysts, and gas sensors. It is clear that  $\text{MoS}_2$  is attracting more and more attention in these applications.

$\text{MoS}_2$  exhibits unique advantages over graphene-based or hBN-based nanomaterials in these applications. In detail, in

batteries,  $\text{MoS}_2$  is used as an electrode material due to its high specific surface area and unique layer-like structure.<sup>10</sup> In catalysts,  $\text{MoS}_2$  is a promising alternative to the precious metal Pt catalysts for hydrogen reaction evolution (HER) and



**Fig. 1** (a) Statistics of  $\text{MoS}_2$  core publications in batteries, catalysts, and gas sensors. (b) Percentage of core publications of  $\text{MoS}_2$  in different applications in the last decade (up to May 2022).

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photocatalytic water splitting, while  $\text{MoS}_2$  can be used in combination with other materials to improve visible light catalytic activity for the degradation of organic pollutants in industrial wastewater.<sup>11,12</sup> In terms of gas-sensitive properties,  $\text{MoS}_2$  has good responsiveness and selectivity to some gases at room temperature (RT), which has led to widespread research and application of  $\text{MoS}_2$  materials in gas sensors.<sup>13</sup>

Recent years, many reviews about  $\text{MoS}_2$  nanomaterials were published. Some researchers have reviewed the application and preparation of  $\text{MoS}_2$  in energy (such as batteries and catalysts),<sup>14–16</sup> some have reviewed the application and preparation of  $\text{MoS}_2$  in electronic components (such as memristors and field-effect transistors),<sup>17–20</sup> some focus on  $\text{MoS}_2$  for detection and sensing applications,<sup>21–23</sup> some have listed in detail the synthesis and application of 1T  $\text{MoS}_2$ ,<sup>24–26</sup> and others have focused on the synthesis method of  $\text{MoS}_2$ .<sup>27</sup> Based on the previous researches and summaries, in this review, we comprehensively and systematically describe the applications of  $\text{MoS}_2$  and  $\text{MoS}_2$ -based composites in rechargeable ion batteries, catalysts and gas sensors in recent years, and summarize the corresponding preparation schemes.

## 2. Applications and synthesis strategies of $\text{MoS}_2$ in rechargeable ion batteries

To meet future energy storage needs, rechargeable ion batteries based on  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{Al}^{3+}$  and  $\text{Zn}^{2+}$  have been widely studied and prepared.<sup>28–31</sup>  $\text{MoS}_2$  has a layered structure, which are connected by van der Waals forces with weak interlayer interactions and large layer spacing.<sup>32</sup> High theoretical capacity, high charging rate and excellent stability make  $\text{MoS}_2$  become a promising electrode material. In this work, we will focus on the application and preparation of  $\text{MoS}_2$  as electrode materials.

### 2.1 Lithium-ion batteries

Using  $\text{MoS}_2$  or composites of  $\text{MoS}_2$  for the anode materials is beneficial to lithium-ion batteries (LIBs). Wei *et al.*<sup>33</sup> studied the electrochemical reactions of  $\text{MoS}_2$  nanosheets in LIBs. Their study represented that intercalation of Li ions into  $\text{MoS}_2$  anode contributes the electrochemical charge storage. However, the low conductive of  $\text{MoS}_2$  and its aggregation during the electrode manufacturing process greatly hinder the development of LIBs.<sup>34,35</sup> In order to improve the performance of  $\text{MoS}_2$  as an electrode material for LIBs, there are two main options, one is to change the structure of  $\text{MoS}_2$  material, and the other is to prepare  $\text{MoS}_2$  composites.

On the one hand, Zhao *et al.*<sup>36</sup> studied  $\text{MoS}_2$  materials with nanotube structures to improve electrochemical performance. They reported a facile wet etching method for the preparation of low crystalline  $\text{MoS}_2$  nanotubes. First,  $\text{MoO}_3$  nanobelts ( $\text{MoO}_3$  NBs) were prepared by hydrothermal method. Sodium molybdate dihydrate ( $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$ ) and nitric acid were used in this step. Second, 3D  $\text{MoS}_2$  nanomasks were grown *in situ* on  $\text{MoO}_3$  NBs, which was obtained by the chemical reaction of sublimed sulfur with  $\text{MoO}_3$  NBs in CVD quartz tube. Finally,

$\text{MoS}_2$  nanotubes ( $\text{MoS}_2$  NTs) were synthesized by mixing the previously obtained  $\text{MoO}_x/\text{MoS}_2$  NBs with concentrated hydrochloric acid. As demonstrated in Fig. 2a, the inner  $\text{MoO}_x$  are etched with concentrated hydrochloric acids to yield low crystalline  $\text{MoS}_2$  NTs. With the increase of etching times, the molybdenum oxide is gradually removed which allowed the internal cavity of  $\text{MoS}_2$  NTs to be emptied. After the fourth etching process, most of the molybdenum oxides were removed to give  $\text{MoS}_2$  NTs (Fig. 2b).

The electrochemical test results illustrated that  $\text{MoS}_2$  NTs, as the anode material for LIBs, reached a specific capacity of  $1253 \text{ mA g}^{-1}$  at a current rate of  $200 \text{ mA g}^{-1}$  and was stabilized after 250 cycles. Obviously, the low crystalline  $\text{MoS}_2$  NTs have even higher specific capacity and cyclic performance than the reported electrode materials.<sup>37,38</sup>

On the other hand, some researchers have investigated  $\text{MoS}_2$  nanocomposites to improve the electrochemical properties of  $\text{MoS}_2$  in LIBs.

Wu *et al.*<sup>34</sup> reported an electrode material of two-layer carbon-coated  $\text{MoS}_2$ /carbon nanofiber ( $\text{MoS}_2/\text{C/C}$  fiber) which prepared by hydrothermal and electrospinning method. First,  $\text{MoS}_2$  spheres were obtained by hydrothermal. Hexaammonium heptamolybdate tetrahydrate ( $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ), thiourea ( $\text{NH}_2\text{CSNH}_2$ ), and polyvinylpyrrolidone (PVP) were used in this step. Second,  $\text{MoS}_2/\text{C}$  spheres were fabricated by using glucose and the above-obtained  $\text{MoS}_2$  spheres. Finally, they synthesized  $\text{MoS}_2/\text{C/C}$  nanofiber by electrospinning method. Polyacrylonitrile (PAN), *N,N*-dimethylformamide (DMF) and the above obtained  $\text{MoS}_2/\text{C}$  spheres were used. The preparation process of  $\text{MoS}_2/\text{C/C}$  fiber is shown in Fig. 2c.

Meanwhile, Zhang *et al.*<sup>35</sup> synthesized  $\text{TiO}_2/\text{C}/\text{MoS}_2$  microspheres as anodes for LIBs.  $\text{TiO}_2/\text{C}/\text{MoS}_2$  microspheres were prepared by solvent-thermal method and calcination. First of all they used PVP, acetic acid and tetrabutyltitanate (TBT) in a Teflon-lined autoclave for the reaction to prepare  $\text{TiO}_2/\text{C}$  materials. Secondly,  $\text{TiO}_2/\text{C}/\text{MoS}_2$  was synthesized by the obtained  $\text{TiO}_2/\text{C}$ , ammonium molybdate tetrahydrate ( $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ) and thiourea ( $\text{CH}_4\text{N}_2\text{S}$ ). The preparation process of  $\text{TiO}_2/\text{C}/\text{MoS}_2$  microsphere is shown in Fig. 2e.

No matter  $\text{MoS}_2$  is compounded with carbon materials or  $\text{TiO}_2$  materials, the electrochemical properties of  $\text{MoS}_2$  materials have been improved. On the one hand, for the  $\text{MoS}_2/\text{C/C}$  electrode, the double-layer carbon coating (Fig. 2d) could not only suppress the irreversible reaction, but also confine the volume change during the lithiation/delithiation process.<sup>34</sup> Moreover,  $\text{MoS}_2/\text{C/C}$  fiber has better cycling performance than  $\text{MoS}_2$  spheres (Fig. 2g). On the other hand, the unique structure with flower-shaped of  $\text{TiO}_2/\text{C}/\text{MoS}_2$  (Fig. 2f) could not only enlarge the electrolyte-electrode interface area but also shorten the diffusion length of  $\text{Li}^+$  intercalation/deintercalation.<sup>35</sup> Compared with  $\text{MoS}_2$  materials, the cycling performance of  $\text{TiO}_2/\text{C}/\text{MoS}_2$  are enhanced (Fig. 2h).

### 2.2 Sodium-ion batteries

Sodium ion batteries (SIBs) are considered as an alternative to LIBs because of their abundant reserves and low cost. However,



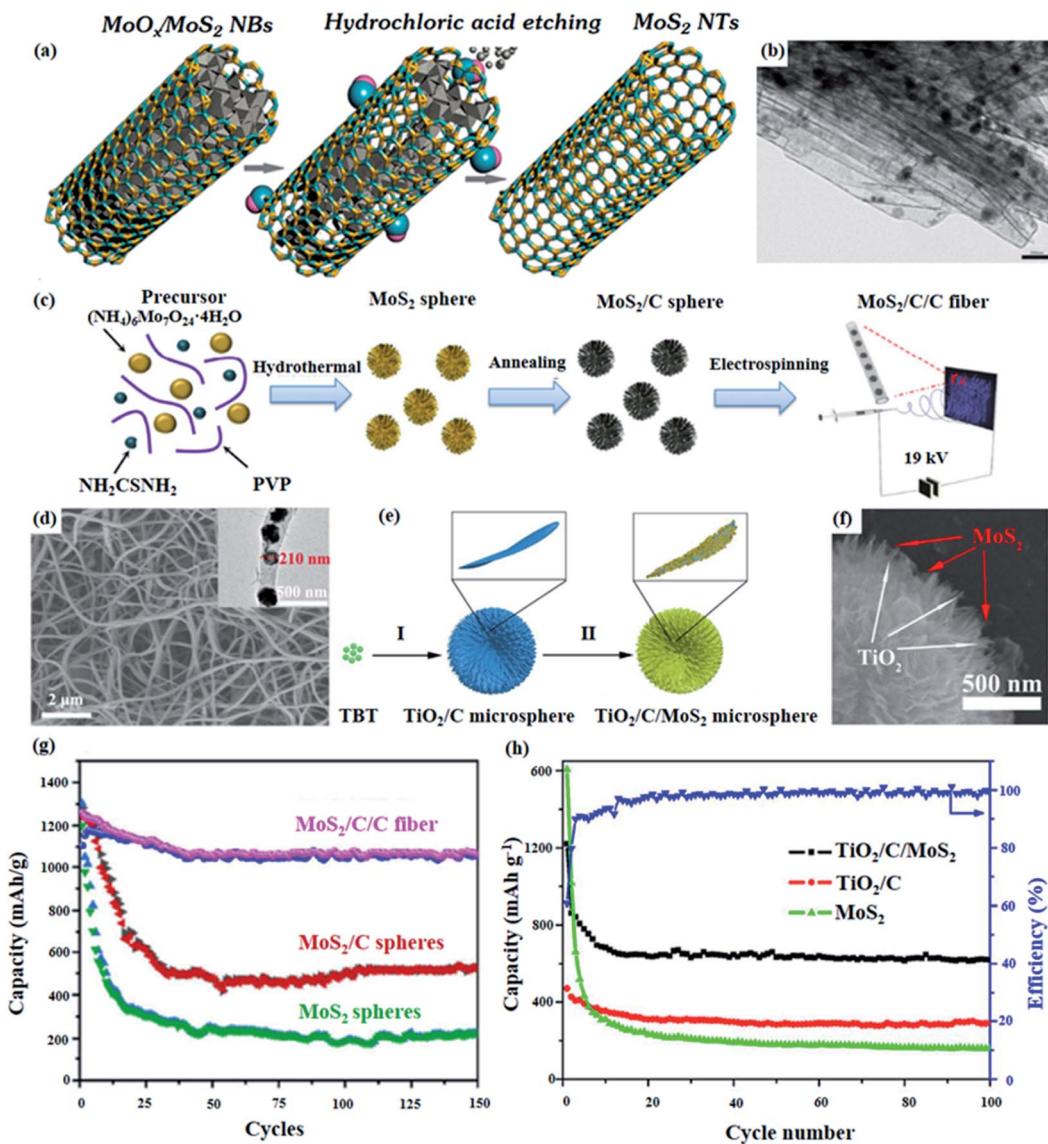


Fig. 2 (a) MoS<sub>2</sub> NTs are obtained after etching MoO<sub>x</sub>/MoS<sub>2</sub> NBs with concentrated hydrochloric acid.<sup>36</sup> (b) MoS<sub>2</sub> NTs obtained from the fourth etching.<sup>36</sup> (c) Schematic illustration of the preparation process of MoS<sub>2</sub>/C/C fiber.<sup>34</sup> (d) SEM images of MoS<sub>2</sub>/C/C fiber. The inset is a magnified TEM image of the sample.<sup>34</sup> (e) Schematic diagram of the synthesis of TiO<sub>2</sub>/C/MoS<sub>2</sub> microsphere.<sup>35</sup> (f) SEM images of TiO<sub>2</sub>/C/MoS<sub>2</sub> microsphere.<sup>35</sup> (g) Capacity retention of the MoS<sub>2</sub>, MoS<sub>2</sub>/C, and MoS<sub>2</sub>/C/C fiber electrodes at a current density of 0.2 A g<sup>-1</sup> for the subsequent 150 cycles.<sup>36</sup> (h) Comparative cycling performance of MoS<sub>2</sub>, TiO<sub>2</sub>/C and the TiO<sub>2</sub>/C/MoS<sub>2</sub> microsphere at a current density of 100 mA g<sup>-1</sup>.<sup>35</sup>

