MoS₂ Nanosheets Sensitized with Quantum Dots for Room-Temperature Gas Sensors

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HIGHLIGHTS

- Highly sensitive and selective room-temperature NO₂ gas sensors by sensitizing MoS₂ nanosheets with PbS quantum dots were demonstrated. In this device architecture, the receptor and transduction function as well as the utility factor of semiconductor gas sensors could be enhanced simultaneously.
- The strategy of sensitizing 2D semiconductors with quantum dots as sensitive and selective receptors for gas molecules may offer a powerful new degree of freedom to the surface and interface engineering of semiconductor gas sensors.

ABSTRACT The Internet of things for environment monitoring requires high performance with low power-consumption gas sensors which could be easily integrated into large-scale sensor network. While semiconductor gas sensors have many advantages such as excellent sensitivity and low cost, their application is limited by their high operating temperature. Two-dimensional (2D) layered materials, typically molybdenum disulfide (MoS₂) nanosheets, are emerging as promising gas-sensing materials candidates owing to their abundant edge sites and high in-plane carrier mobility. This work aims to overcome the sluggish and weak response as well as incomplete recovery of MoS₂ gas sensors at room temperature by sensitizing MoS₂ nanosheets with PbS quantum dots (QDs). The huge amount of surface dangling bonds of QDs enables them to be ideal receptors for gas molecules. The sensitized MoS₂ gas sensor exhibited fast and recoverable response when operated at room temperature, and the limit of NO₂ detection was estimated to be 94 ppb. The strategy of sensitizing 2D nanosheets with sensitive QD receptors may enhance receptor and transducer functions as well as the utility factor that determine the sensor performance, offering a powerful new degree of freedom to the surface and interface engineering of semiconductor gas sensors.

KEYWORDS Gas sensor; Room temperature; Molybdenum disulfide; Quantum dot; Nitrogen dioxide
1 Introduction

Hazardous air pollutants have become a serious problem for the ecosystem and public health [1, 2]. Nitrogen dioxide (NO₂) primarily gets in the air from the burning of fuel. Exposure to NO₂ may potentially increase susceptibility to respiratory infections, and a 5-min emergency exposure limit of 35 ppm NO₂ exposure has been proposed by the American Industrial Hygiene Association [1, 3]. The large-scale networking of gas sensors for achieving online NO₂ monitoring requires the power consumption of the sensors to be lower. While semiconductor gas sensor have been widely used in home alarm system owing to their high sensitivity, simple operation, and low cost [4–6], their scale-up application in environmental internet has not been achieved due to the limitation of high operating temperature (typically above 300 °C) which raises the power consumption. The high operating temperature of semiconductor gas sensors also sets a limit to their integrability with CMOS technology or flexible electronic system. Thereby, novel nanostructured materials [7–10] with the potentials for room-temperature gas sensors have become a hot research topic.

MoS₂ is a well-known 2D graphene-like transition metal dichalcogenides (TMDs). With relatively high carrier mobility, large surface-to-volume ratio, and abundant edge sites which can provide active adsorption sites for gas molecules [11–14], MoS₂ has been demonstrated as one of the promising materials candidates for room-temperature NO₂ gas sensors. Liu et al. [13] reported CVD growth of monolayer MoS₂ for room-temperature detection of NO₂ with a response time of several minutes without a full recovery to the initial state. Cho et al. [15] demonstrated a charge-transfer-based sensitive NO₂ gas sensor by CVD-synthesized atomic-layered MoS₂, with a sensitivity of 220% and a long time (more than 30 min) to recovery. Similarly, chemical exfoliated MoS₂ prepared by Jung et al. had an incompletable recovery to NO₂ at room temperature [16]. Kumar et al. fabricated a high-performance NO₂ sensor based on MoS₂ with abundant active edge sites. When operated at 60 °C, it had a fast response (16 s) with complete recovery (172 s) with a relative response of 18.1% to 5 ppm NO₂ [17]. As an alternative strategy, UV light irradiation or gate effect was employed to improve sensitivity toward NO₂ of MoS₂ sensor [18–21]. Pham et al. [18] employed LED illumination to improve sensitivity of CVD grown single-layer MoS₂, achieving sub-ppb limit of NO₂ gas detection. However, the comparatively high sensitivity and fast response/recovery kinetics at room temperature were not simultaneously obtained for pristine MoS₂ gas sensors. They suffer from the trade-off between receptor and transducer function. For semiconductor gas sensors, the structural defects are always necessary for gas molecule reception and, on the contrary, may decrease the electronic transduction.

Recently, MoS₂-based nanocomposites or hybrids through surface modification with noble metals [11], architecture design of hetero-nanostructures with metal oxide nanoparticles [22, 23], and functionalization with other 2D-layered materials such as graphene [24–28] have been demonstrated with improved sensitivity and fast response/recovery kinetics. Motivated by this strategy, we proposed to improve the room-temperature response and recovery by sensitizing MoS₂ nanosheets with quantum dots (QDs), a highly tunable zero-dimensional (0D) nanomaterial with size-dependent bandgap and excellent solution processability [29–35]. The huge amount of surface dangling bonds of QDs makes them sensitive receptors for gas molecules. Herein, the PbS QDs-sensitized MoS₂ nanosheets were obtained via a two-step solution process. The sensor had an excellent response of 6.15, to 10 ppm NO₂ at room temperature, almost five times greater than that of pristine MoS₂ nanosheets. The sensing mechanism was attributed to the enhanced receptor and transducer functions as well as the utility factor which determine the performance of semiconductor gas sensors.

2 Experimental

2.1 Preparation of MoS₂ Nanosheets

In a typical hydrothermal synthesis of MoS₂ nanosheets [36], as shown in Fig. 1a, 1 mmol hexaammonium heptamolybdate tetrahydrate ((NH₄)₆Mo₇O₂₄·4H₂O) and 14 mmol thiourea were dissolved into 35 mL of deionized water under stirring for several minutes to form a homogeneous solution. The mixed solution was transferred into a 50-mL Teflon-lined stainless steel autoclave to react at 220 °C for 18 h and then naturally cooled down to room temperature.
temperature. The final product was rinsed with deionized water and absolute ethanol several times to remove any possible ions. After drying at 70 °C for 6 h, black MoS₂ nanosheet powder was obtained.

