



Volatile Organic Compounds Gas Sensors Based on Molybdenum Oxides: A Mini Review

Jingxuan Wang¹, Qu Zhou^{1*}, Shudi Peng², Lingna Xu¹ and Wen Zeng^{3*}

¹ College of Engineering and Technology, Southwest University, Chongqing, China, ² Chongqing Electric Power Research Institute, State Grid Chongqing Electric Power Company, Chongqing, China, ³ College of Materials Science and Engineering, Chongqing University, Chongqing, China

OPEN ACCESS

Edited by:

Liwei Wang,
Guangxi University, China

Reviewed by:

Zhaoxiong Yan,
Jiangnan University, China
Zhe Chen,
Jilin Institute of Chemical
Technology, China

*Correspondence:

Qu Zhou
zhouqu@swu.edu.cn
Wen Zeng
wenzeng@cqu.edu.cn

Specialty section:

This article was submitted to
Nanoscience,
a section of the journal
Frontiers in Chemistry

Received: 27 February 2020

Accepted: 01 April 2020

Published: 05 May 2020

Citation:

Wang J, Zhou Q, Peng S, Xu L and
Zeng W (2020) Volatile Organic
Compounds Gas Sensors Based on
Molybdenum Oxides: A Mini Review.
Front. Chem. 8:339.
doi: 10.3389/fchem.2020.00339

As a typical n-type semiconductor, MoO₃ has been widely applied in the gas-detection field due to its competitive physicochemical properties and ecofriendly characteristics. Volatile organic compounds (VOCs) are harmful to the atmospheric environment and human life, so it is necessary to quickly identify the presence of VOCs in the air. This review briefly introduced the application progress of an MoO₃-based sensor in VOCs detection. We mainly emphasized the optimization strategies of a high performance MoO₃, which consists of morphology-controlled synthesis and electronic properties functional modification. Besides the general synthesis methods, its gas-sensing properties and mechanism were briefly discussed. In conclusion, the application status of MoO₃ in gas-sensing and the challenges still to be solved were summarized.

Keywords: MoO₃, gas sensors, volatile organic compounds, functional modification, gas-sensing mechanism

INTRODUCTION

Volatile organic compounds (VOCs) mainly come from the exhaust gases generated by fuel combustion and transportation, as well as emissions from building materials, decorative materials, and furniture. People can suffer headaches, nausea, and even more severe issues such as convulsions and comas when exposed to a certain concentration of VOCs (Chu et al., 2010; Sui et al., 2015). Moreover, many carcinogens that damage the liver, kidneys, brain, and nervous system were found in VOCs. Therefore, the problem of air pollution by VOCs has attracted extensive attention in many countries (Yang et al., 2018; He S. H. et al., 2019). Currently, there are two common techniques—photo ionization detector (PID) and flame ionization detector (FID)—to detect VOCs, however, the application of these methods in industry are limited due to the relatively high cost and complicated maintenance. Considering the characteristics of small size, low cost, and convenient fabrication, semiconductor gas sensor technology plays an important role in many fields (Lu et al., 2018; Xiao et al., 2018; Zhang D. Z. et al., 2018; Zhang Q. Y. et al., 2018; Zhou et al., 2018c, 2019; Wang et al., 2019a; Wei et al., 2020), so it is reasonable to propose the employment of a gas sensor to realize the online monitoring of VOCs.

As a typical n-type semiconductor material with a suitable band gap (2.39–2.9 eV) (Yan et al., 2016), MoO₃ has attracted wide attention because of its distinctive gas sensing performances in the detection of many gases (Liu et al., 2015; Xia et al., 2016; Li, 2017; Zhou et al., 2017; Yang et al., 2018). Researchers have been devoted to designing nanomaterials with more suitable properties, and two methods have proved effective through unremitting efforts. One is to synthesize materials

with larger specific surface areas, which is attributed to the conclusion that the micromorphology features have an impact on the gas-sensitive process (Zhou et al., 2018b; Zhu et al., 2018; Wang et al., 2019b; Wei Z. J. et al., 2019). Considering the changes in the materials that are caused by doping and compounding or the catalytic effect of the introduced material on the sensing process, it is also desirable to improve the properties of the materials by introducing other elements or substances (Mousavi-Zadeh and Rahmani, 2018; Zhou et al., 2018a; Wang et al., 2019c; Xu et al., 2019). Therefore, the optimization strategies of MoO₃ based on controllable morphology synthesis and functional modification were comprehensively summarized in this mini review. Besides, several typical synthesis pathways of MoO₃ nanomaterials, as well as the gas-sensing performances and mechanism to VOCs, were introduced.