Na<sup>+</sup> has larger radius than Li<sup>+</sup>,<sup>39</sup> which hinders the development of SIBs. As a highly promising electrode material, MoS<sub>2</sub> has not only a layered structure but also a large interlayer spacing, which promises to solve the inherent defects of SIBs. However, MoS<sub>2</sub> also has inherent limitations, such as low intrinsic electron conductivity. In response to these characteristics, some researchers have prepared composites of MoS<sub>2</sub><sup>40-43</sup> and others have improved the structure of MoS<sub>2</sub> by doping or inserting molecules to achieve improved electrochemical properties.<sup>40-45</sup>

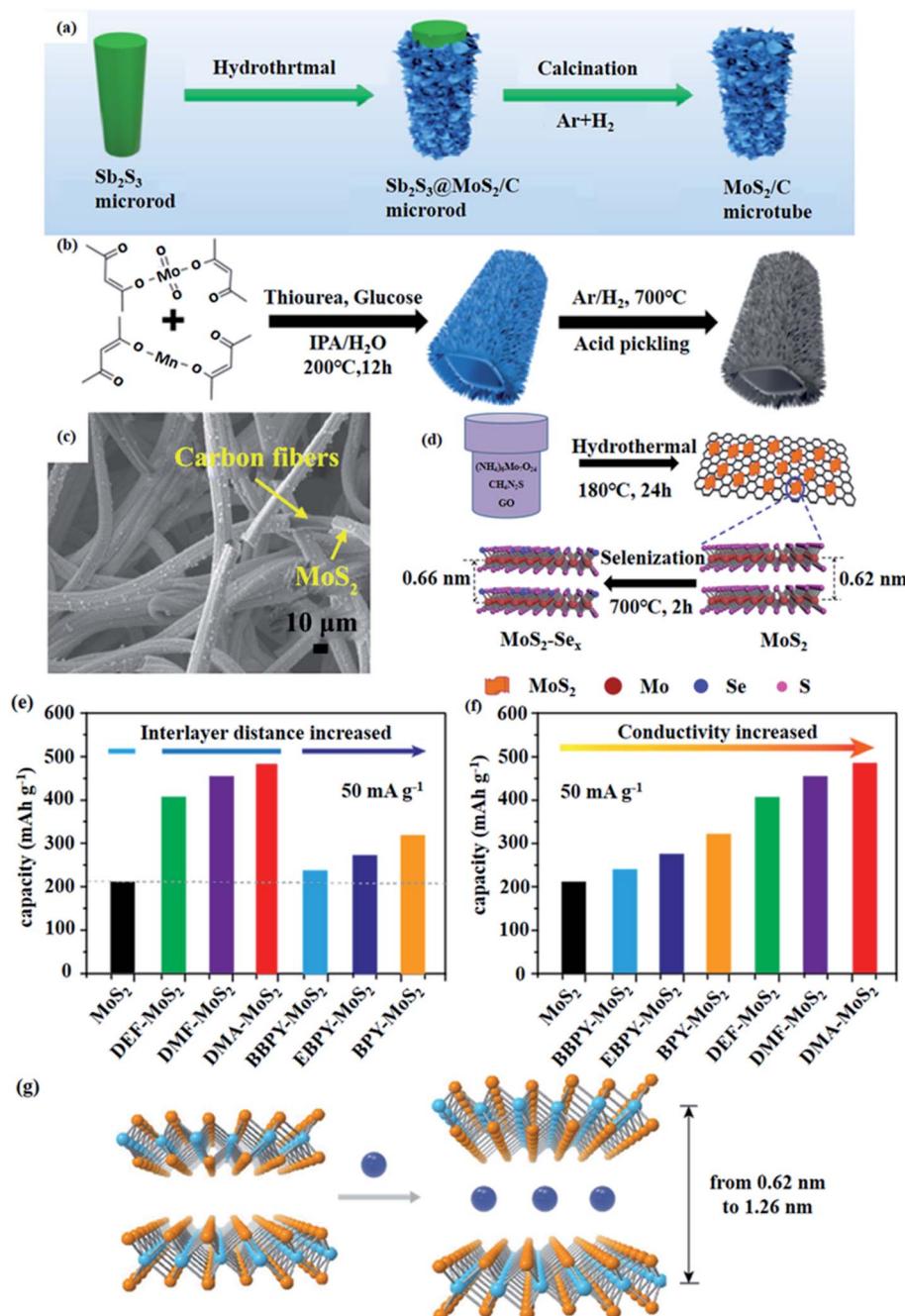
Pan *et al.*<sup>42</sup> reported a simple template method to prepared MoS<sub>2</sub>/amorphous carbon (C) microtubes (MTs) composed of heterostructured MoS<sub>2</sub>/C nanosheets. The synthesis of MoS<sub>2</sub>/C MTs was achieved by a three-step procedure: first, obtaining Sb<sub>2</sub>S<sub>3</sub> microrods by a simple hydrothermal method, second,

MoS<sub>2</sub>/C nanosheets were grown on the outer surface of Sb<sub>2</sub>S<sub>3</sub> microrods by using sodium molybdate dehydrate (Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O), N<sub>2</sub>H<sub>4</sub>CS, and glucose (C<sub>6</sub>H<sub>12</sub>O<sub>6</sub>) in a Teflon-lined stainless steel autoclave for chemical reaction, and third, MoS<sub>2</sub>/C MTs were obtained by removing Sb<sub>2</sub>S<sub>3</sub> microrods *via* annealing. The synthesis schematic is shown in Fig. 3a. Electrochemical measurements demonstrated that MoS<sub>2</sub>/C MTs possessed high specific capacity and excellent stability, improving the electrochemical performance of SIBs.

Similarly, some researchers have also reported composites of MoS<sub>2</sub> for enhancing the electrochemical performance of SIBs.

The MoS<sub>2</sub>/carbon nanofibers (MoS<sub>2</sub>/CNFs) were prepared by a two-step procedures: first, obtaining ammonium tetrathiomolybdate (AMT), and second, synthesizing MoS<sub>2</sub>/CNFs by





**Fig. 3** (a) Schematic illustration of the synthesis process of  $\text{MoS}_2/\text{C}$  MTs.<sup>42</sup> (b) Schematic diagram of the fabrication process of  $\text{MoS}_2-\text{C}$  hollow rhomboids.<sup>41</sup> (c) FESEM images of OMSCF calcined in air at  $400^\circ\text{C}$  (OMSCF-400).<sup>43</sup> (d) Schematic illustration of the synthesis of  $\text{MoS}_{2-x}\text{Se}_x/\text{G}$ .<sup>45</sup> (e) Capacity of all intercalated  $\text{MoS}_2$  at  $50\ \text{mA g}^{-1}$  arranged according to the interlayer distance, respectively.<sup>44</sup> (f) Capacity of all intercalated  $\text{MoS}_2$  at  $50\ \text{mA g}^{-1}$  arranged according to conductivity, respectively.<sup>44</sup> (g) Schematic of intercalation of molecules into  $\text{MoS}_2$ .<sup>44</sup>

electrospinning and high temperature carbonization.  $\text{MoS}_2/\text{CNFs}$  have a large specific surface area and high electrical conductivity, which enhances Na storage performance.<sup>40</sup>

The  $\text{MoS}_2-\text{C}$  hollow rhomboids (MCHRs) were fabricated by a sample one-pot solvothermal reaction (Fig. 3b). First of all, manganese(II)acetylacetone ( $\text{Mn}(\text{acac})_2$ ), molybdenyl acetylacetone ( $\text{MoO}_2(\text{acac})_2$ ) were dispersed in distilled water and isopropanol. And then, glucose and thiourea were incorporated

into the mixture. Finally, the mixture was annealed after reaction in a Teflon-lined autoclave and washed several times with dilute hydrochloric acid and deionized water to obtain MCHRs. Electrochemical measurements revealed that MCHRs had better Na storage performance, higher rate capability, more stable cycling performance and superior reversible specific capacity.<sup>41</sup>

The vertically oxygen-incorporated  $\text{MoS}_2$  nanosheets coated on carbon fiber (OMSCF) were synthesized by hydrothermal process and calcination reaction in air. First, carbon fiber was extracted from commercial wet tissue (Vinda Paper Group) with concentrated hydrochloric acid. Second, graphite oxide (GO) was synthesized through the modified Hummers' method. Finally,  $\text{MoS}_2$ /carbon fibers (MSCF) were obtained by hydrothermal method. The FESEM images of OMSCF are shown in Fig. 3c. Oxygen atoms are incorporated into  $\text{MoS}_2$  by the MSCF calcined in air. The incorporation of oxygen not only creates more defects, but also expands the interlayer spacing. The composite of carbon fiber and  $\text{MoS}_2$  nanosheets not only

improves electronic conductivity, but also enhances structural stability.<sup>43</sup>

In addition, Zhang *et al.*<sup>45</sup> prepared ternary  $\text{MoS}_{2-x}\text{Se}_x$  alloy/graphene ( $\text{MoS}_{2-x}\text{Se}_x/\text{G}$ ) composite through hydrothermal reaction and selenization treatment (Fig. 3d). The interlayer spacing of  $\text{MoS}_2$  is expanded due to the doping of Se atoms which facilitates  $\text{Na}^+$  fast transfer. Meanwhile, the electronic conductivity of composite is enhanced due to graphene, which boosts the electrochemical performance for NIBs.