2.2 Synthesis of MoS₂ Nanosheets Sensitized with QDs

Figure 1a shows the synthesis of MoS₂ nanosheets sensitized with PbS QDs. Organo-hot injection method has always been proven as an effective method for QD synthesis [37–39]. First, the as-prepared MoS₂ powders (20 mg) were dissolved in 4 mL of oleic acid (OA). Ultrasonic dispersion was conducted for 30 min to ensure the black powder was completely dispersed in the solution. PbO (2 mmol), OA (2 mmol), 1-octadecene (ODE) (20 mL), and as-prepared MoS₂ (OA) solution (530 μL) were all mixed in a three-neck flask and heated to 90 °C under a vacuum for 6 h. Then, the reaction temperature was raised to 120 °C and 0.33 mmol bis(trimethylsilyl) sulfide (TMS) mixed with ODE (10 mL) was rapidly injected under an inert atmosphere. The reaction lasted for 30 s, and the mixture was then transferred to cold water bath for rapid cooling to room temperature. The nucleation and growth of QDs anchoring in the surface of MoS₂ nanosheets occurred in this process. The product was precipitated by acetone and re-dispersed in toluene several times to prepare PbS–MoS₂ solution for device fabrication.

2.3 Sensor Fabrication

The layer-by-layer spin-coating deposition technique of the sensitized MoS₂-based thin film was carried out in ambient air at room temperature (a schematic illustration can be seen in Fig. 1b). Alumina ceramic substrates (15×15×0.8 mm³) prepatterned with a pair of interdigital Ag electrode (the spacing and width are 5 mm) were prepared via screen printing. Then 70 μL of PbS–MoS₂ solution was dropped onto the substrate, which was then spun at 2350 rpm for 30 s. Next, four drops of NaNO₂ diluted in methanol (10 mg mL⁻¹) were added dropwise to the film for ligand exchange, with a wait time of 45 s, and spun dry at 2500 rpm for 30 s, followed by repeating the NaNO₂ treatment twice. Finally, the film was washed by methanol flush and then spun dry three times to obtain 3-layers thin-film device. The film deposition process was
repeated three times. For comparison, the pristine MoS$_2$ nanosheet device was prepared according to the following steps. First, the prepared substrates were placed in a hot-plate with a heating temperature of 135°C. Next, a drop of MoS$_2$ ethanol solution was deposited dropwise onto the thermal substrate and naturally dried for a few seconds, followed by repeating the process twice. Finally, the fabricated MoS$_2$ sensor was maintained under the thermal treatment for 20 min.

2.4 Characterization and Measurements

A field emission scanning electron microscope (FE-SEM, GeminiSEM 300, Zeiss, Oberkochen, Germany) equipped with an energy-dispersive X-ray spectrometer (EDS, X-MAX, Oxford, UK) was used to obtain SEM images and elemental mapping data. Transmission electron microscopy (TEM) images were recorded with a Tecnai G2 20 microscope operating at an accelerating voltage of 200 kV. X-ray diffraction (XRD) measurements were obtained using a diffractometer (Empyrean, PANalytical B. V., Netherlands) with Cu Kα radiation in the 2θ range of 10–70°C. An energy-dispersive X-ray spectrometer (EDS) was performed on a XL 30 ESEM FEG. X-ray photoelectron spectroscopy (XPS) measurements were using by an AXIS-ULTRA DLD-600 W with an Al source, and C 1s peak at 284.5 eV is used as reference. Similarly, ultraviolet photoelectron spectroscopy (UPS) measurement was also performed by using the same system with a He-Iα 21.22 eV UV light. Work functions were measured by a KP 020 K probe (KP Technology, Wick, Scotland). UV–Vis–NIR absorption spectra were measured using a PerkinElmer Lambda 950 UV–Vis–NIR spectrophotometer.

The NO$_2$ sensing measurements were carried out by a computer-connected source meter system (Model Keithley 2450/6487, Keithley Instruments, USA) under static conditions controlled with the relative humidity (RH) being 19–85% at room temperature (sensor setup details as shown in Fig. S1). The sensor response was defined as the ratio of $R_a$ to $R_g$, where $R_a$ is the baseline resistance in the ambient atmosphere and $R_g$ is the resistance of the sensor device in the presence of NO$_2$ gas. The response time ($T_{90}$) and the recovery time ($T_{10}$) were defined as the time taken by the sensor response to reach 90% of its maximum value upon exposure to NO$_2$ gas and drop to within 10% of its original baseline value after removal of gas.

3 Results and Discussion

3.1 Structural Properties of MoS$_2$ Nanosheets and QD-Sensitized MoS$_2$ Nanosheets

The morphology of the MoS$_2$ and QD-sensitized MoS$_2$ nanosheets was characterized with SEM and TEM, respectively. Figure 2a displays a low-magnification TEM image of MoS$_2$ nanosheets revealing the ultrathin nanosheet morphology with slightly assembly character. Further, more lattice fringes were clearly indicated from high-magnification TEM image (Fig. 2b), revealing the labeled lattice spacing of 0.625 nm, which was in a good agreement with the (002) lattice plane with MoS$_2$ nanosheets. The abundant MoS$_2$ nanosheets layers provide large quantities of edge sites, which may beneficial for gas molecules absorption. Moreover, Fig. S2 shows an SEM image of the as-prepared MoS$_2$ nanosheets distributed on the alumina ceramic substrate, and the observable flowerlike MoS$_2$ nanosheets were uniformly assembled by a mass of bent flakes. Similarly, TEM images of different magnifications in Fig. 2c, d used to observe more detailed microstructure information of the QD-sensitized MoS$_2$ nanosheets. A large amount of QDs formed on the edge sites of the MoS$_2$ nanosheets as demonstrated in Fig. 2c. This could be attributed to the edge area defects, which provide more active sites for the nucleation of PbS QDs. Pb atoms can fill the vacancy on the MoS$_2$ surface, which may weaken the MoS$_2$ defects [40]. Equally important is that the MoS$_2$ surface might be spontaneously functionalized with the excessive OA molecules in the reaction process, and then the strong hydrophobic interaction [41, 42] of the OA ligands on both the QDs and MoS$_2$ surfaces leading to the noncovalent binding of QDs to MoS$_2$. However, the detailed mechanisms regarding how the OA ligands or molecules take part in the synthesis of MoS$_2$ nanosheets sensitized with QDs need further investigation. The efficient attachment and coverage of the QDs onto the MoS$_2$ nanosheets are further indicated by the high-resolution TEM image in Fig. 2d. Well-crystallized QDs with diameters of approximately 3.26 nm were uniformly separated on the surface of the MoS$_2$ nanosheets.
The lattice spacings of these spherically shaped QDs were 0.21 and 0.34 nm, corresponding to the (220) and (111) lattice planes of PbS, respectively. The edges of the MoS$_2$ nanosheets were not continuous, probably because some defects were generated in the synthesis processes. The typical elemental mapping data were characterized by EDS, as shown in Fig. S3a–e, which also confirmed the even distribution of the Pb and Mo element in the final actual device, revealing the formation of well-distributed PbS QDs in the MoS$_2$ nanosheets.