SYNTHESIS METHODS OF MoO₃

The preparation of materials with more useful properties has always been a research hotspot in the field of gas detection, and has attracted extensive attention from scholars. In recent years, material preparation craft is constantly updated and developed with the emergence of new technology. At present, solid phase method, liquid phase method, and template method are mainly employed to synthesize MoO₃ materials with admirable performance.

The process of preparing materials by solid phase method is to transform the solid phase raw materials into target powders. Using ammonium molybdate as raw material, Qin et al. (2017) successfully obtained MoO₃ nanoplate arrays in the air through a solid phase chemical synthesis route. By hydrolyzing a mixture of one or more soluble metal salts solution and then evaporating and sublimating them, the liquid phase method adopts a series of processes to separate the solute from the solvent, where finally the nanoparticles with uniform shape are produced by crystallizing metal ions. Nowadays, spray pyrolysis technique, sol-gel route, and hydrothermal method have been reported as common liquid phase methods for the preparation of MoO₃ materials. Sau et al. (2019) used the sol-gel method to heat the solution after the molybdenum source was fully dissolved to a gelatinous state under specific PH (7–8) conditions. Finally they prepared α -MoO₃ nanoparticles through annealing and drying. Pandeeswari and Jeyaprakash (2014) successfully obtained MoO₃ thin films with a thickness of 520 nm on a glass substrate maintained at 250°C by spray pyrolysis route. Zhu et al. (2019) synthesized hollow MoO₃ microcages by a facile one-step hydrothermal process, which had gone through four steps of heating, cooling, centrifugation, and washing. The template method is designed to generate nanomaterials based on the template of appropriate structure, which can effectively influence the growth direction and morphology of the materials. Zhang et al. (2017) deposited MoS₂@MnCO₃ powder based on an MnCO₃ template, and prepared MoS₂ by adding hydrochloric acid to remove MnCO₃. Finally, they obtained hierarchical MoO₃ microboxes by calcining MoS₂ powder.

OPTIMIZATION STRATEGIES OF MoO₃

The sensitivity of the gas sensors is closely related to the changes in the resistance that is attributed to the adsorption and desorption of target gas molecules on the surface of materials, which implies that the gas-sensing properties mainly depend on their own electronic characteristics (carrier concentration, energy band structure, etc.) and morphological characteristics (specific surface area, aperture, etc.). Based on this, the main strategies to enhance the gas-sensing performances of materials are morphology control and electronic properties improvement.

Controllable Synthesis of Diversified MoO₃

In recent years, the production of MoO₃ gas-sensitive materials with high quality morphology has become an important research approach for performance enhancement. In this regard, MoO₃ gas-sensitive materials with different morphologies and dimensions have been prepared through different methods to conduct gas-sensing experiments. In this section, we review and summarize the excellent achievements of MoO₃ morphology control and several typical morphologies are shown in **Figures 1A–C**.

One-dimensional (1D) structures, such as nanofibers, nanorods, and nanoribbons, have limited specific surface areas, but their reaction sites are directly exposed to external environments, leading to the susceptible variation of interface ion transport when some changes occur to environmental factors. Hence, 1D material has the potential to be applied as excellent sensors. The remarkable selectivity and response-recovery characteristics of α -MoO₃ nanorods gas sensors to triethylamine was reported (He S. H. et al., 2019). Besides, the rapid adsorption/desorption processes were confirmed to be the reason for prominent gas-sensing characteristics. By optimizing reaction time and pulse temperature in hydrothermal reaction, Mandal et al. (2019) synthesized uniform MoO₃ nanobelts and MoO₃ nanofibers. The experimental results illustrated that the enhanced ethanol detection performances of nanofibers could be ascribed to the larger specific surface area and surface defects compared with the nanowires.