Dai *et al.*<sup>44</sup> reported a series of molecule-intercalated  $\text{MoS}_2$  as anode materials for SIBs. The molecular intercalation method expands the interlayer spacing as well as increases the electrical

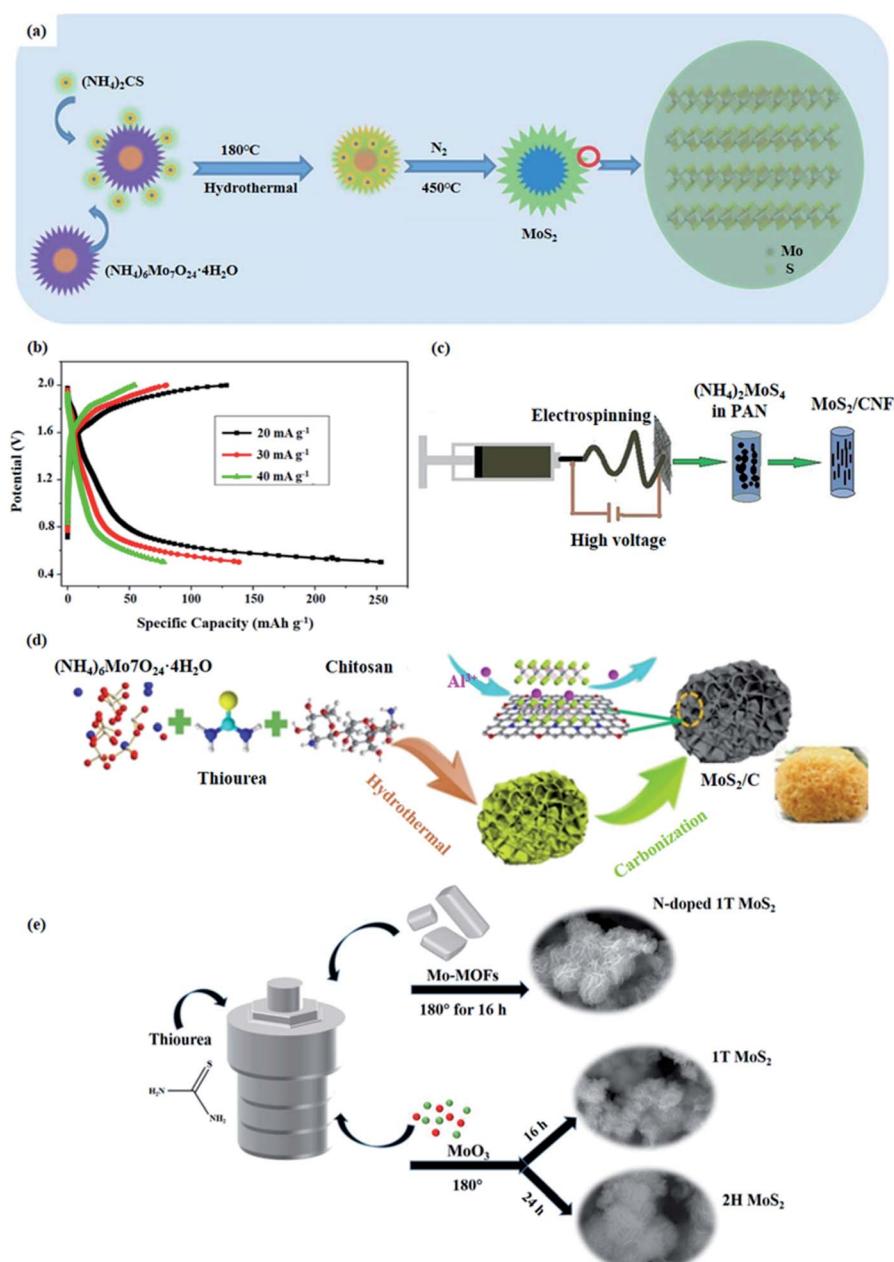


Fig. 4 (a) Schematic illustration of  $\text{MoS}_2$  microspheres prepared by hydrothermal method.<sup>47</sup> (b) The first discharge–charge curves at different current densities.<sup>47</sup> (c) Schematic illustration of the preparation process of  $\text{MoS}_2/\text{CNFs}$ .<sup>48</sup> (d) The preparation process of MNC.<sup>49</sup> (e) The synthesis of N-doped 1T  $\text{MoS}_2$ , pure 1T  $\text{MoS}_2$ , and 2H  $\text{MoS}_2$ .<sup>50</sup>



conductivity of  $\text{MoS}_2$  (Fig. 3e and f). The interlayer spacing can be varied in the range of 0.62 to 1.26 nm precisely by inserting different molecules (Fig. 3g).

In the example of the dimethylacetamide- $\text{MoS}_2$  (DAM- $\text{MoS}_2$ ) construct,  $\text{MoS}_2$  was synthesized by hydrothermal method firstly. Second, squeezing small DAM molecules into the layers.<sup>46</sup> Specifically, DAM,  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ,  $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ ,  $\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$  and deionized water were mixed. Then, the mixture was placed in Teflon-liner autoclave and heated at 230 °C for 24 h. Finally, dark powders were collected after naturally cooled to RT. Benefiting from the expanded interlayer spacing and improved conductivity, the electrochemical performance of SIBs with  $\text{MoS}_2$  as the electrode material has been enhanced.

### 2.3 Other rechargeable batteries

Aluminum ion batteries (AIBs) are also members of energy storage systems.  $\text{MoS}_2$  and its composites can be used as cathode materials for AIBs. Li *et al.*<sup>47</sup> prepared  $\text{MoS}_2$  microspheres structure by hydrothermal method. The preparation process is shown in the Fig. 4a. First, the  $\text{MoS}_2$  microsphere precursor was synthesized by using  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$  and  $(\text{NH}_4)_2\text{CS}$  in a hydrothermal method. And then,  $\text{MoS}_2$  microsphere was obtained by heat treatment in a nitrogen atmosphere.

Fig. 4b depicts the electrochemical performance of  $\text{MoS}_2$  microspheres. Obviously, the electrochemical performance of AIBs with  $\text{MoS}_2$  microsphere cathode material is not excellent. The reason for this can be attributed to the inherent defects of  $\text{MoS}_2$ . Therefore, future research focusing on enhancing the electrochemical properties of  $\text{MoS}_2$  electrode materials is needed.

Yang *et al.*<sup>48</sup> reported a flexible free-standing  $\text{MoS}_2/\text{CNFs}$  cathode for rechargeable AIBs. As shown in Fig. 4c, the  $\text{MoS}_2/\text{CNFs}$  are prepared by electrospinning and annealing treatment. As electrode materials for AIBs,  $\text{MoS}_2/\text{CNFs}$  exhibit better cycling stability and higher rate capacity than  $\text{MoS}_2$  microspheres.

In order to overcome the defects of  $\text{MoS}_2$  and achieve the improved electrochemical performance of AIBs, another method is to use N-doped carbon materials compounded with  $\text{MoS}_2$  as a cathode material for AIBs. Guo *et al.*<sup>49</sup> synthesized interlayer-expanded  $\text{MoS}_2/\text{N-doped carbon}$  (MNC) with a three-dimensional (3D) hierarchical structure by a hydrothermal method and calcination. Fig. 4d represents the synthesis of MNC. Electrochemical test results illustrated that MNC had excellent cycling ability and high discharge capacity, which were owing to the unique 3D structure provides a large specific surface area and the N-doped carbon expands the interlayer spacing of  $\text{MoS}_2$ .

Aqueous zinc ion batteries (ZIBs) are one of the rechargeable batteries based on divalent cations. Nevertheless,  $\text{Zn}^{2+}$  has strong interactions with water molecules, increasing the difficulty of  $\text{Zn}^{2+}$  diffusion and intercalation,<sup>54</sup> which hinders the development of ZIBs. To address these problems, researchers used  $\text{MoS}_2$  as an electrode material to improve the electrochemical performance of ZIBs by increasing its interlayer spacing through doping with nitrogen or oxygen.<sup>50,54</sup>

In the example of the N-doped  $\text{MoS}_2$ , Mo-organic framework (Mo-MOF) served as the nitrogen source. Basing on the one-step hydrothermal sulfurization, N-doped  $\text{MoS}_2$  was prepared.<sup>50</sup> Ideally, the 1T and 2H phases of  $\text{MoS}_2$  can be obtained by different reaction conditions (Fig. 4e).

The electrochemical test results illustrated that N-doped 1T  $\text{MoS}_2$  has not only high multiplicative performance but also superior cycling stability, which greatly improves the electrochemical performance of ZIBs.

In order to better display the synthesis and application of  $\text{MoS}_2$ -based nanomaterials in electrode materials, the preparation methods and batteries performance are summarized in Table 1. In addition, we also collected some typical nanomaterials for battery applications to compare with  $\text{MoS}_2$ .<sup>51-53</sup>

## 3. Applications and synthesis strategies of $\text{MoS}_2$ in catalyst for water splitting

The use of large amounts of fossil fuels has led to increasing environmental degradation, therefore, it is essential to produce clean, renewable energy. Hydrogen energy, as one of the clean energy sources, has been widely researched in recent years. Electrocatalytic water splitting and photocatalytic water splitting are recognized as efficient methods for the preparation of hydrogen.<sup>55-60</sup> The water splitting reaction requires an efficient catalyst. It is well known that  $\text{MoS}_2$  is a lamellar structure with abundant active sites at the edges. This property makes it a promising non-precious metal catalyst with large numbers of applications in catalysis. However, the defects of  $\text{MoS}_2$  with low bulk conductivity and anisotropic electrical transport restrict the catalytic efficiency. Therefore, researchers have developed amount of  $\text{MoS}_2$  composite catalysts to improve the catalytic efficiency.

### 3.1 Electrocatalyst

According to previous reports, either 1T-phase  $\text{MoS}_2$  catalysts or  $\text{MoS}_2$  composites catalysts have efficient catalytic performance in the HER. In detail, 1T-phase  $\text{MoS}_2$  has higher catalytic performance than 2H-phase  $\text{MoS}_2$ , benefiting from the fast charge transfer rate in the metal phase.<sup>61</sup> The compounding of  $\text{MoS}_2$  with MoN can not only improve the electrical conductivity of  $\text{MoS}_2$ , but also make  $\text{MoS}_2$  have good stability in acidic and alkaline environments.<sup>62</sup> The compounding of  $\text{MoS}_2$  with CNFs can improve the electrical conductivity of  $\text{MoS}_2$  and restrict the growth of  $\text{MoS}_2$  nanosheets.<sup>63</sup> In addition,  $\text{MoS}_2$  composites can be used as bifunctional and efficient electrocatalysts for water splitting. For example,  $\text{CoS}_2-\text{C}@\text{MoS}_2$  exhibits both excellent HER catalytic performance and good oxygen evolution reaction (OER) catalytic performance.<sup>64</sup>  $\text{MoS}_2$  compounded with  $\text{Mo}_2\text{N}$ -containing multichannel hollow CNFs ( $\text{Mo}_2\text{N}-\text{MoS}_2$  MCNFs) also possesses excellent HER and OER catalytic properties.<sup>65</sup> Subsequently, the preparation of these materials will be described.

1T- $\text{MoS}_2$  was synthesized by hydrothermal reaction. Specifically,  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$  and  $\text{N}_2\text{H}_4\text{CS}$  were dissolved in