To further confirm the structural information of the MoS$_2$ and QD-sensitized MoS$_2$, the XRD patterns of the samples are shown in Fig. 3. It indicates that the four sharp diffraction peaks centered at approximately 2θ = 13.9°, 33.4°, 39.4°, and 58.9° of the powder MoS$_2$ could be well-indexed, respectively, to the (002), (100) + (101), (103), and (110) lattice planes of PbS.
(110) planes of the hexagonal phase MoS₂ (JCPDS card No. 73-1508). The strong (002) peak at 2θ = 13.9° with a d-spacing of approximately 0.625 nm corresponded to a well-stacked layered structure along the c axis as well as the TEM results. Compared to the pristine MoS₂, the XRD patterns of the sensitized structure in Fig. 3b contained some extra peaks other than the main characteristic peaks of MoS₂. The peaks at approximately 2θ = 25.3°, 29.6°, 42.8°, and 51.4° were not only well matched with the (111), (200), (220), and (311) planes of cubic PbS (JCPDS card No. 78-1054), which indicated the successful growth of PbS QDs on the surface of MoS₂ nanosheet, but also consistent with the TEM characteristics presented in Fig. 2d. The significantly broadened peak that appeared on PbS could possibly be attributed to the quantum size feature of the QDs, according to the Debye–Scherrer equation.

The surface elements and chemical states of the sensitized MoS₂-based film were characterized by X-ray photoelectron spectroscopy (XPS) in the supporting information. As expected, Pb, Mo, and S were detected on the film, which was consistent with the EDX results. Figure S4a–c shows the high-resolution XPS spectra of Pb 4f, S 2p, and Mo 3d, respectively. Two peaks located at 142.7 and 137.8 eV correspond to the 4f5/2 and 4f7/2 of the Pb²⁺ state exhibited in Fig. S4a. Most of the Mo signal is from its Mo⁴⁺ state at the peak positions around 228.5 and 229.2 eV, mainly corresponding to Mo⁴⁺ 3d₅/₂ and 3d₇/₂ of the Pb²⁺ state exhibited in Fig. S4c. Two dominant S 2p peaks were observed around 161.5 and 162.2 eV (Fig. S4b), accompanied by a slightly flat peak at 163.8 eV, which were assigned to the divalent sulfide ions (S²⁻) of the MoS₂ and PbS.

### 3.2 NO₂ Gas-Sensing Properties

The NO₂-sensing performance was measured using a homemade computer-connected source meter system under room temperature. We performed repeatability test for the both devices at the same time and measured the relative response to six and four successive cycles toward 10 ppm NO₂ for pristine MoS₂ nanosheets and the sensitized MoS₂ gas sensors, respectively (Fig. S5a). The pristine MoS₂ sensor showed the complete recovery at room temperature without any extra stimulus such as optical or thermal source; however, the completed response/recovery cycle required a slightly time. After sensitization by the PbS QDs, the sensitized MoS₂ sensor exhibited an obviously enhanced response to the same concentration of NO₂ gas, also with a fast response/recovery time and excellent reversibility. Transient resistance characteristic of MoS₂ nanosheets and the sensitized MoS₂ gas sensors to 10 ppm NO₂ is shown in Fig. S5b, exhibiting p-type gas-sensing behavior for both sensors. The improved performance can be attributed to the excellent access of gas molecules adsorption by the PbS QDs as NO₂ receptors, as well as the favorable 0D-2D interface for charge transfer, which will be discussed in detail later. Three kinds of theoretical Mo to Pb molar ratio (2%, 5%, and 8%) were used in the precursor solutions during the synthesis, and we found that sensor response was much higher by a medium molar ratio of 5% (Fig. S6). Thus, we used this optimal molar ratio to sensor fabrication in this work. The representative time-resolved response and recovery curves of the pristine MoS₂ and the sensitized MoS₂ gas sensor were illustrated in more detail in Fig. 4a, b. In general, many defects may occur in the surface of MoS₂, which can lead to a strong chemisorption between MoS₂ and gas molecules, so that NO₂ or other gases such as O₂ are difficult to desorb from the MoS₂ [43], resulting in a weakened recovery kinetics, as shown in Fig. 4a. The sensitized MoS₂ sensor exhibited a superior performance not only with an excellent response of 6.15 to 10 ppm NO₂, which was almost five times greater than the pristine MoS₂ device, but also with an outstanding response/recovery ability, with the time improving from 50/233 to 15/62 s, respectively.

To further investigate the NO₂-sensing properties of the sensors, the dynamic response curves were recorded with the NO₂ concentration of 1, 2, 5, 10, and 20 ppm, respectively, shown in Fig. 4c. Both devices showed recoverable response under room temperature, and the response values gradually increased with the increasing NO₂ gas concentration. Obviously, the device based on MoS₂ nanosheets sensitized with QDs was more sensitive than the pristine MoS₂ for NO₂ gas detection and indicated potential for a lower limit of detection (LOD). The pristine MoS₂ had less of a response when exposed to 1 ppm NO₂, while the sensitized MoS₂ sensor still performed 2.30 toward the same concentration with a rapid response/recovery rate, which even better than the measurement to 20 ppm of pristine MoS₂ device (details are shown in Fig. S7). Owing to this improvement, the theoretical LOD for NO₂ was calculated to be 174 and 94 ppb in the case of pristine MoS₂ and QD-sensitized MoS₂, respectively (calculation details in Fig. S8). However, the measurement error of the LOD for both sensors is mainly from accuracy...
of gas concentration and errors in test results. The dependence of the sensor response on gas concentrations range from 1 to 20 ppm is also analyzed in Fig. 4d. The fitting equation between the response value \( (S) \) and NO\(_2\) concentration \( (C) \) can be illustrated as a power law relationship, and the exponent was estimated to be 0.1089 together with a coefficient of determination \( (R^2) \) value of 0.988 for the MoS\(_2\) sensor, while the values were 0.4523 and 0.991 for the sensitized MoS\(_2\) sensor. Importantly, the theoretical analysis of the relationship between the response values and gas concentrations was significant for the gas sensor, which will facilitate the determination of gas concentrations in practical applications. Selectivity is considered as an important parameter for gas sensors, and we compared the response of the sensitized MoS\(_2\) gas sensors toward several gases in our lab. As shown in Fig. 5, the sensors exhibited high response to 10 ppm NO\(_2\) gas and negligible response to 10 ppm H\(_2\), SO\(_2\), NH\(_3\) and 200 ppm C\(_2\)H\(_5\)OH vapor, respectively, at room temperature. The inset showed the dynamic response curves upon gas exposure and release of the intervening gases, respectively. We also investigated the NO\(_2\)-sensing performance of the sensitized MoS\(_2\) sensors in the range of RH of 19%, 29%, 48%, 65%, and 85%. The sensor response toward 10 ppm NO\(_2\) had a tendency to grow over the RH gradually increased (shown in Fig. S9a). While the functional relationship between relative humidity and response could be further