Materials with two-dimensional structures such as nanoplates and nanosheets have a larger specific surface area, which further improves the gas-sensitive responses. The prominent electron depletion layer that derived from the thin morphologic features of nanoplates was verified as beneficial due to the ultrahigh gas-sensing performances. Moreover, the porous structure caused by the combination of nanoplates could effectively facilitate gas diffusion on the surface of MoO₃, providing convenience for the gas-sensing process (Cho et al., 2014). The study of Jiang et al. (2018) demonstrated that MoO₃ microsheets with a large number of oxygen vacancies exhibit superior sensing properties, and the strong reaction between adsorbed oxygen and target gases to be confirmed was also an important factor to promote the gas-sensing performances.

Three-dimensional structures with large specific surface areas are generally assembled from low-dimensional structures, which have more reaction sites for gas adsorption, leading to better gas-sensitive responses and lower gas detection limits.

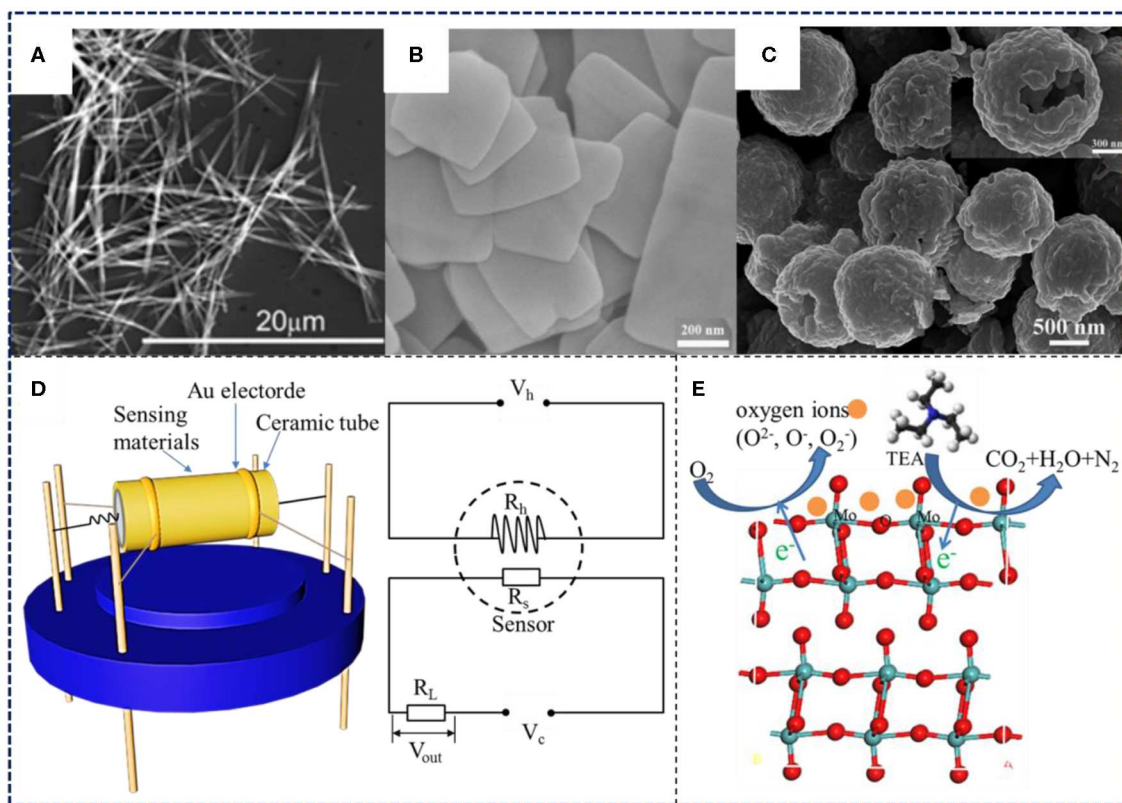


FIGURE 1 | (A) Nanoribbons. Reprinted with permission from Kwak et al. Copyright (2019) American Chemical Society. (B) Nanosheets. Reprinted with permission from Shen et al. Copyright (2019) American Chemical Society. (C) Hollow microspheres. Reprinted with permission from Zhang et al. Copyright (2019) American Chemical Society. (D) Schematic diagram of sensor and detection circuit. (E) Gas sensing mechanism.

Furthermore, more gas diffusion channels are provided by the assembled porous structure, which are conducive to gas sensitivity reaction. Common three-dimensional structures of MoO₃ include nanoarrays, nanoflowers, and nanospheres. For example, Ji et al. (2019a) synthesized three hierarchical MoO₃ flower-like samples with different petal shapes and found that the material with the thinnest petals had the most outstanding gas-sensing performance. Specifically, the thin nanosheets assembled flower-like MoO₃ has a larger specific surface area that provides more potential for gas-sensitive reactions, and the thinness allows electrons to transfer rapidly across the surface, which implied the procedure of gas-sensing became easier. In addition, the curved edges of thin petals make it harder for gas molecules to leave the surface, facilitating the full process of adsorption. Cong et al. (2016) proved the sensors based on MoO₃ nanoarrays assembled from a large number of long nanorods exhibited more reactive sites and more active surface electrical properties than the nanoarrays with fewer nanorods.

Functional Modification Methods

Functional modification is of great significance to improving the properties of gas-sensitive materials. In the present studies, the modification of MoO₃ mainly includes two approaches