Table 1  $\text{MoS}_2$ -based nanocomposites for electrode materials

No.	Materials	Preparation	Mo source	S source	Morphology of $\text{MoS}_2$	Battery electrodes	Specific capacity (mA h g <sup>-1</sup> )	Cycling number	Current rate (mA g <sup>-1</sup> )	Ref.
1	$\text{MoS}_2$	Wet etching method	$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	Sulfur	Nanotube	LIBs cathode	1150	250	200	36
2	$\text{MoS}_2/\text{C/C}$	Hydrothermal and electrospinning method	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	$\text{N}_2\text{H}_4\text{CS}$	Sphere	LIBs anode	1062	150	200	34
3	$\text{TiO}_2/\text{C}/\text{MoS}_2$	Solvent-thermal method and calcination	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	$\text{N}_2\text{H}_4\text{CS}$	Fish-scale-shaped (10 nm in size)	LIBs anode	621	100	100	35
4	$\text{MoS}_2/\text{C}$	Template method	$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	$\text{N}_2\text{H}_4\text{CS}$	AMT	Nanosheet	484.9	1500	2000	42
5	$\text{MoS}_2/\text{CNFs}$	Electrospinning and high temperature carbonization	$\text{MoO}_2(\text{acac})_2$	$\text{N}_2\text{H}_4\text{CS}$	Single-layer structure	SIBs anode	485	100	100	40
6	MCHRs	One-pot solvothermal reaction	$\text{MoO}_2(\text{acac})_2$	$\text{N}_2\text{H}_4\text{CS}$	Nanosheet	SIBs anode	265	3000	10 000	41
7	OMSCF	Hydrothermal process and calcination	$\text{Na}_2\text{MoO}_4$	$\text{N}_2\text{H}_4\text{CS}$	Nanosheet	SIBs anode	330	100	100	43
8	$\text{MoS}_{2-x}\text{Se}_x/\text{G}$	Hydrothermal reaction and selenization treatment	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	$\text{N}_2\text{H}_4\text{CS}$	—	SIBs anode	178	700	2000	45
9	DAM- $\text{MoS}_2$	Hydrothermal method	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	$\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$	Layered structure (0.62–1.24 nm in size)	SIBs anode	420	600	100	44
10	$\text{MoS}_2$	Hydrothermal method	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	$\text{N}_2\text{H}_4\text{CS}$	Microsphere	LIBs cathode	66.7	100	40	47
11	$\text{MoS}_2/\text{CNFs}$	Electrospinning and annealing treatment	$(\text{NH}_4)_2\text{MoS}_4$	$(\text{NH}_4)_2\text{MoS}_4$	Nanosheet	LIBs cathode	130	200	100	48
12	MNC	Hydrothermal method and calcination	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	$\text{N}_2\text{H}_4\text{CS}$	Nanosheet	LIBs cathode	127.5	1700	1000	49
13	N-doped $\text{MoS}_2$	One-step hydrothermal sulfurization	Mo-MOF	$\text{N}_2\text{H}_4\text{CS}$	Nanoflower	ZIBs cathode	98.1	1000	3000	50
14	hBN/C	Liquid-phase shear exfoliation method	—	—	—	LIBs separators	158	100	—	51
15	rGO/Al	Electrospraying	—	—	—	LIBs cathode	—	840	—	52
16	$\text{P}_4\text{Nb}_2\text{O}_{15}@\text{CNTs}$	Solvothermal method	—	—	—	LIBs anode	250	500	—	53

distilled water to form a homogeneous solution, and then the solution was put into a Teflon-lined stainless steel autoclave for reaction. The formation of 1T phase or 2H phase depends on the reaction temperature.

Hierarchical  $\text{MoS}_2/\text{MoN}$  heterostructures were obtained by a simple hydrothermal reaction and nitridation treatment.  $\text{MoS}_2$  nanospheres were synthesized from  $\text{N}_2\text{H}_4\text{CS}$  and hexaammonium molybdate in a hydrothermal reaction. Subsequently, the layered  $\text{MoS}_2/\text{MoN}$  heterostructures were synthesized by nitriding under ammonia atmosphere.

$\text{MoS}_2$ -carbon CNFs were prepared by electrospinning and graphitization treatment. First,  $(\text{NH}_4)_2\text{MoS}_4$  was dissolved in PAN solution and used for electrospinning to prepare PAN/

$(\text{NH}_4)_2\text{MoS}_4$  (PANAMo) nanofibers. Afterwards, the precursor nanofibers were graphitized to obtain  $\text{MoS}_2$ -CNFs hybrids.

$\text{CoS}_2-\text{C}@\text{MoS}_2$  core-shell nanofibers were fabricated by electrospinning method, carbonization treatment and hydrothermal synthesis. First, a certain amount of PAN and  $\text{Co}(\text{Ac})_2 \cdot 4\text{H}_2\text{O}$  were dissolved in DMF to prepare  $\text{Co}(\text{Ac})_2/\text{PAN}$  membranes by electrospinning method. Later, the Co-C nanofibers were obtained by carbonization under Ar atmosphere. Second,  $\text{CoS}_2-\text{C}@\text{MoS}_2$  core-shell nanofibers were prepared by a simple hydrothermal method using  $(\text{NH}_4)_2\text{MoS}_4$  as the S source.

As depicted in Fig. 5a, the synthesis of  $\text{Mo}_2\text{N}-\text{MoS}_2$  MCNFs was achieved by a four-step procedure. First, a certain amount

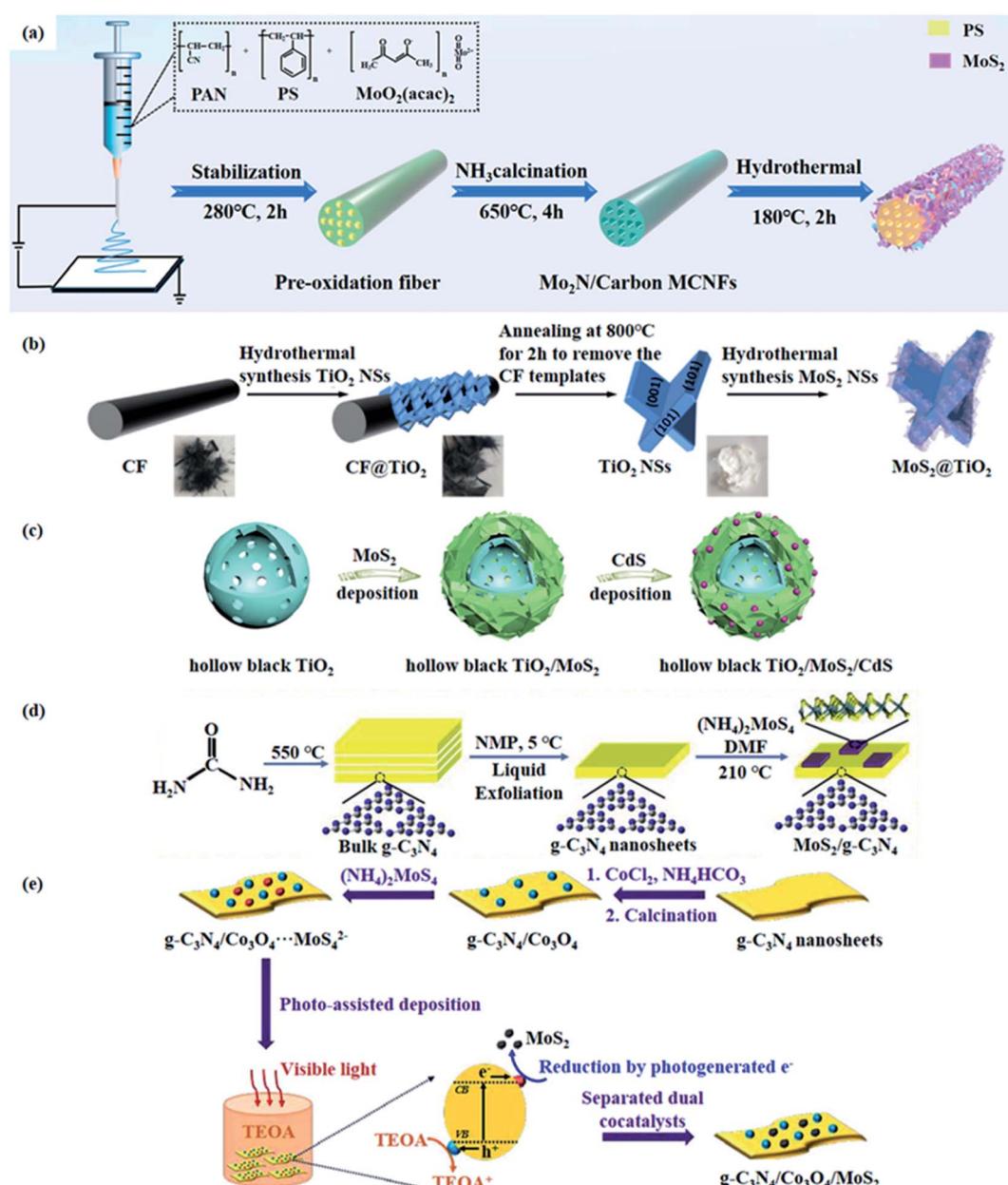


Fig. 5 The diagrammatic sketch for the preparation of (a)  $\text{Mo}_2\text{N}-\text{MoS}_2$  MCNFs,<sup>65</sup> (b)  $\text{MoS}_2@\text{TiO}_2$  composites,<sup>68</sup> (c)  $\text{TiO}_2/\text{MoS}_2/\text{CdS}$  tandem heterojunction,<sup>69</sup> (d) 2D–2D  $\text{MoS}_2/\text{g-C}_3\text{N}_4$  composites<sup>70</sup> and (e)  $\text{g-C}_3\text{N}_4/\text{Co}_3\text{O}_4/\text{MoS}_2$  heterojunction.<sup>71</sup>



Table 2  $\text{MoS}_2$ -based nanocomposites for electrocatalyst and photocatalyst

No.	Materials	Preparation	Mo source	S source	Morphology of $\text{MoS}_2$	Electrocatalyst		Overpotential (mV vs. RHE) at $J = 10 \text{ mA cm}^{-2}$	Ref.
						Tafel slope (mV dec $^{-1}$ )	214 (HER)		
1	1T- $\text{MoS}_2$	Hydrothermal reaction	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	Thiourea	Nanosheet	54 (HER)	214 (HER)	61	61
2	$\text{MoS}_2/\text{MoN}$	Hydrothermal reaction and nitridation treatment	Hexaammonium molybdate	Thiourea	Nanosphere	98 (HER, KOH); 87 (HER, $\text{H}_2\text{SO}_4$ )	132 (HER, KOH); 117 (HER, $\text{H}_2\text{SO}_4$ )	62	62
3	$\text{MoS}_2/\text{CNFs}$	Electrospinning and graphitization treatment	$(\text{NH}_4)_2\text{MoS}_4$	$(\text{NH}_4)_2\text{MoS}_4$	Nanoplate	42 (HER)	93 (HER)	63	63
4	$\text{CoS}_2-\text{O}@\text{MoS}_2$	Electrospinning method, carbonization treatment and hydrothermal synthesis	$(\text{NH}_4)_2\text{MoS}_4$	$(\text{NH}_4)_2\text{MoS}_4$	Nanosheet	61 (HER); 46 (OER)	173 (HER); 391 (OER)	64	64
5	$\text{Mo}_2\text{N}-\text{MoS}_2$ MCNFs	Electrospinning method, $\text{NH}_3$ calcination and hydrothermal synthesis	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$	Thiourea	Nanosheet	68.9 (HER); 57.2 (OER)	131 (HER); 270 (OER)	65	65
6	Graphene-hBN	Exfoliation and Hummer's method	—	—	—	—	390 (HER)	66	66
7	Cobalt- and nitrogen-codoped graphene	Annealing strategy	—	—	—	73 (OER)	210 (OER)	67	67
Photocatalyst									
No.	Materials	Preparation	Mo source	S source	Morphology of $\text{MoS}_2$	Photocatalyst		$\text{H}_2$ evolution rate (mmol h $^{-1}$ g $^{-1}$ )	Ref.
8	$\text{MoS}_2@\text{TiO}_2$	Hydrothermal/annealing treatment and subsequent photoreduction method	$(\text{NH}_4)_2\text{MoS}_4$	$(\text{NH}_4)_2\text{MoS}_4$	Nanosheet	2.16	68		
9	$\text{TiO}_2/\text{MoS}_2/\text{CdS}$	Template-free solvothermal approach, solvothermal approach and wet chemical method	$\text{MoO}_3$	Thiourea	Nanosheet	9	69		
10	$\text{MoS}_2/g-\text{C}_3\text{N}_4$	Direct heating of urea and a solvent-thermal method	$(\text{NH}_4)_2\text{MoS}_4$	$(\text{NH}_4)_2\text{MoS}_4$	Nanosheet	1.155	70	70	70
11	$g-\text{C}_3\text{N}_4/\text{Co}_3\text{O}_4/\text{MoS}_2$	Two-step thermal treatment, coprecipitation-calcination strategy and <i>in situ</i> photodeposition	$(\text{NH}_4)_2\text{MoS}_4$	$(\text{NH}_4)_2\text{MoS}_4$	$\text{MoS}_2$ nanocrystal	5.25	71	71	71
12	Sulfur-doped h-BN	CVD	—	—	—	1.3485	72	72	72