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**Fig. 4** Time-resolved response and recovery curves of a MoS\(_2\) nanosheets and b the sensitized MoS\(_2\) gas sensors exposed to 10 ppm NO\(_2\) at room temperature. c Transient relative response of both sensors toward different NO\(_2\) concentrations. d The relative response versus the NO\(_2\) concentration illustration of the MoS\(_2\) and the sensitized MoS\(_2\) sensors.
defined clearly, we can use humidity compensation methods to make our sensors satisfy the practical application under environment with a wider range of the RH. More details are shown in Fig. S9b about the real-time sensing curves toward 10 ppm NO2 at different RH based on the sensitized MoS2 gas sensors, revealing fast response/recovery kinetics under any RH environments. For this specific investigation, the RH value was intentionally controlled at certain values with an accuracy of 2%. The average sensitivity to 10 ppm NO2 under RH ~ 65% was 6.19, which was close to the average sensitivity of 6.14 under RH ~ 62% (Fig. 4d). Therefore, the RH ranged from 62 to 65% was within the error range. Under high RH environments, we suspected that water molecules preadsorbed on the surface of the sensitized MoS2, dissociating into OH− and H+ to form hydroxyl groups. Hydroxyl groups as an electron donor lead to increase in resistance of the materials [44]. NO2 has strong adsorption properties compared with the physical adsorption of water molecules. When NO2 injected, they could kick out the physical adsorption of water molecules and cause a further decrease in resistance, thus achieving a higher response. Actually, it is reported that the hydroxyl groups could improve the NO2-sensing performance in recent study [35, 45–47].

Compared to other MoS2-based NO2 sensors (Table 1), our MoS2 nanosheets-based sensor only maintained a general level at room-temperature (RT) operation; however, under the same conditions, the sensitized MoS2 sensor had a superior performance with no thermal treatment or UV illumination [21, 48]. Compared to the most MoS2-based gas sensors in the current published papers, the sensitized MoS2 gas sensor exhibited an excellent response from 6.15 to 10 ppm NO2 at room temperature, accompanied by a rapid response/recovery time of 15/62 s, indicating high sensitivity.

![Fig. 5](https://example.com/f5.png)

**Fig. 5** Selectivity of QD-sensitized MoS2 gas sensors toward different gases: 10 ppm NO2, H2, SO2, NH3 and 200 ppm C2H5OH

| Materials                  | Method                    | Work temperature (°C) | Concentration (ppm) | Response (%) | T90/T10 (s) | References |
|----------------------------|---------------------------|-----------------------|---------------------|--------------|-------------|------------|
| Few-layer MoS2             | Mechanically exfoliating  | RT                    | 100                 | 60           | 180/600     | [12]       |
| Monolayer MoS2             | CVD                       | RT                    | 0.4                 | 80           | ~420/- (incomplete) | [13]       |
| Few-layer MoS2             | CVD                       | RT                    | 10                  | 60           | ~60/~1000   | [14]       |
| Atomic-layered MoS2        | CVD                       | RT                    | 1.2                 | 150          | ~60/~1800   | [15]       |
| MoS2 nanowires             | CVD                       | RT                    | 60                  | 5            | 18.1        | [17]       |
| Single-layer MoS2          | CVD                       | RT with LED light     | 0.1                 | ~6           | ~500/~1     | [18]       |
| Multilayer MoS2            | Mechanically exfoliating  | RT with gate effect   | 100                 | 4            | ~60/~60     | [19]       |
| Multilayer MoS2            | CVD                       | RT with UV light      | 100                 | 35           | 29/350      | [48]       |
| Mixed MoS2 flakes          | CVD                       | RT with UV light      | 10                  | 21.78        | 6.09/146.49 | [21]       |
| SnO2 NC-MoS2 NS            | Chemical exfoliation      | RT                    | 10                  | 28           | 400/180     | [22]       |
| ZnO NPs/MoS2 NSs           | Wet chemical method       | RT                    | 5                   | 3050         | 40/~600     | [23]       |
| MoS2-RGO                   | Liquid exfoliation and    |                       |                     |              |             | [25]       |
|                            | hydrothermal              |                       |                     |              |             |            |
| WS2 functionalized MoS2    | Hydrothermal process      | RT                    | 160                 | 3            | 129         | 8/20       | [26]       |
| MoS2 nanosheets            | Hydrothermal              | RT                    | 10                  | 133          | 50/233      | This work  |
| MoS2 nanosheets sensitized| Hydrothermal and organo-   | RT                    | 10                  | 615          | 15/62       | This work  |

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and outstanding recovery ability. In addition, as shown in Fig. S9c, long-term stability test of the sensitized MoS$_2$ sensor upon 10 ppm NO$_2$ was consistent with the effect of relative humidity on the sensing performance. Furthermore, QD-sensitized MoS$_2$ nanosheets with excellent solution processability are particularly attractive for next-generation gas sensors compatible with silicon-based or flexible substrates.