of element doping and multi-component compounding, which have been proven to be effective methods in optimizing the electronic properties of materials. In this section, the advances of MoO₃ modification research were briefly summarized.

Metal doping is an alternative approach to acquire the modified characteristics of MoO₃. On the one hand, suitable metal doping can effectively reduce the activation energy of chemisorption reaction for the measured gases. On the other hand, the metal elements play the role of the catalytic activity center, leading to the optimization of the gas-sensing performances. Scholars have studied the influence of different doping elements on the properties of MoO₃ materials. For instance, Cr-doped MoO₃ nanorods had more oxygen vacancy induced by doping, which is meaningful for the promotion of sensitivity (Li et al., 2019). Similar results were obtained when the W element was doped in MoO₃ nanobelts (Li et al., 2017b). As for the dope of Ni, not only did more adsorbed oxygen that can promote the change of resistance in the sensing process appear on the surface of MoO₃, but also the morphology changed with the increase of the doping amount, which is related to the inhibition of lattice growth by the introduction of doped Ni elements (Jiang et al., 2019). Yang et al. (2017) prepared Zn-doped MoO₃ nanobelts using the hydrothermal method. They found that the doped zinc caused the reduction of the band gap of

MoO₃ and increased the amount of adsorbed ethanol molecules, which contributed to the excellent performance.

Many researchers have been devoted to the preparation of hybrid structures that affected properties such as grain boundary barrier, energy band, carrier concentration, and depletion layer, thus improving the performance of gas sensing. For instance, the Au nanoparticle with a larger work function than MoO₃ received electrons from MoO₃ nanosheets, leading to the appearance of electron depletion layer at the Au/MoO₃ Schottky junction, and the enhanced ethanol detection capabilities were attributed to the resulting high resistance (Yan et al., 2016). Considering Pt nanoparticles combined MoO₃ nanobelts, the superior selectivity to formaldehyde was conducted, which was ascribed to the catalytic effect of loaded particles on formaldehyde during the surface gas sensing process (Fu et al., 2019). As for the RuO₂ nanoparticles modified MoO₃ nanobelts, oxygen vacancies produced on the surface, creating more adsorption-desorption sites for gas molecules (Wei Q. et al., 2019). With regard to heterostructure, Li et al. (2018) synthesized the CoMoO₄/MoO₃ nanostructure with p-n heterojunction using the dipping-annealing method. The enhancement of the adsorption to oxygen by p-type CoMoO₄ and the barrier formed at the p-n junction were verified to be favorable to the improved gas response.