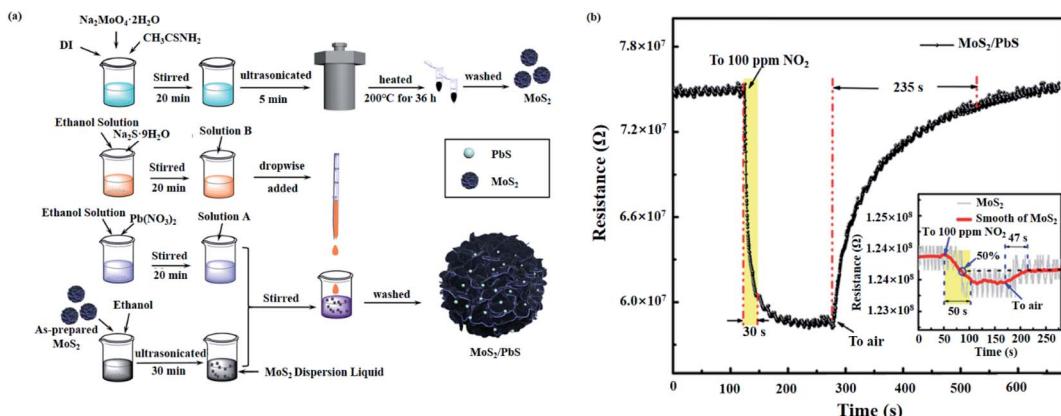


Fig. 6 (a) Preparation process of MoS<sub>2</sub>/PbS composites.<sup>78</sup> (b) Transient response characteristic of MoS<sub>2</sub>/PbS gas sensor at 100 ppm NO<sub>2</sub>.<sup>78</sup>

of PAN and polystyrene (PS) were dissolved in DMF, stirred well and then MoO<sub>2</sub>(acac)<sub>2</sub> was added to form a precursor solution for electrospinning to obtain MoO<sub>2</sub>(acac)<sub>2</sub>@PAN/PS fiber. Second, previously obtained fiber was pre-oxidized in air. Third,

Mo<sub>2</sub>N/C MCFs were prepared by calcination of the pre-oxidation fiber under NH<sub>3</sub> atmosphere. During calcination, PS gradually decomposed, leading to the formation of channels in the fibers. Finally, Mo<sub>2</sub>N-MoS<sub>2</sub> MCNFs were successfully prepared by

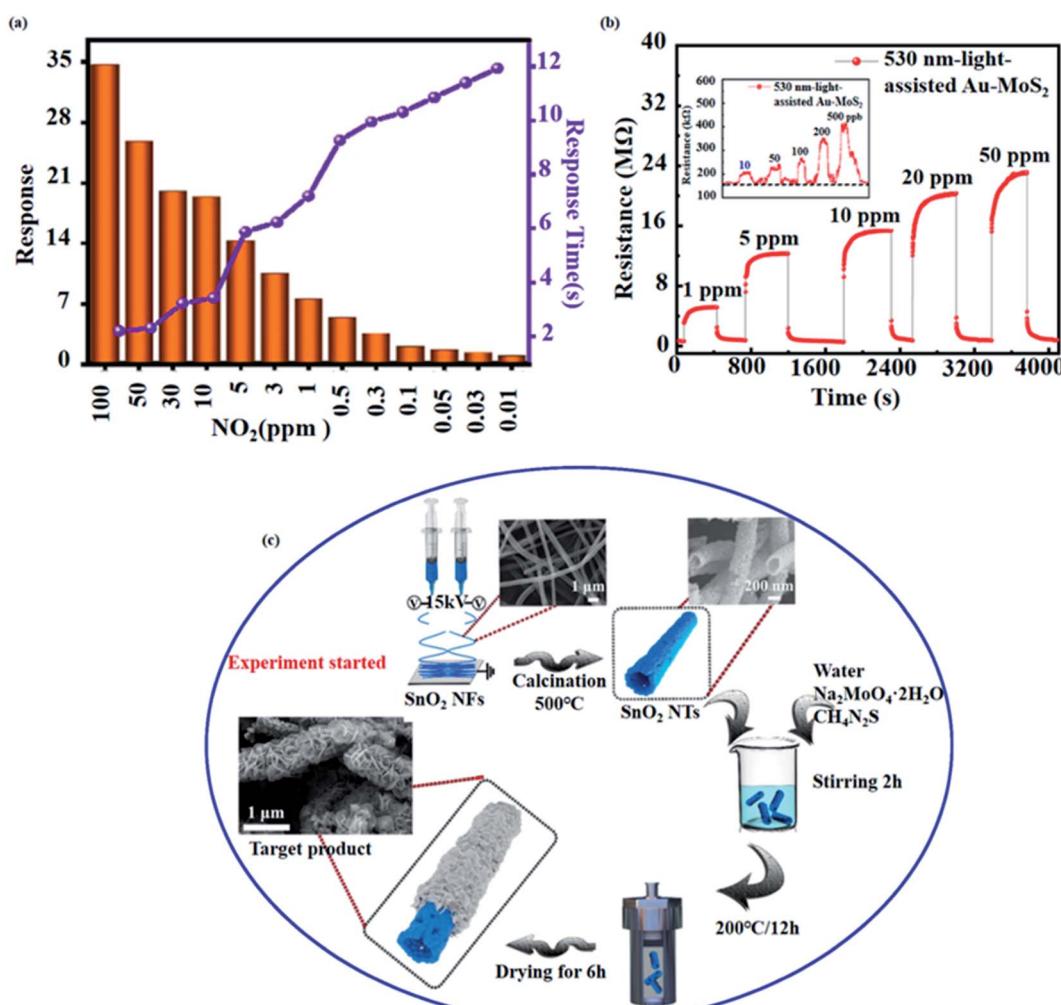


Fig. 7 (a) Response and response time of MoS<sub>2</sub>@SnO<sub>2</sub> sensor to 0.01–100 ppm NO<sub>2</sub>.<sup>79</sup> (b) Real-time sensing response curves of the 530 nm-light-assisted Au–MoS<sub>2</sub> sensor at 1–50 ppm NO<sub>2</sub>.<sup>80</sup> (c) Schematic diagram of the synthesis of MoS<sub>2</sub>@SnO<sub>2</sub>.<sup>79</sup>

hydrothermal method to grow  $\text{MoS}_2$  nanosheets on the surface of  $\text{Mo}_2\text{N}/\text{Carbon MCNFs}$ .

### 3.2 Photocatalyst

Photocatalytic water splitting reaction is considered as one of the effective ways to prepare green, renewable energy, due to its ability to convert solar energy into hydrogen energy. In recent years, with the development of hydrogen preparation reaction by photocatalytic water splitting, more and more photocatalysts have been studied and prepared, including those prepared with graphite carbon nitride ( $\text{g-C}_3\text{N}_4$ ),  $\text{TiO}_2$  or  $\text{CdS}$  as materials. It has been shown that the compound of  $\text{MoS}_2$  with the above materials can improve the catalytic activity of the photocatalyst and promote the preparation of hydrogen by water splitting.<sup>68–71,73</sup>

Hu *et al.*<sup>68</sup> prepared  $\text{MoS}_2@\text{TiO}_2$  composites by using combination of hydrothermal/annealing treatment with subsequent photoreduction method. It is noted that  $\text{MoS}_2$  nanosheets can be selectively deposited on the (101) facets of  $\text{TiO}_2$ , allowing for increased photocatalytic hydrogen production activity of the  $\text{MoS}_2@\text{TiO}_2$  composites. Sun *et al.*<sup>69</sup> fabricated a hollow  $\text{TiO}_2/\text{MoS}_2/\text{CdS}$  tandem heterojunction *via* three main steps. First, the hollow mesoporous  $\text{TiO}_2$  spheres were synthesized by a template-free solvothermal approach. Second,  $\text{MoS}_2$  nanosheets were coated on the surface of  $\text{TiO}_2$  by a solvothermal approach. Finally,  $\text{CdS}$  nanoparticles were selectively deposited on the edges of  $\text{MoS}_2$

nanosheets though a wet chemical method.  $\text{MoS}_2$  not only serves as an excellent cocatalyst, but also promotes charge separation and effectively inhibits the complexation of photogenerated electrons and holes. Yuan *et al.*<sup>70</sup> obtained 2D–2D  $\text{MoS}_2/\text{g-C}_3\text{N}_4$  photocatalyst though a simple probe sonication assisted liquid exfoliation method and a solvent-thermal method. The large surface area of  $\text{g-C}_3\text{N}_4$  nanosheets and the large 2D nanointerface between  $\text{MoS}_2$  and  $\text{g-C}_3\text{N}_4$  nanosheets greatly enhance the catalytic hydrogen production activity of the photocatalyst. Zhao *et al.*<sup>71</sup> synthesized  $\text{g-C}_3\text{N}_4/\text{Co}_3\text{O}_4/\text{MoS}_2$  heterojunction *via* chemical deposition and photo-deposition method.  $\text{Co}_3\text{O}_4$  and  $\text{MoS}_2$  were used as co-catalysts with efficient photocatalytic activity under visible light irradiation. Their synthesis schematic is demonstrated in Fig. 5b–e.

In order to better display the synthesis and application of  $\text{MoS}_2$ -based nanomaterials in catalysis, the preparation methods and catalytic performance are summarized in Table 2. Furthermore, for comparison, we summarize performance parameters of some typical nanomaterials in electrocatalysis and photocatalysis at the end of the table.<sup>66,67,72</sup>

## 4. Applications and synthesis strategies of $\text{MoS}_2$ in gas sensors

Important factors affecting the performance of gas sensors have been reported to include specific surface area, semiconductor properties, and redox reaction active sites.<sup>74</sup> As mentioned

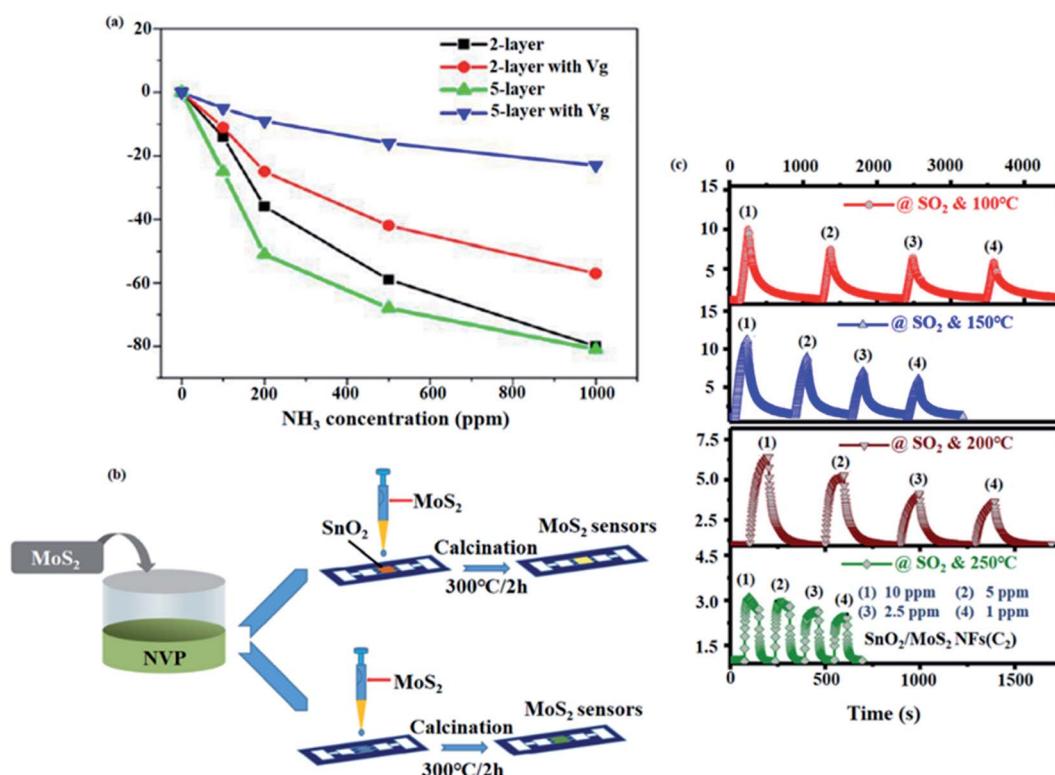


Fig. 8 (a) Sensitivity of 2-layer and 5-layer  $\text{MoS}_2$  as a function of  $\text{NH}_3$  concentration.<sup>74</sup> (b) Schematic diagram of the fabrication of  $\text{MoS}_2$  sensors and  $\text{MoS}_2/\text{SnO}_2$  sensors.<sup>81</sup> (c) Response of  $\text{MoS}_2/\text{SnO}_2$  sensors to different concentrations of  $\text{SO}_2$  gas at different operating temperatures.<sup>81</sup>



earlier,  $\text{MoS}_2$  is a graphene-like material possessing a 2D layer structure with a large specific surface area and excellent semiconductor properties. In addition, it has been pointed out that  $\text{MoS}_2$  has different affinities for different molecules,<sup>75</sup> which makes  $\text{MoS}_2$  one of the promising materials for the preparation of gas sensors.