### 3.3 Gas-Sensing Mechanisms

As previously noted, the gas sensor based on MoS$_2$ nanosheets sensitized with QD had a good NO$_2$-sensing performance at room temperature, which was quite possible for the combinational effects between the PbS QDs and MoS$_2$ nanosheets. Therefore, we proposed three basic factors of receptor function, transducer function and utility [49], as well as an interface energy band diagram to investigate the sensing mechanism of QD-sensitized MoS$_2$ nanosheets. As illustrated in Fig. 6a, PbS QDs always exhibited p-type conduction behavior in air atmosphere because of physisorbed O$_2$ molecules, which consumed electrons and introduced lots of holes as well. When exposed to NO$_2$ gas, according to our previous research [32, 34, 35], due to the strong binding energy compared to O$_2$, NO$_2$ kicks out the originally physisorbed O$_2$ molecules and binds to Pb$^{2+}$ through O, introducing more charge-transfer-driven p-type doping and developing a hole concentration in the p-type PbS QDs. For pristine p-type MoS$_2$ nanosheets, the defects mainly on the edge sites of the MoS$_2$ acted as active sites for NO$_2$ molecules, and these defects dominated process contributing to the poor response, slow rates of response, or even incomplete recovery due to high energy binding sites [50], especially operation at room temperature without any illumination. Thus, the inevitable receptor–transducer function [51] conflict cannot be well addressed in the pristine MoS$_2$-based gas sensor. After sensitization with QDs (illustrated in Fig. 6b), most of the high energy binding sites on the surface of MoS$_2$ were occupied by the highly active QD receptors which had larger surface-to-volume ratio as well as abundant surface defects (mainly from dangling bonds, surface Pb sites, sulfur vacancies, etc.) capable of active interaction with NO$_2$ gas molecules adsorption, contributing to a marked enhancement in the response. Furthermore, the adsorption energies of NO$_2$ on the MoS$_2$ and PbS were calculated based on the density functional theory (DFT) in the previous literature, indicating that the adsorption energy of NO$_2$ on the PbS is significantly larger than that on MoS$_2$ [52]. Therefore, PbS QDs may serve as receptors of NO$_2$ molecules and enhance the receptor function of the MoS$_2$ sensors.

![Fig. 6 Schematic illustration of the NO$_2$-sensing mechanism of MoS$_2$ nanosheets sensitized with QDs. a Receptor function of PbS QDs. b Transducer function of MoS$_2$ nanosheets and the utility factor involved for the sensitized MoS$_2$ nanosheets. c Interface band structure of PbS QD-MoS$_2$ nanosheet.](image)
Combining with Fig. 6b, we also used an interface energy band diagram to further study the sensing mechanism. To simulate the actual environment, Kelvin probe measurement was carried out in ambient air. The work function (W_F) of the PbS QD and MoS_2 nanosheet was approximately 4.61 and 4.96 eV, respectively. Next, we used ultraviolet photoelectron spectroscopy (UPS) to confirm the valence-band edge \(E_v\) \([53]\) and the scan of the spectra for both as shown in Fig. S10. The \(E_v\) value was calculated to be 5.20 and 5.46 eV for the PbS QD and MoS_2 nanosheet, respectively. We also introduced a UV–Vis–NIR absorption spectrum mainly to evaluate the energy bandgaps \(E_g\) of the MoS_2 nanosheet and PbS QD. As shown in the MoS_2 spectrum in Fig. S11a, the characteristic absorption peaks that appeared in the visible regions were consistent with the general features of TMDs with trigonal prismatic coordination, which confirmed the 2H polytype of the MoS_2 nanosheet \([54]\). The intercept was interpolated inside giving the value to \(E_g\) of 1.50 eV for MoS_2 through the Kubelka–Munk transformed reflectance spectra, indicating that the prepared MoS_2 with few-layer nanosheets possesses a bandgap larger than the bulk materials. Figure S11b shows that an exciton absorption peak appeared in 992 nm, from which we could obtain the calculated \(E_g\) of 1.25 eV of PbS QD. It exhibited a significantly broadened bandgap compared to the bulk PbS (0.41 eV), confirming a conservation of strong quantum confinement effect \([55]\). Taking together the above experimental parameters, the initial condition (before mutual contact) of the energy band structure for PbS QD and MoS_2 nanosheet could be illustrated in Fig. S12. Because of the difference in work functions (4.61 vs. 4.96 eV), when the PbS and the MoS_2 were brought into contact, the electrons pass from the PbS to MoS_2, creating a positive charge region closed to the PbS surface and opposite one near the MoS_2 surface. Finally, interface band structure was developed for both sides as band bending occurred and a potential barrier of 0.35 eV \((\varphi_F = W_F(PbS) - W_F(MoS_2))\) formed in the contact position, which was accompanied by the balanced \(E_F\). As exhibited in the diagram in Fig. 6c, a majority of the NO_2 molecules adsorbed on the surface of the QD receptors may form donor-like surface states in general, and a direct electron extraction from the conduction band of QD into the NO_2 molecules, which also meant hole injection from the NO_2 into the valence band of QD. Anyway, a mass of holes will accumulate at the interface closed to the side of the PbS QDs during its receptor function process. Equally important was that the MoS_2 nanosheets served as the conductive path in the system, leading the NO_2-induced holes flow to the electrode for collection, easily overcoming the relatively low potential barrier generated at the interface of the valence-band edge. DFT calculation results recently demonstrated that the diffusion barrier is only dozens of meV for NO_2 on MoS_2, which also proved that NO_2 gas molecules may easily diffuse rapidly on MoS_2 surface \([40]\). Thus, MoS_2 nanosheets can serve as the charge transport highway for the effective transducer function of the sensitized surface adsortion of NO_2 gas molecules into an electrical resistance change of the sensor.

Concluded from the above discussion, the sensitized MoS_2 sensor had a good response and recovery kinetics even at room temperature because of the favorable 0D QD-2D MoS_2 interface, combining the improvement of both receptor function and transducer function \([49, 51, 56]\). Beyond that, the utility factor is one of the important factors which concerns the gas-sensing performance and goes up with the smaller pore size as well as thinner gas-sensitive film \([49]\). We took characterization about SEM cross-section morphology of the sensitized MoS_2 based on alumina ceramic substrate. However, it was difficult to observe the thickness of such nanothin film clearly on the rough ceramic substrate because it was hard for cutting. Hence, we employed the comparative smooth silicon substrate for material deposition. Figure S13a displays the cross section of the three-layer QD-sensitized MoS_2 thin film on silicon substrate, revealing a conformal film deposition, and the film thickness was estimated to be 135 nm. Thus, the utility factor could be benefited greatly from the relatively porous thin-film features, which enhanced the accessibility of inner sulfide grains to the NO_2 molecules, leading to enhanced gas diffusion and reaction, thereby achieving higher response along with shorter response/recovery time. We further provided more details in Fig. S13b about NO_2-sensing performance of different deposited layers and finally found that the three-layer thin-film-based sensors had a stable response together with a fast recovery time. In brief, our sensitized MoS_2 gas sensors exhibited a better NO_2 gas-sensing performance at room temperature than that of the pristine MoS_2 sensors. The sensitized MoS_2 architecture overcome the receptor–transducer function conflict limitation, as well as enhanced the utility factor by sensitizing MoS_2 nanosheets with QDs. More importantly, a deeper understanding of the 0D-QDs...
with tunable bandgaps will further promote progress in the
engineering of energy band alignment at the 0D-2D het-
terojunction interface, paving a promising way to develop
gas-sensing performance of 2D layered materials.