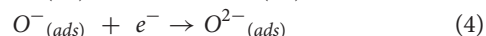
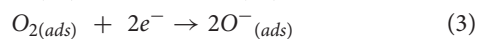
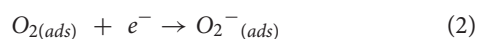
Above all, previous studies have focused on the optimization of MoO₃ through synthesizing different samples with multiple morphologies, the doping of transition metals such as Cr, W, Ag, Au, Fe, Zn, and Ni, and decorating with other nanomaterials (Au nanoparticles, RuO₂ nanoparticles, Fe₂O₃ nanoparticles, CoMoO₄ nanoparticles, NiCo₂O₄ nanosheets, etc.). Thus, in

order to improve the gas sensitivity of MoO₃, many potential materials for the modification of innovative synthesis methods with controllable morphology need to be explored.

GAS-SENSING APPLICATION OF MoO₃

Gas-sensing Mechanism of MoO₃

The theory of sensitivity generated by changes in material resistance during the gas-sensing process has been widely accepted by scholars in the investigation of the gas-sensitive mechanism of metal oxides. As shown in **Figure 1E**, the reaction between the target gas molecules and the adsorbed oxygen ions (O₂⁻, O⁻, O²⁻) on the surface of the gas-sensitive materials leads to the change of the electrical conductivity, which is key to detecting the corresponding response (Li et al., 2015). MoO₃ is an n-type semiconductor with electrons as internal carriers. Mass of oxygen molecules in the air tends to be adsorbed by the MoO₃, forming adsorbed oxygen ions accompanied by the acceptance of electrons from the conduction band of MoO₃. Thus, the electron depletion layer was formed on the surface of MoO₃, which caused the increase of resistance (Ji et al., 2019a). The specific process can be expressed by the following equation:

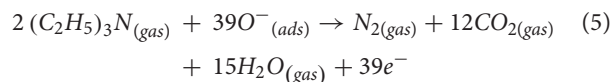


When the MoO₃ sensor was exposed to the atmosphere of the target gas, the adsorbed oxygen ions underwent a reduction

TABLE 1 | Summary of recent researches on MoO₃-based sensors for VOCs detection.

Gas	Sensing material	Concentration (ppm)	Temperature (°C)	Response	References
Formaldehyde	Ni-doped -MoO ₃ nanolamella	100	255	41	Shen et al., 2017
	Pt-decorated MoO ₃ nanobelts	200	27	19.1%	Fu et al., 2019
Methanol	α-MoO ₃ nanorod arrays	500	300	7.8	Cong et al., 2016
	ZnO microcube/MoO ₃ micrograss	500	200	56	Mandal et al., 2018
Ethanol	nanofiber-assembled hierarchical MoO ₃	400	300	32	Ji et al., 2019b
	Au nanoparticles/MoO ₃ nanobelts	500	200	50	Wang et al., 2018
	α-MoO ₃ nanobelts	500	300	80	Mo et al., 2020
	Zn-doped MoO ₃ nanobelts	250	240	52	Yang et al., 2017
Xylene	α-MoO ₃ nanoarrays	1,000	370	83.9	Qin et al., 2017
	Fe-doped α-MoO ₃ nanoarrays	1,000	340	166.3	Wang et al., 2020
	Fe ₂ O ₃ nanoparticles/MoO ₃ nanobelts	100	233.5	22.48	Qu et al., 2019
	Ni-doped MoO ₃ nano-pompon	100	250	62.6	Jiang et al., 2019
Trimethylamine	Ce-doped MoO ₃ nanobelts	50	240	17.4	Li et al., 2017a
	Au nanoparticles/MoO ₃ nanobelts	50	280	70	Zhang et al., 2016
	porous α-MoO ₃ nanosheets	10	133	51.47	Shen et al., 2019
Triethylamine	MoO ₃ nanobelts	50	240	582.3	Yang et al., 2016
	MoO ₃ microsheets	100	275	27.1	Jiang et al., 2018
	α-Fe ₂ O ₃ /α-MoO ₃ nanostructure	50	280	76	Liu et al., 2019
	Cr-doped α-MoO ₃ nanorods	100	200	150.25	Li et al., 2019
	Ag nanoparticles/α-MoO ₃ nanorods	100	200	408.6	He K. et al., 2019