#### 4.1 $\text{MoS}_2$ -based gas sensors toward nitrogen dioxide

Nitrogen dioxide ( $\text{NO}_2$ ) is one of the prevalent pollutants in the air, as well as a toxic gas that endangers human health, causing great damage to human eyes and respiratory tracts even when exposed to concentrations as low as 3 ppm.<sup>76</sup> Therefore, it is urgent to develop gas sensors that can detect  $\text{NO}_2$  effectively and rapidly. The detection of  $\text{NO}_2$  by pure  $\text{MoS}_2$  or  $\text{MoS}_2$  composites as gas-sensitive elements is one of the main focuses of gas sensors research in recent years.

Using pure  $\text{MoS}_2$  as gas sensitive element, some researches have prepared  $\text{MoS}_2$  by chemical vapor deposition (CVD) method. For instance, Kumar *et al.*<sup>77</sup> obtained 2D  $\text{MoS}_2$  by CVD

with  $\text{MoO}_3$  powder and sulfur as precursors. The test results revealed that the  $\text{MoS}_2$  gas sensor had a response time of 29 s and a recovery time of 350 s for 100 ppm concentration of  $\text{NO}_2$  when operating in a RT environment irradiated by UV lamps ( $\sim 365$  nm). Similarly, Kim *et al.*<sup>13</sup> fabricated layer-controlled  $\text{MoS}_2$  by CVD with molybdenum hexacarbonyl ( $\text{Mo}(\text{CO})_6$ ) and hydrogen sulfide ( $\text{H}_2\text{S}$ ). It is found that the Schottky barrier changes due to the change in the number of  $\text{MoS}_2$  layers, which results in an improved response of the gas sensor. Zheng *et al.*<sup>75</sup> synthesized n-type and p-type  $\text{MoS}_2$  films by CVD and soft-chemistry route, respectively. In CVD process,  $\text{MoO}_3$  and sulfur were used as precursors, while in the soft-chemistry route, molybdate sol-gel (contain 1% W) was used as precursors. Uniquely, they prepared a novel p-n junction gas sensor by stacking n-type and p-type  $\text{MoS}_2$  atomic layers. The results represented that compared with n-type  $\text{MoS}_2$  gas sensor, the p-type  $\text{MoS}_2$  has a faster response to  $\text{NO}_2$ . More importantly, the p-n junction sensor not only has a 20-fold increase in sensitivity to 20 ppm  $\text{NO}_2$ , but also has a lower detection limit of 8 ppb.

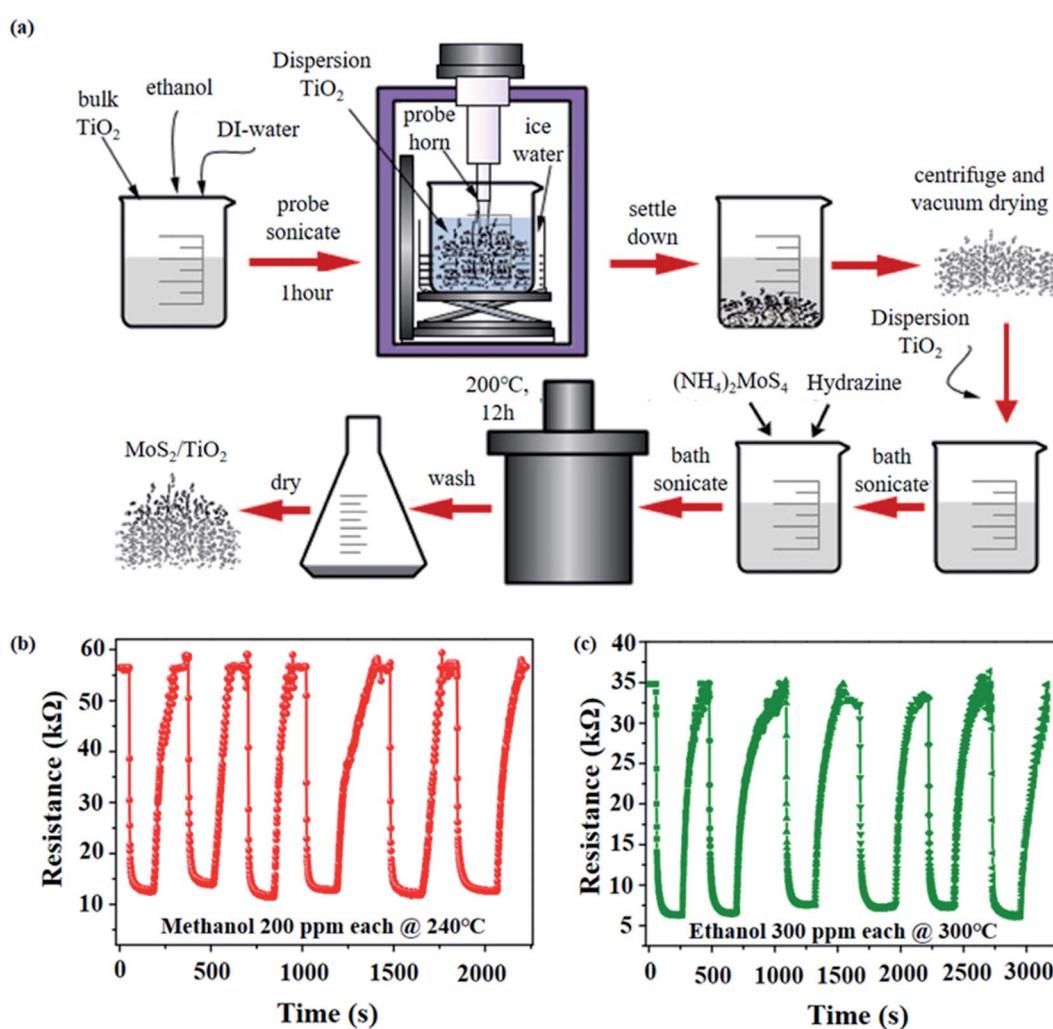
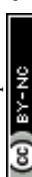


Fig. 9 (a) Schematic diagram of the synthesis of  $\text{MoS}_2/\text{TiO}_2$  composite.<sup>82</sup> (b) Repeatability testing of 200 ppm methanol for six consecutive cycles at an operating temperature of  $240^\circ\text{C}$ .<sup>82</sup> (c) Repeatability testing of 300 ppm ethanol for six consecutive cycles at an operating temperature of  $300^\circ\text{C}$ .



Table 3 MoS<sub>2</sub>-based nanocomposites for gas sensors

No.	Materials	Preparation	Mo source	S source	Morphology	Target Gas	Res/Rec (s)	Response ( $R_g/R_a$ )	T (°C)	Detection limits	Ref.
1	MoS <sub>2</sub>	CVD	MoO <sub>3</sub>	Sulfur	Film	100 ppm of NO <sub>2</sub>	29/350	1.3516	RT (UV)	—	77
2	MoS <sub>2</sub>	CVD	Mo(CO) <sub>6</sub>	H <sub>2</sub> S	Film	10 ppm of NO <sub>2</sub>	—/—	1.6	RT	—	13
3	MoS <sub>2</sub>	CVD	MoO <sub>3</sub>	Sulfur	Film	20 ppm of NO <sub>2</sub>	150/30	—	RT (UV)	8 ppb	75
4	MoS <sub>2</sub> /PbS	Hydrothermal method combined with chemical precipitation	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	CH <sub>3</sub> CSNH <sub>2</sub>	Fluffy ball-like structure	100 ppm of NO <sub>2</sub>	30/235	—	RT	—	78
5	MoS <sub>2</sub> @SnO <sub>2</sub>	Electrospinning and hydrothermal growth	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	N <sub>2</sub> H <sub>4</sub> CS	Nanoflake	100 ppm of NO <sub>2</sub>	2.2/10.54	0.02884	RT	10 ppb	79
6	Au-MoS <sub>2</sub>	Hydrothermal method	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	CH <sub>3</sub> CSNH <sub>2</sub>	Fluffy flower-like structure	1 ppm of NO <sub>2</sub>	—/27	8.1	RT (530 nm LED)	10 ppb	80
7	MoS <sub>2</sub>	Micromechanical exfoliation method	Bulk MoS <sub>2</sub> crystal	Bulk MoS <sub>2</sub>	Layered	1000 ppm of NO <sub>2</sub>	—/—	14.72	RT	—	74
8	MoS <sub>2</sub>	Micromechanical exfoliation method	Bulk MoS <sub>2</sub> crystal	Bulk MoS <sub>2</sub>	Layered	1000 ppm of NH <sub>3</sub>	—/—	1.86	RT	—	74
9	SnO <sub>2</sub> /MoS <sub>2</sub>	Electrospinning and drop-coated process	MoS <sub>2</sub> powder		Nanosheet	10 ppm of SO <sub>2</sub>	—/—	11.1	150	5 ppt (parts-per-trillion)	81
10	MoS <sub>2</sub> /TiO <sub>2</sub>	Low-cost hydrothermal method	(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub>	(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub>	Layered	500 ppm of ethanol	50/100	nearly 0	300	—	82
11	MoS <sub>2</sub> /TiO <sub>2</sub>	Low-cost hydrothermal method	(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub>	(NH <sub>4</sub> ) <sub>2</sub> MoS <sub>4</sub>	Layered	500 ppm of methanol	—/—	0.15	240	—	82
12	CuO/rGO	LB self-assemble	—	—	—	1 ppm of CO	70/160	1.0256	RT	—	83
13	Single-walled carbon nanotubes	—	—	—	—	100 ppb of NO	—/—	0.7136	RT	—	84
14	Graphene oxide	Thermal reduction	—	—	—	5 ppm of NO <sub>2</sub>	—/—	0.83	RT	—	85
15	DETA doped graphene	CVD and vapor-phase molecular doping	—	—	—	50 ppm of NO <sub>2</sub>	—/—	0.23	RT	0.83 ppq (parts per quadrillion)	86

Just as pure  $\text{MoS}_2$  gas sensors exhibit gas-sensitive performance on  $\text{NO}_2$  gas,  $\text{MoS}_2$  composite gas sensors also have excellent gas-sensitive properties. For example, the  $\text{PbS}$  quantum dots modified  $\text{MoS}_2$  ( $\text{MoS}_2/\text{PbS}$ ) composite gas sensor prepared by *Xin et al.*<sup>78</sup> has excellent gas-sensitive performance for  $\text{NO}_2$  due to the high response of  $\text{PbS}$  quantum dots to  $\text{NO}_2$  and the prevention of  $\text{MoS}_2$  oxidation.  $\text{MoS}_2/\text{PbS}$  was prepared by hydrothermal and chemical precipitation methods, and the specific preparation is shown in Fig. 6a. First of all, pure  $\text{MoS}_2$  was prepared from  $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$  and  $\text{CH}_3\text{CSNH}_2$  by hydrothermal reaction under an Teflon-lined autoclave at  $200\text{ }^\circ\text{C}$ . Secondly, the doping of  $\text{PbS}$  quantum dots was achieved by chemical precipitation using  $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$  and  $\text{Pb}(\text{NO}_3)_2$  as precursors. Compared with pure  $\text{MoS}_2$ , the  $\text{MoS}_2/\text{PbS}$  gas sensor has higher response and recovery performance for 100 ppm  $\text{NO}_2$  gas at RT (Fig. 6b).