4 Conclusions

In summary, we proposed a facile synthesis strategy for
sensitizing MoS$_2$ nanosheets with PbS quantum dots
as NO$_2$ gas molecules. The sensitized MoS$_2$ gas sensor
exhibited sensitive and recoverable response at room
temperature, with the response/recovery time shortened
from 50/233 to 15/62 s upon 10 ppm of NO$_2$ exposure/
release cycle, respectively, compared to the pristine MoS$_2$
nanosheets. The gas-sensing mechanism was attributed to
the fundamental factors of receptor function, transducer
function and utility, as well as the favorable 0D-2D inter-
face between QDs and MoS$_2$ nanosheets. Through the
surface sensitization of MoS$_2$ nanosheets with PbS QDs
as sensitive and selective NO$_2$ receptors, combined with
the favorable charge transfer at interfaces and excellent
charge transport, the receptor and transducer function as
well as the utility factor were desirable enhanced, thereby
achieving the enhanced performance for NO$_2$ gas sens-
ing. This work demonstrated a novel sensitized MoS$_2$ gas
sensor with superb sensitivity and extremely low power
consumption. The solution-processable and room-tem-
perature operable gas sensors could be integrated with
silicon-based or even flexible substrates to achieve smart
on-chip electronic nose.

5 Supplementary Material

Homemade sensor setup; SEM image of the flowerlike MoS$_2$
nanosheets; EDS elemental mapping of QD-sensitized MoS$_2$
nanosheets; XPS characterization of QD-sensitized MoS$_2$
nanosheets; repeatability curves and transient resistance
characteristic of the MoS$_2$ nanosheets and QD-sensitized
MoS$_2$ nanosheets sensors; sensor response of QD-sensitized
MoS$_2$ with different Pb:Mo; transient relative response of
MoS$_2$ sensors toward different NO$_2$ concentrations; LOD
calculation of MoS$_2$ nanosheets sensor and QD-sensitized
MoS$_2$ sensor; sensor response at different relative humid-
ity and long-term stability of the QD-sensitized MoS$_2$ gas
sensors; UPS characterization of MoS$_2$ nanosheets and PbS
QDs; UV–Vis–NIR spectra of MoS$_2$ nanosheets and PbS
QDs; the initial energy band structure of PbS QD and MoS$_2$
nanosheet; SEM cross-section morphology of QD-sensitized
MoS$_2$ thin film; and NO$_2$-sensing properties of QD-sensi-
tized MoS$_2$ with different deposition layers.

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References

1. Environmental Protection Agency (EPA). https://www.epa.gov/
learn-issues/learn-about-air/ for “Air Pollution, 2013” (2013)
2. F. Xian, B. Zong, S. Mao, Metal-organic framework-based sen-
sors for environmental contaminant sensing. Nano-Micro Lett.
10, 64 (2018). https://doi.org/10.1007/s40820-018-0218-0
3. T. Xu, Y. Pei, Y. Liu, D. Wu, Z. Shi, J. Xu, Y. Tian, X. Li,
High-response NO$_2$ resistive gas sensor based on bilayer
MOS$_2$ grown by a new two-step chemical vapor deposition
method. J. Alloys Compd. 725, 253–259 (2017). https:
//doi.org/10.1016/j.jallcom.2017.06.105
4. I. Lee, S.J. Choi, K.M. Park, S.S. Lee, S. Choi, I.D. Kim,
C.O. Park, The stability, sensitivity and response transients of
ZnO, SnO$_2$ and WO$_3$ sensors under acetone, toluene and H$_2$S
environments. Sens. Actuators. B 197, 300–307 (2014). https:
//doi.org/10.1016/j.snb.2014.02.043
5. Z. Yuan, J. Zhang, F. Meng, Y. Li, R. Li et al., Highly sensi-
tive ammonia sensors based on Ag-decorated WO$_3$ nanorods.
IEEE Trans. Nanotechnol. 17(6), 1252–1258 (2018). https:
//doi.org/10.1109/TNANO.2018.2871675
6. S. Zhang, C. Wang, F. Qu, S. Liu, C.T. Lin et al., ZnO nanoflowers modified with RuO₂ for enhancing acetylen sensing performance. Nanotechnology 31(11), 115502 (2019). https://doi.org/10.1088/1361-6528/ab5cd9

7. F. Qu, H. Jiang, M. Yang. Designed formation through a metal organic framework route of ZnO/ZnCo₂O₄ hollow core-shell nanocages with enhanced gas sensing properties. Nanoscale 8(36), 16349–16356 (2016). https://doi.org/10.1039/C6NR05187A

8. Y. Wang, G. Duan, Y. Zhu, H. Zhang, Z. Xu, Z. Dai, W. Cai, Room temperature H₂S gas sensing properties of In₅O₃ micro/nanostructured porous thin film and hydrolyzation-induced enhanced sensing mechanism. Sens. Actuators B 228, 74–84 (2016). https://doi.org/10.1016/j.snb.2016.01.002

9. F. Meng, H. Zeng, Y. Sun, M. Li, J. Liu, Trimethylamine sensors based on Au-modified hierarchical porous single-crystalline ZnO nanosheets. Sensors 17, 1478 (2017). https://doi.org/10.3390/s17071478

10. Z. Yuan, J. Zhao, F. Meng, W. Qin, Y. Chen, M. Yang, M. Ibrahim, Y. Zhao, Sandwich-like composites of double-layer Co₃O₄ and reduced graphene oxide and their sensing properties to volatile organic compounds. J. Alloys Compd. 793, 24–30 (2019). https://doi.org/10.1016/j.jallcom.2019.03.386

11. Q. He, Z. Zeng, Z. Yin, H. Li, S. Wu, X. Huang, H. Zhang, Fabrication of flexible MoS₂ thin-film transistor arrays for practical gas-sensing applications. Small 8(19), 2994–2999 (2012). https://doi.org/10.1002/smll.201201224