reaction. Further, electrons are released back into the conduction band of MoO₃, and the depletion layer narrows, which results in a decrease in the resistance of the material and completes the whole gas sensing process. Take triethylamine for example, this process can be expressed as the following equation (Wei Q. et al., 2019).



Gas Sensing Properties of MoO₃

Nowadays, many researchers focus on the application of MoO₃ materials in gas sensors, while the ultimate goal of the investigation is to obtain higher performance MoO₃-based sensing materials. Notably, MoO₃ with prominent gas-sensing properties has been proven to be an alternative sensing material to detect VOCs. We summarized the representative research on VOCs detection, which mainly focused on the use of formaldehyde (HCHO), methanol (CH₃OH), ethanol (CH₃CH₂OH), xylene (CH₃C₆H₄CH₃), trimethylamine ((CH₃)₃N), and triethylamine ((C₂H₅)₃N), and listed them in **Table 1**. **Figure 1D** shows the structure diagram of the side heat sensor and the gas-sensing test circuit. The sensing-materials were coated on the alumina ceramic tube. A Ni-Cr resistance wire that could conveniently control the current was inserted in the coating tube and the change of resistances was tested by electrodes. The gas response (S) of MoO₃ based sensors to reducing gas is calculated by $S = R_a/R_g$, while to oxidizing gas it is $S = R_g/R_a$ (Jiang et al., 2019).

CONCLUSION

This mini review focused on the latest advances in synthetic methods, morphological control, functional modification, and gas-sensing application including properties and mechanism of MoO₃ materials in the detection of VOCs. The studies of morphologically-controlled synthesis proved that MoO₃ with a high specific surface area possesses superior gas-sensing

performances and provided reference experience for further MoO₃ gas-sensing material design. Further, appropriate element doping or material hybridization could improve properties of MoO₃, such as energy band gap and adsorbed oxygen content, which is advantageous to the gas sensing process. Scholars have made great efforts to develop more efficient MoO₃-based VOCs sensors and have shown objective achievement, but there are still challenges in practical application. The design of porous structures or hierarchical structures with more reactive gas pathways and reaction sites to further improve the specific surface area of MoO₃ material is an issue that needs to be further explored. In addition, more alternative modification materials should be selected through experimental verification. All of these issues should continue to be addressed to obtain MoO₃-based materials with a higher response, better selectivity, superior stability, and lower operating temperature. Finally, the gas-sensing mechanism was not complete. By combining theoretical calculation and analysis, the changes of electronic properties at the micro level should be analyzed, which will allow for further understanding of the nature of gas sensing and provide guidance for designing MoO₃ materials with better gas-sensing performances in the future.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

This work has been supported in part by the National Natural Science Foundation of China (No. 51507144), Fundamental Research Funds for the Central Universities (No. XDJK2019B021), the Chongqing Science and Technology Commission (CSTC) (No. cstc2016jcyjA0400), and the project of China Scholarship Council (CSC).