Composites of  $\text{MoS}_2$  nanosheets with  $\text{SnO}_2$  nanotubes were prepared for gas-sensitive properties by *Bai et al.*  $\text{MoS}_2@\text{SnO}_2$  heterostructure exhibits impressive sensitivity and selectivity for the detection of  $\text{NO}_2$  gas at RT. Tests illustrated that the  $\text{MoS}_2@\text{SnO}_2$  gas sensor had a fast response time (2.2 s), a short recovery time (10.54 s), a low detection limit (10 ppb) and excellent stability (20 weeks) (Fig. 7a).<sup>79</sup> Another reported composite is  $\text{MoS}_2$  nanoflowers modified with Au nanoparticles prepared by *Chen et al.* Surprisingly, the Au– $\text{MoS}_2$  gas sensor exhibits an extremely low detection limit (10 ppb) for  $\text{NO}_2$  at RT with strong resistance to moisture interference under 530 nm light illumination (Fig. 7b).<sup>80</sup>

The preparation of  $\text{MoS}_2@\text{SnO}_2$  was achieved by electrostatic spinning and hydrothermal methods, as presented in Fig. 7c. First, stannous chloride ( $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ ) was mixed with anhydrous ethanol, DMF and PVP to make electrospinning solution, and  $\text{SnO}_2$  NTs were obtained by spinning technique and subsequent high-temperature calcination treatment. Second,  $\text{N}_2\text{H}_4\text{CS}$  and  $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$  were used as the S and Mo sources, respectively, to mix with the previously prepared  $\text{SnO}_2$  NTs, and the reaction was carried out in an autoclave at  $200\text{ }^\circ\text{C}$  to realize  $\text{MoS}_2$  on  $\text{SnO}_2$  NTs growth.<sup>79</sup>

The fabrication of Au– $\text{MoS}_2$  composites was achieved by a two-step hydrothermal method. Firstly,  $\text{MoS}_2$  was obtained by reacting  $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$  and thioacetamide ( $\text{CH}_3\text{CSNH}_2$ ) in a Teflon-lined autoclave at  $200\text{ }^\circ\text{C}$  for 36 h. Secondly, Au– $\text{MoS}_2$  was synthesized by mixing sodium citrate tribasic dihydrate ( $\text{C}_6\text{H}_5\text{Na}_3\text{O}_7 \cdot 2\text{H}_2\text{O}$ ), tannic acid ( $\text{C}_{76}\text{H}_{52}\text{O}_{46}$ ) and previously prepared  $\text{MoS}_2$ , then adding gold chloride trihydrate ( $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$ ) solution dropwise and stirring well, and then reacting in a Teflon-lined autoclave.<sup>80</sup>

## 4.2 $\text{MoS}_2$ -based gas sensors for other gases

The  $\text{MoS}_2$ -based gas sensors not only detect  $\text{NO}_2$  gas extremely well, but also reveal excellent gas sensitivity to  $\text{NH}_3$ ,  $\text{SO}_2$  and alcohol gases.

*Dattatray J. Late et al.*<sup>74</sup> prepared layered  $\text{MoS}_2$  films by micromechanical exfoliation method in 2013 for the preparation of gas sensors to detect  $\text{NH}_3$  gas. The experimental results demonstrated that the 2-layer  $\text{MoS}_2$  and 5-layer  $\text{MoS}_2$  have

excellent gas-sensitive performance to  $\text{NH}_3$ , and the 5-layer  $\text{MoS}_2$  is more sensitive to detect  $\text{NH}_3$ . In addition, when the  $\text{MoS}_2$  gas sensor is applied with a positive gate voltage, the electric field formed at the interface will repel the electrons given by  $\text{NH}_3$  as an electron donor, resulting in a decrease in the sensitivity of  $\text{MoS}_2$  to  $\text{NH}_3$ . Fig. 8a shows the curves of sensitivity with  $\text{NH}_3$  concentration for 2-layer and 5-layer  $\text{MoS}_2$  with and without gate voltage.

*Nguyen Ngoc Viet et al.*<sup>81</sup> prepared  $\text{MoS}_2/\text{SnO}_2$  sensors for  $\text{SO}_2$  gas detection by on-chip electrostatic spinning and subsequently dropping  $\text{MoS}_2$  nanosheets-dispersed solution, and the fabrication is depicted in Fig. 8b. The test results indicated that the  $\text{MoS}_2/\text{SnO}_2$  gas sensor had good gas-sensitive performance for 10 ppm  $\text{SO}_2$  gas at  $150\text{ }^\circ\text{C}$  (Fig. 8c).

*Sukhwinder Singh et al.*<sup>82</sup> prepared  $\text{MoS}_2/\text{TiO}_2$  composite for the detection of methanol and ethanol. As shown in Fig. 9a,  $\text{MoS}_2/\text{TiO}_2$  hybrid was obtained by two steps: first, pure  $\text{TiO}_2$  powder was mixed with ethanol and other solvents for probe sonication, and second,  $(\text{NH}_4)_2\text{MoS}_4$  was mixed with the produced  $\text{TiO}_2$  suspension to prepare  $\text{MoS}_2/\text{TiO}_2$  composites by hydrothermal method. The test results revealed that the best working temperatures of  $\text{MoS}_2/\text{TiO}_2$  composites for methanol and ethanol were  $240\text{ }^\circ\text{C}$  and  $300\text{ }^\circ\text{C}$ , respectively, and more importantly, the  $\text{MoS}_2/\text{TiO}_2$  sensor had good response and better stability (Fig. 9b and c).

The gas sensing performance of  $\text{MoS}_2$ -based nanomaterials and the preparation methods are listed in Table 3. As a comparison, the gas-sensitive properties of some typical materials are collected at the end of the table.<sup>83–86</sup>

## 5. Conclusion

This review highlights recent advances in  $\text{MoS}_2$ -based materials synthesis and their applications toward batteries, catalysts and gas sensors. First of all,  $\text{MoS}_2$ , due to the large specific surface area and abundant active sites, has become one of the most popular electrode materials. In addition, the compound of  $\text{MoS}_2$  with CNFs and  $\text{TiO}_2$  materials overcomes the inherent defects of  $\text{MoS}_2$  and greatly improves the electrochemical performance of the battery. Second,  $\text{MoS}_2$  has catalytic active sites on the edges, which makes it one of the most popular candidates to replace noble metal catalysts. The composite of  $\text{MoS}_2$  with  $\text{MoN}$ ,  $\text{CoS}_2$  and  $\text{C}_3\text{N}_4$  improved the catalytic performance of the catalyst. Finally,  $\text{MoS}_2$  can be used in gas sensors due to the semiconductor properties and non-zero forbidden bandwidth. The compound of  $\text{MoS}_2$  with materials such as  $\text{SnO}_2$  and  $\text{PbS}$  can enhance the sensitivity of the gas sensor to the gas to be detected and reduce the detection limit.

It is worth noting that while  $\text{MoS}_2$  has made good progress in these areas, challenges remain in its future development. First,  $\text{MoS}_2$  has low electrical conductivity and multilayer  $\text{MoS}_2$  tends to accumulate and aggregate in the preparation, which is not conducive to electron transport. Second, the active sites of  $\text{MoS}_2$  are mainly at the edges but not at the basal plane, which has a significant impact on both the sensing performance and catalytic performance. Therefore, it is necessary to further explore the compounding of  $\text{MoS}_2$  with other materials or to



optimize the structure of  $\text{MoS}_2$  (*e.g.*, preparation of  $\text{MoS}_2$  NTs, *etc.*). In addition, 1T- $\text{MoS}_2$  has better electrical conductivity compared with 2H- $\text{MoS}_2$ , and there are also interesting electrical properties using 1T- $\text{MoS}_2$  compounded with other materials.

In a word,  $\text{MoS}_2$  has promising applications in energy and gas sensors due to its excellent and unique physicochemical properties. We believe that with the joint efforts of researchers in the future, better progress will be made in the applications and synthesis of  $\text{MoS}_2$ .

## Conflicts of interest

There are no conflicts to declare.

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## References

- 1 K. S. Novoselov, D. Jiang, F. Schedin, T. Booth, V. Khotkevich, S. Morozov and A. K. Geim, *Proc. Natl. Acad. Sci.*, 2005, **102**, 10451–10453.
- 2 S. Z. Butler, S. M. Hollen, L. Cao, Y. Cui, J. A. Gupta, H. R. Gutiérrez, T. F. Heinz, S. S. Hong, J. Huang and A. F. Ismach, *ACS Nano*, 2013, **7**, 2898–2926.
- 3 G. R. Bhimanapati, Z. Lin, V. Meunier, Y. Jung, J. Cha, S. Das, D. Xiao, Y. Son, M. S. Strano and V. R. Cooper, *ACS Nano*, 2015, **9**, 11509–11539.
- 4 Z. Wang and B. Mi, *Environ. Sci. Technol.*, 2017, **51**, 8229–8244.
- 5 H. Wang, C. Li, P. Fang, Z. Zhang and J. Z. Zhang, *Chem. Soc. Rev.*, 2018, **47**, 6101–6127.
- 6 U. Krishnan, M. Kaur, K. Singh, M. Kumar and A. Kumar, *Superlattices Microstruct.*, 2019, **128**, 274–297.
- 7 T. Nawz, A. Safdar, M. Hussain, D. Sung Lee and M. Siyar, *Crystals*, 2020, **10**.
- 8 D. Saha and P. Kruse, *J. Electrochem. Soc.*, 2020, 167.
- 9 O. Samy and A. El Moutaouakil, *Energies*, 2021, **14**.
- 10 Y. Zhang, H. Tao, S. Du and X. Yang, *ACS Appl. Mater. Interfaces*, 2019, **11**, 11327–11337.
- 11 R. Bose, Z. Jin, S. Shin, S. Kim, S. Lee and Y. S. Min, *Langmuir*, 2017, **33**, 5628–5635.
- 12 Y. Wang, J. Sunarso, F. Wang, B. Zhao, X. Liu and G. Chen, *Ceram. Int.*, 2017, **43**, 11028–11033.
- 13 Y. Kim, S. K. Kang, N. C. Oh, H. D. Lee, S. M. Lee, J. Park and H. Kim, *ACS Appl. Mater. Interfaces*, 2019, **11**, 38902–38909.
- 14 Z. Liu, L. Zhao, Y. Liu, Z. Gao, S. Yuan, X. Li, N. Li and S. Miao, *Appl. Catal., B*, 2019, **246**, 296–302.
- 15 E. Singh, K. S. Kim, G. Y. Yeom and H. S. Nalwa, *ACS Appl. Mater. Interfaces*, 2017, **9**, 3223–3245.
- 16 X. Li and H. Zhu, *J. Materomics*, 2015, **1**, 33–44.
- 17 Y. Qiao, T. Hirtz, F. Wu, G. Deng, X. Li, Y. Zhi, H. Tian, Y. Yang and T.-L. Ren, *ACS Appl. Electron. Mater.*, 2019, **2**, 346–370.
- 18 Y. Liu and F. Gu, *Nanoscale Adv.*, 2021, **3**, 2117–2138.
- 19 O. Samy, S. Zeng, M. D. Birowosuto and A. El Moutaouakil, *Crystals*, 2021, **11**.
- 20 Y. P. Venkata Subbaiah, K. J. Saji and A. Tiwari, *Adv. Funct. Mater.*, 2016, **26**, 2046–2069.
- 21 W. Zhang, P. Zhang, Z. Su and G. Wei, *Nanoscale*, 2015, **7**, 18364–18378.
- 22 H. S. Nalwa, *RSC Adv.*, 2020, **10**, 30529–30602.
- 23 S. Barua, H. S. Dutta, S. Gogoi, R. Devi and R. Khan, *ACS Appl. Nano Mater.*, 2017, **1**, 2–25.
- 24 S. Shi, Z. Sun and Y. H. Hu, *J. Mater. Chem. A*, 2018, **6**, 23932–23977.
- 25 L. Lei, D. Huang, G. Zeng, M. Cheng, D. Jiang, C. Zhou, S. Chen and W. Wang, *Coord. Chem. Rev.*, 2019, **399**, 213020.
- 26 Y. Jiao, A. M. Hafez, D. Cao, A. Mukhopadhyay, Y. Ma and H. Zhu, *Small*, 2018, **14**, e1800640.
- 27 J. Sun, X. Li, W. Guo, M. Zhao, X. Fan, Y. Dong, C. Xu, J. Deng and Y. Fu, *Crystals*, 2017, **7**(7), 198.
- 28 Z. Liu, X. Wang, Z. Liu, S. Zhang, Z. Lv, Y. Cui, L. Du, K. Li, G. Zhang, M. C. Lin and H. Du, *ACS Appl. Mater. Interfaces*, 2021, **13**, 28164–28170.
- 29 N. Qiu, Z. Yang, R. Xue, Y. Wang, Y. Zhu and W. Liu, *Nano Lett.*, 2021, **21**, 2738–2744.
- 30 S. G. Stolyarova, A. A. Kotsun, Y. V. Shubin, V. O. Koroteev, P. E. Plyusnin, Y. L. Mikhlin, M. S. Mel'gunov, A. V. Okotrub and L. G. Bulusheva, *ACS Appl. Energy Mater.*, 2020, **3**, 10802–10813.
- 31 Z. Yuan, L. Wang, D. Li, J. Cao and W. Han, *ACS Nano*, 2021, **15**, 7439–7450.
- 32 C. Zhu, X. Mu, P. A. van Aken, Y. Yu and J. Maier, *Angew. Chem., Int. Ed. Engl.*, 2014, **53**, 2152–2156.
- 33 C.-Y. Wei, P.-C. Lee, C.-W. Tsao, L.-H. Lee, D.-Y. Wang and C.-Y. Wen, *ACS Appl. Energy Mater.*, 2020, **3**, 7066–7072.
- 34 H. Wu, C. Hou, G. Shen, T. Liu, Y. Shao, R. Xiao and H. Wang, *Nano Res.*, 2018, **11**, 5866–5878.
- 35 J. Zhang, Y. Li, T. Gao, X. Sun, P. Cao and G. Zhou, *Ceram. Int.*, 2018, **44**, 8550–8555.
- 36 X. Zhao, Z. Liu, W. Xiao, H. Huang, L. Zhang, Y. Cheng and J. Zhang, *ACS Appl. Nano Mater.*, 2020, **3**, 7580–7586.
- 37 S. Ding, D. Zhang, J. S. Chen and X. W. Lou, *Nanoscale*, 2012, **4**, 95–98.
- 38 Y. Lu, X. Yao, J. Yin, G. Peng, P. Cui and X. Xu, *RSC Adv.*, 2015, **5**, 7938–7943.
- 39 K. Yao, Z. Xu, J. Huang, M. Ma, L. Fu, X. Shen, J. Li and M. Fu, *Small*, 2019, **15**, e1805405.
- 40 A. Cheng, H. Zhang, W. Zhong, Z. Li, Y. Tang and Z. Li, *J. Electroanal. Chem.*, 2019, **843**, 31–36.
- 41 L. Han, S. Wu, Z. Hu, M. Chen, J. Ding, S. Wang, Y. Zhang, D. Guo, L. Zhang, S. Cao and S. Chou, *ACS Appl. Mater. Interfaces*, 2020, **12**, 10402–10409.
- 42 Q. Pan, Q. Zhang, F. Zheng, Y. Liu, Y. Li, X. Ou, X. Xiong, C. Yang and M. Liu, *ACS Nano*, 2018, **12**, 12578–12586.