12. D.J. Late, Y.K. Huang, B. Liu, J. Acharya, S.N. Shirodkar et al., Sensing behavior of atomically thin-layered MoS₂ transistors. ACS Nano 7(6), 4879–4891 (2013). https://doi.org/10.1021/nn400026u

13. B. Liu, L. Chen, G. Liu, A.N. Abbas, M. Fathi, C. Zhou, High-performance chemical sensing using Schottky-contacted chemical vapor deposition grown monolayer MoS₂ transistors. ACS Nano 8(5), 5304–5314 (2014). https://doi.org/10.1021/nn5015215

14. Y. Kim, S.K. Kang, N.C. Oh, H.D. Lee, S.M. Lee, J. Park, H. Kim, Improved sensitivity in schottky contacted two-dimensional MoS₂ gas sensor. ACS Appl. Mater. Interfaces 11(42), 38902–38909 (2019). https://doi.org/10.1021/acsami.9b10861

15. B. Cho, A.R. Kim, Y. Park, J. Yoon, Y.J. Lee et al., Bifunctional sensing characteristics of chemical vapor deposition synthesized atomic-layered MOS₂. ACS Appl. Mater. Interfaces 7(4), 2952–2959 (2015). https://doi.org/10.1021/am508535x

16. S.Y. Cho, Y. Lee, H.J. Koh, H. Jung, J.S. Kim, H.W. Yoo, J. Kim, H.T. Jung, Superior chemical sensing performance of black phosphorus: comparison with MOS₂ and graphene. Adv. Mater. 28(32), 7020–7028 (2016). https://doi.org/10.1002/adma.201601167

17. R. Kumar, N. Goel, M. Kumar, High performance NO₂ sensor using MOS₂ nanowires network. Appl. Phys. Lett. 112(5), 053502 (2018). https://doi.org/10.1063/1.5019296

18. T. Pham, G. Li, E. Belyakov, M.E. Itkis, A. Mulchandani, MoS₂-based optoelectronic gas sensor with sub-parts-per-billion limit of NO₂ gas detection. ACS Nano 13(3), 3196–3205 (2019). https://doi.org/10.1021/acsnano.8b08778

19. H. Im, A. Almutairi, S. Kim, M. Sridharan, S. Kim, Y. Yoon, On MoS₂ thin-film transistor design consideration for a NO₂ gas sensor. ACS Sens. 4(11), 2930–2936 (2019). https://doi.org/10.1021/acssensors.9b01307

20. Y. Kang, S. Pyo, E. Jo, J. Kim, Light-assisted recovery of reacted MoS₂ for reversible NO₂ sensing at room temperature. Nanotechnology 30(35), 355504 (2019). https://doi.org/10.1088/1361-6528/ab2277

21. A.V. Agrawal, R. Kumar, S. Venkatesan, A. Zakhidov, G. Yang, J. Bao, M. Kumar, M. Kumar, Photoactivated mixed in-plane and edge-enriched p-type MoS₂ flake-based NO₂ sensor working at room temperature. ACS Sens. 3(5), 998–1004 (2018). https://doi.org/10.1021/acssensors.8b00146

22. S. Cui, Z. Wen, X. Huang, J. Chang, J. Chen, Stabilizing MoS₂ nanosheets through SnO₂ nanocrystal decoration for high-performance gas sensing in air. Small 11(19), 2305–2313 (2015). https://doi.org/10.1002/smll.201402923

23. Y. Han, D. Huang, Y. Ma, G. He, J. Hu et al., Design of hetero-​nanostructures on MoS₂ nanosheets to boost NO₂ room-temperature sensing. ACS Appl. Mater. Interfaces 10(26), 22640–22649 (2018). https://doi.org/10.1021/acsami.8b05811

24. B. Cho, J. Yoon, S.K. Lim, A.R. Kim, D.H. Kim et al., Chemical sensing of 2D graphene/MoS₂ heterostructure device. ACS Appl. Mater. Interfaces 7(30), 16775–16780 (2015). https://doi.org/10.1021/acsami.5b04541

25. Z. Wang, T. Zhang, C. Zhao, T. Han, T. Fei, S. Liu, G. Lu, Rational synthesis of molybdenum disulfide nanoparticles decorated reduced graphene oxide hybrids and their application for high-performance NO₂ sensing. Sens. Actuators B 260, 508–518 (2018). https://doi.org/10.1016/j.snb.2017.12.181

26. M. Ikram, L. Liu, Y. Liu, L. Ma, H. Lv et al., Fabrication and characterization of a high-surface area MoS₂@WS₂ heterojunction for the ultra-sensitive NO₂ detection at room temperature. J. Mater. Chem. A 7(24), 14602–14612 (2019). https://doi.org/10.1039/C9TA03452H

27. H.S. Hong, N.H. Phuong, N.T. Huong, N.H. Nam, N.T. Hue, Highly sensitive and low detection limit of resistive NO₂ gas sensor based on a MoS₂/graphene two-dimensional heterostructures. Appl. Surf. Sci. 492, 449–454 (2019). https://doi.org/10.1016/j.apsusc.2019.06.230

28. T. Chen, W. Yan, J. Xu, J. Li, G. Zhang, D. Ho, Highly sensitive and selective NO₂ sensor based on 3D MoS₂/rGO composites prepared by a low temperature self-assembly method. J. Alloys Compd. 793, 541–551 (2019). https://doi.org/10.1016/j.jallcom.2019.04.126

29. M. Yuan, M. Liu, E.H. Sargent, Colloidal quantum dot solids for solution-processed solar cells. Nat. Energy 1(3), 16016 (2016). https://doi.org/10.1038/nenergy.2016.16

30. V. Sukhovatkin, S. Hinds, L. Brzozowski, E.H. Sargent, Colloidal quantum-dot photodetectors exploiting multiexciton generation. Science 324(5934), 1542–1544 (2009). https://doi.org/10.1126/science.1173812
31. X. Dai, Z. Zhang, Y. Jin, Y. Niu, H. Cao et al., Solution-processed, high-performance light-emitting diodes based on quantum dots. Nature 515(7525), 96–99 (2014). https://doi.org/10.1038/nature13829

32. H. Liu, M. Li, O. Voznyy, L. Hu, Q. Fu et al., Physically flexible, rapid-response gas sensor based on colloidal quantum dot solids. Adv. Mater. 26(17), 2718–2724 (2014). https://doi.org/10.1002/adma.201304366