REFERENCES

- Cho, Y. H., Ko, Y. N., Kang, Y. C., Kim, I. D., and Lee, J. H. (2014). Ultraselective and ultrasensitive detection of trimethylamine using MoO₃ nanoplates prepared by ultrasonic spray pyrolysis. *Sens. Actuat. B Chem.* 195, 189–196. doi: 10.1016/j.snb.2014.01.021
- Chu, X. F., Liang, S. M., Sun, W. Q., Zhang, W. B., Chen, T. Y., and Zhang, Q. F. (2010). Trimethylamine sensing properties of sensors based on MoO₃ microrods. *Sens. Actuat. B Chem.* 148, 399–403. doi: 10.1016/j.snb.2010.05.049
- Cong, S. R., Sugahara, T., Wei, T. T., Jiu, J. T., Hirose, Y., Nagao, S., et al. (2016). Diverse adsorption/desorption abilities originating from the nanostructural morphology of VOC gas sensing devices based on molybdenum trioxide nanorod arrays. *Adv. Mater. Interf.* 3:1600252. doi: 10.1002/admi.201600252
- Fu, X. X., Yang, P. Y., Xiao, X. F., Zhou, D., Huang, R., Zhang, X. H., et al. (2019). Ultra-fast and highly selective room-temperature formaldehyde gas sensing of Pt-decorated MoO₃ nanobelts. *J. Alloy. Compd.* 797, 666–675. doi: 10.1016/j.jallcom.2019.05.145
- He, K., He, S. H., Yang, W., and Tian, Q. F. (2019). Ag nanoparticles-decorated α-MoO₃ nanorods for remarkable and rapid triethylamine-sensing response boosted by pulse-heating technique. *J. Alloy. Compd.* 808:151704. doi: 10.1016/j.jallcom.2019.151704
- He, S. H., Li, W. D., Feng, L., and Yang, W. (2019). Rational interaction between the aimed gas and oxide surfaces enabling high-performance sensor: the case of acidic α-MoO₃ nanorods for selective detection of triethylamine. *J. Alloy. Compd.* 783, 574–582. doi: 10.1016/j.jallcom.2018.12.349
- Ji, H. C., Zeng, W., and Li, Y. Q. (2019a). Assembly of 2D nanosheets into lower-like MoO₃: New insight into the petal thickness affect on gas-sensing properties. *Mater. Res. Bull.* 118:110476. doi: 10.1016/j.materresbull.2019.05.001
- Ji, H. C., Zeng, W., and Li, Y. Q. (2019b). New insight into the gas-sensing properties of nanofiber-assembled and nanosheet-assembled hierarchical MoO₃ structures. *Phys. E.* 114:113646. doi: 10.1016/j.physe.2019.113646
- Jiang, W. H., Meng, L. L., Zhang, S. F., Chuai, X. H., Zhou, Z. J., Hu, C. H., et al. (2019). Design of highly sensitive and selective xylene gas sensor based on Ni-doped MoO₃ nano-pompon. *Sens. Actuat. B Chem.* 299:126888. doi: 10.1016/j.snb.2019.126888