43 Y. Zhang, H. Tao, T. Li, S. Du, J. Li, Y. Zhang and X. Yang, *ACS Appl. Mater. Interfaces*, 2018, **10**, 35206–35215.

44 H. Dai, M. Tang, J. Huang and Z. Wang, *ACS Appl. Mater. Interfaces*, 2021, **13**, 10870–10877.

45 Y. Zhang, H. Tao, S. Du and X. Yang, *ACS Appl. Mater. Interfaces*, 2019, **11**, 11327–11337.

46 H. Dai, J. Sun, Y. Zhou, Z. Zhou, W. Luo, G. Wei and H. Deng, *ACS Sustainable Chem. Eng.*, 2020, **8**, 8102–8110.

47 Z. Li, B. Niu, J. Liu, J. Li and F. Kang, *ACS Appl. Mater. Interfaces*, 2018, **10**, 9451–9459.

48 W. Yang, H. Lu, Y. Cao, B. Xu, Y. Deng and W. Cai, *ACS Sustainable Chem. Eng.*, 2019, **7**, 4861–4867.

49 S. Guo, H. Yang, M. Liu, X. Feng, H. Xu, Y. Bai and C. Wu, *ACS Appl. Energy Mater.*, 2021, **4**, 7064–7072.

50 Z. Sheng, P. Qi, Y. Lu, G. Liu, M. Chen, X. Gan, Y. Qin, K. Hao and Y. Tang, *ACS Appl. Mater. Interfaces*, 2021, **13**, 34495–34506.

51 A. C. M. de Moraes, W. J. Hyun, N. S. Luu, J. M. Lim, K. Y. Park and M. C. Hersam, *ACS Appl. Mater. Interfaces*, 2020, **12**, 8107–8114.

52 G. Zhang, K. Lin, X. Qin, L. Zhang, T. Li, F. Lv, Y. Xia, W. Han, F. Kang and B. Li, *ACS Appl. Mater. Interfaces*, 2020, **12**, 37034–37046.

53 P. Hei, S. Luo, K. Wei, J. Zhou, Y. Zhao and F. Gao, *ACS Sustainable Chem. Eng.*, 2020, **9**, 216–223.

54 H. Liang, Z. Cao, F. Ming, W. Zhang, D. H. Anjum, Y. Cui, L. Cavallo and H. N. Alshareef, *Nano Lett.*, 2019, **19**, 3199–3206.

55 L. Jia, B. Liu, Y. Zhao, W. Chen, D. Mou, J. Fu, Y. Wang, W. Xin and L. Zhao, *J. Mater. Sci.*, 2020, **55**, 16197–16210.

56 D. Wang, X. Zhang, S. Bao, Z. Zhang, H. Fei and Z. Wu, *J. Mater. Chem. A*, 2017, **5**, 2681–2688.

57 X. Han, X. Tong, X. Liu, A. Chen, X. Wen, N. Yang and X.-Y. Guo, *ACS Catal.*, 2018, **8**, 1828–1836.

58 Y.-J. Yuan, P. Wang, Z. Li, Y. Wu, W. Bai, Y. Su, J. Guan, S. Wu, J. Zhong, Z.-T. Yu and Z. Zou, *Appl. Catal., B*, 2019, **242**, 1–8.

59 X.-L. Yin, G.-Y. He, B. Sun, W.-J. Jiang, D.-J. Xue, A.-D. Xia, L.-J. Wan and J.-S. Hu, *Nano Energy*, 2016, **28**, 319–329.

60 Q. Li, W. Liu, L. Xiao, X. Chen and X. Xu, *Mater. Lett.*, 2021, 285.

61 J. Wang, W. Fang, Y. Hu, Y. Zhang, J. Dang, Y. Wu, H. Zhao and Z. Li, *Catal. Sci. Technol.*, 2020, **10**, 154–163.

62 A. Wu, Y. Gu, Y. Xie, H. Yan, Y. Jiao, D. Wang and C. Tian, *J. Alloys Compd.*, 2021, 867.

63 H. Zhu, F. Lyu, M. Du, M. Zhang, Q. Wang, J. Yao and B. Guo, *ACS Appl. Mater. Interfaces*, 2014, **6**, 22126–22137.

64 Y. Zhu, L. Song, N. Song, M. Li, C. Wang and X. Lu, *ACS Sustainable Chem. Eng.*, 2019, **7**, 2899–2905.

65 D. Xie, G. Yang, D. Yu, Y. Hao, S. Han, Y. Cheng, F. Hu, L. Li, H. Wei, C. Ji and S. Peng, *ACS Sustainable Chem. Eng.*, 2020, **8**, 14179–14189.

66 S. Bawari, N. M. Kaley, S. Pal, T. V. Vineesh, S. Ghosh, J. Mondal and T. N. Narayanan, *Phys. Chem. Chem. Phys.*, 2018, **20**, 15007–15014.

67 Q. Zhang, Z. Duan, M. Li and J. Guan, *Chem. Commun.*, 2020, **56**, 794–797.

68 X. Hu, S. Lu, J. Tian, N. Wei, X. Song, X. Wang and H. Cui, *Appl. Catal., B*, 2019, **241**, 329–337.

69 B. Sun, W. Zhou, H. Li, L. Ren, P. Qiao, W. Li and H. Fu, *Adv. Mater.*, 2018, **30**, e1804282.

70 Y.-J. Yuan, Z. Shen, S. Wu, Y. Su, L. Pei, Z. Ji, M. Ding, W. Bai, Y. Chen, Z.-T. Yu and Z. Zou, *Appl. Catal., B*, 2019, **246**, 120–128.

71 H. Zhao, Z. Jiang, K. Xiao, H. Sun, H. S. Chan, T. H. Tsang, S. Yang and P. K. Wong, *Appl. Catal., B*, 2021, 280.

72 G. Zhao, A. Wang, W. He, Y. Xing and X. Xu, *Adv. Mater. Interfaces*, 2019, **6**, 1900062.

73 N. Qin, J. Xiong, R. Liang, Y. Liu, S. Zhang, Y. Li, Z. Li and L. Wu, *Appl. Catal., B*, 2017, **202**, 374–380.

74 D. J. Late, Y. K. Huang, B. Liu, J. Acharya, S. N. Shirodkar, J. Luo, A. Yan, D. Charles, U. V. Waghmare and V. P. Dravid, *ACS Nano*, 2013, **7**, 4879–4891.

75 W. Zheng, Y. Xu, L. Zheng, C. Yang, N. Pinna, X. Liu and J. Zhang, *Adv. Funct. Mater.*, 2020, **30**, 2000435.

76 T. Pham, G. Li, E. Belyarova, M. E. Itkis and A. Mulchandani, *ACS Nano*, 2019, **13**, 3196–3205.

77 R. Kumar, N. Goel and M. Kumar, *ACS Sens.*, 2017, **2**, 1744–1752.

78 X. Xin, Y. Zhang, X. Guan, J. Cao, W. Li, X. Long and X. Tan, *ACS Appl. Mater. Interfaces*, 2019, **11**, 9438–9447.

79 X. Bai, H. Lv, Z. Liu, J. Chen, J. Wang, B. Sun, Y. Zhang, R. Wang and K. Shi, *J. Hazard. Mater.*, 2021, **416**, 125830.

80 P. Chen, J. Hu, M. Yin, W. Bai, X. Chen and Y. Zhang, *ACS Appl. Nano Mater.*, 2021, **4**, 5981–5991.

81 N. N. Viet, L. V. Thong, T. K. Dang, P. H. Phuoc, N. H. Chien, C. M. Hung, N. D. Hoa, N. Van Duy, N. Van Toan, N. T. Son and N. Van Hieu, *Anal. Chim. Acta*, 2021, **1167**, 338576.

82 S. Singh and S. Sharma, *Sens. Actuators, B*, 2022, 350.

83 D. Zhang, C. Jiang, J. Liu and Y. Cao, *Sens. Actuators, B*, 2017, **247**, 875–882.

84 D.-W. Jeong, K. H. Kim, B. S. Kim and Y. T. Byun, *Appl. Surf. Sci.*, 2021, 550.

85 Y. R. Choi, Y.-G. Yoon, K. S. Choi, J. H. Kang, Y.-S. Shim, Y. H. Kim, H. J. Chang, J.-H. Lee, C. R. Park, S. Y. Kim and H. W. Jang, *Carbon*, 2015, **91**, 178–187.

86 B. Kwon, H. Bae, H. Lee, S. Kim, J. Hwang, H. Lim, J. H. Lee, K. Cho, J. Ye, S. Lee and W. H. Lee, *ACS Nano*, 2022, **16**, 2176–2187.