33. H. Liu, S. Xu, M. Li, G. Shao, H. Song et al., Chemiresistive gas sensors employing solution-processed metal-oxide quantum dot films. Appl. Phys. Lett. 105(16), 163104 (2014). https://doi.org/10.1063/1.4900405

34. M. Li, W. Zhang, G. Shao, H. Kan, Z. Song et al., Sensitive NO2 gas sensors employing spray-coated colloidal quantum dots. Thin Solid Films 618, 271–276 (2016). https://doi.org/10.1016/j.tsf.2016.08.023

35. Z. Song, Z. Huang, J. Liu, Z. Hu, J. Zhang et al., Fully stretchable and humidity-resistant quantum dot gas sensors. ACS Sens. 3(5), 1048–1055 (2018). https://doi.org/10.1021/acssens.8b00263

36. J. Xie, H. Zhang, S. Li, R. Wang, X. Sun et al., Defect-rich MoS2 ultrathin nanosheets with additional active edge sites for enhanced electrocatalytic hydrogen evolution. Adv. Mater. 25(40), 5807–5813 (2013). https://doi.org/10.1002/adma.201302685

37. C.B. Murray, D.J. Norris, M.G. Bawendi, Synthesis and characterization of nearly monodisperse CdE (E = sulfur, selenium, tellurium) semiconductor nanocrystallites. J. Am. Chem. Soc. 115(19), 8706–8715 (1993). https://doi.org/10.1021/ja00720a025

38. S.G. Kwon, Y. Piao, J. Park, S. Angappane, Y. Jo, N.-M. Hwang, J.-G. Park, T. Hyeon, Kinetics of monodisperse iron oxide nanocrystal formation by “heating-up” process. J. Am. Chem. Soc. 129(41), 12571–12584 (2007). https://doi.org/10.1021/ja074633q

39. J. Zhang, J. Gao, E.M. Miller, J.M. Luther, M.C. Beard, Diffusion-controlled synthesis of PbS and PbSe quantum dots with in situ halide passivation for quantum dot solar cells. ACS Nano 8(1), 614–622 (2013). https://doi.org/10.1021/nn4005236k

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

41. D. Wang, J.K. Baral, H. Zhao, B.A. Gonfa, V.V. Truong, M.A. El Khakani, R. Izquierdo, D. Ma, Controlled fabrication of PbS quantum-dot/carbon-nanotube nanoarchitecture and its significant contribution to near-infrared photon-to-current conversion. Adv. Funct. Mater. 21(21), 4010–4018 (2011). https://doi.org/10.1002/adfm.201100824

42. R.J. Chen, S. Bangsaruntip, K.A. Drouvalakis, N.W. Kam, M. Shim et al., Noncovalent functionalization of carbon nanotubes for highly specific electronic biosensors. Proc. Natl. Acad. Sci. U.S.A. 100(9), 4984–4989 (2003). https://doi.org/10.1073/pnas.0837064100

43. H. Nan, Z. Wang, W. Wang, Z. Liang, Y. Lu et al., Strong photoluminescence enhancement of MoS2 through defect engineering and oxygen bonding. ACS Nano 8(6), 5738–5745 (2014). https://doi.org/10.1021/nn500532f

44. N. Barsan, U. Weimar, Conduction model of metal oxide gas sensors. J. Electroceram. 7(3), 143–167 (2011). https://doi.org/10.1002/adfm.201603598

45. M. Ridene, I. Iezhokin, P. Offermansand, C.F.J. Flipse, Enhanced sensitivity of epitaxial graphene to NO2 by water coadsorption. J. Phys. Chem. C 120(34), 19107–19112 (2016). https://doi.org/10.1021/acs.jpcc.6b03495

46. J. Wu, S. Feng, X. Wei, J. Shen, W. Lu et al., Facile synthesis of 3D graphene flowers for ultrasensitive and highly reversible gas sensing. Adv. Funct. Mater. 26(41), 7462–7469 (2016). https://doi.org/10.1002/adfm.201603598

47. M. Ridene, I. Iezhokin, P. Offermansand, C.F.J. Flipse, Enhanced sensitivity of epitaxial graphene to NO2 by water coadsorption. J. Phys. Chem. C 120(34), 19107–19112 (2016). https://doi.org/10.1021/acs.jpcc.6b03495

48. R. Kumar, N. Goel, M. Kumar, UV-activated MoS2 based fast and reversible NO2 sensor at room temperature. ACS Sens. 2(11), 1744–1752 (2017). https://doi.org/10.1021/acssensors.7b00731

49. N. Yamazoe, Toward innovations of gas sensor technology. Sens. Actuators B 108, 2–14 (2005). https://doi.org/10.1016/j.snb.2004.12.075

50. H. Long, A.H. Trochimczyk, T. Pham, Z. Tang, T. Shi et al., High surface area MoS2/graphene hybrid aerogel for ultrasensitive NO2 detection. Adv. Funct. Mater. 26(28), 5158–5165 (2016). https://doi.org/10.1002/adfm.201601562

51. N. Yamazoe, New approaches for improving semiconductor gas sensors. Sens. Actuators B 128, 566–573 (1991). https://doi.org/10.1016/0925-4005(91)80213-4

52. X. Zhang, L. Yu, X. Wu, W. Hu, Experimental sensing and density functional theory study of H2S and SOF2 adsorption on Au-modified graphene. Adv. Sci. 2(11), 1500101 (2015). https://doi.org/10.1002/advs.201500101

53. J. Embden, K. Latham, N.W. Duffy, Y. Tachibana, Near-infrared absorbing Cu12Sb4S13 and Cu3SbS4 nanocrystals: synthesis, characterization, and photoelectrochemistry. J. Am. Chem. Soc. 135(31), 11562–11571 (2013). https://doi.org/10.1021/ja402702x

54. K. Wang, J. Wang, J. Fan, M. Lotya, A. O’Neill et al., Ultrafast saturable absorption of two-dimensional MoS2 nanosheets. ACS Nano 7(10), 9260–9267 (2013). https://doi.org/10.1021/nn403886t

55. F.W. Wise, Lead salt quantum dots: the limit of strong quantum confinement. Acc. Chem. Res. 33(11), 773–780 (2000). https://doi.org/10.1021/ar970220q

56. N. Yamazoe, K. Shimanoe, Basic approach to the transducer function of oxide semiconductor gas sensors. Sens. Actuators B 160, 1352–1362 (2011). https://doi.org/10.1016/j.snb.2011.09.075