- Jiang, W. H., Wei, D. D., Zhang, S. F., Chuai, X. H., Sun, P., Liu, F. M., et al. (2018). The facile synthesis of MoO₃ microsheets and their excellent gas-sensing performance toward triethylamine: high selectivity, excellent stability and superior repeatability. *New J. Chem.* 42:15111. doi: 10.1039/c8nj03539c
- Kwak, D., Wang, M. J., Koski, K. J., Zhang, L., Sokol, H., Maric, R., et al. (2019). Molybdenum trioxide (α -MoO₃) nanoribbons for ultrasensitive ammonia (NH₃) gas detection: integrated experimental and density functional theory simulation studies. *ACS Appl. Mater. Interf.* 11, 10697–10706. doi: 10.1021/acsami.8b20502
- Li, T. M., Zeng, W., Zhang, Y. Y., and Hussain, S. (2015). Nanobelt-assembled nest-like MoO₃ hierarchical structure: hydrothermal synthesis and gas-sensing properties. *Mater. Lett.* 160, 476–479. doi: 10.1016/j.matlet.2015.08.031
- Li, W. D., He, S. H., Feng, L., and Yang, W. (2019). Cr-doped α -MoO₃ nanorods for the fast detection of triethylamine using a pulse-heating strategy. *Mater. Lett.* 250, 143–146. doi: 10.1016/j.matlet.2019.05.006
- Li, Y. Q. (2017). Morphology-controllable synthesis of three-dimensional α -MoO₃ and their applications in gas sensing. *Phys. E* 94, 22–24. doi: 10.1016/j.physe.2017.07.010
- Li, Z. Q., Song, P., Yang, Z. X., and Wang, Q. (2018). *In situ* formation of one-dimensional CoMoO₄/MoO₃ heterojunction as an effective trimethylamine gas sensor. *Ceram. Int.* 44, 3364–3370. doi: 10.1016/j.ceramint.2017.11.126
- Li, Z. Q., Wang, W. J., Zhao, Z. C., Liu, X. R., and Song, P. (2017a). One-step hydrothermal preparation of Ce-doped MoO₃ nanobelts with enhanced gas sensing Properties. *RSC Adv.* 7:28366. doi: 10.1039/c7ra02893h
- Li, Z. Q., Wang, W. J., Zhao, Z. C., Liu, X. R., and Song, P. (2017b). Facile synthesis and enhanced trimethylamine sensing performances of W doped MoO₃ nanobelts. *Mat. Sci. Semicond. Proc.* 66, 33–38. doi: 10.1016/j.mssp.2017.04.002
- Liu, C. Y., Xu, H. Y., Chen, Z. R., Ye, Q., Wu, X. W., Wang, J. Q., et al. (2019). Enhanced triethylamine sensing properties by designing an α -Fe₂O₃/ α -MoO₃ nanostructure directly grown on ceramic tubes. *ACS Appl. Nano Mater.* 2, 6715–6725. doi: 10.1021/acsanm.9b01630
- Liu, Y. L., Yang, S., Lu, Y., Podval'naya, N. V., Chen, W., and S., et al. (2015). Hydrothermal synthesis of h-MoO₃ microrods and their gas sensing properties to ethanol. *Appl. Surf. Sci.* 359, 114–119. doi: 10.1016/j.apsusc.2015.10.071
- Lu, Z. R., Zhou, Q., Wang, C. S., Wei, Z. J., Xu, L. N., and Gui, Y. G. (2018). Electrospun ZnO–SnO₂ composite nanofibers and enhanced sensing properties to SF₆ decomposition byproduct H₂S. *Front. Chem.* 6:540. doi: 10.3389/fchem.2018.00540
- Mandal, B., Aaryashree, D., as, M., Htay, M. T., and Mukherjee, S. (2019). Architecture tailoring of MoO₃ nanostructures for superior ethanol sensing performance. *Mater. Res. Bull.* 109, 281–290. doi: 10.1016/j.materresbull.2018.09.041
- Mandal, B., Aaryashree, Singh, R., and Mukherjee, S. (2018). Highly selective and sensitive methanol sensor using rose-like ZnO microcube and MoO₃ micrograss-based composite. *IEEE Sens. J.* 18, 2659–2666. doi: 10.1109/JSEN.2018.2803682
- Mo, Y. F., Tan, Z. P., Sun, L. P., Lu, Y. B., and Liu, X. Z. (2020). Ethanol-sensing properties of α -MoO₃ nanobelts synthesized by hydrothermal method. *J. Alloy. Compd.* 812:152166. doi: 10.1016/j.jallcom.2019.152166
- Mousavi-Zadeh, S. H., and Rahmani, M. B. (2018). Synthesis and ethanol sensing characteristics of nanostructured MoO₃: Zn thin films. *Surf. Rev. Lett.* 25:11850046. doi: 10.1142/S0218625X18500464
- Pandeeswari, R., and Jeyaprakash, B. G. (2014). Nanostructured α -MoO₃ thin film as a highly selective TMA sensor. *Biosens. Bioelectron.* 53, 182–186. doi: 10.1016/j.bios.2013.09.057
- Qin, H. Y., Cao, Y. L., Xie, J., Xu, H., and Jia, D. Z. (2017). Solid-state chemical synthesis and xylene-sensing properties of α -MoO₃ arrays assembled by nanoplates. *Sens. Actuat. B Chem.* 242, 769–776. doi: 10.1016/j.snb.2016.11.081
- Qu, F. D., Zhou, X. X., Zhang, B. X., Zhang, S. D., Jiang, C. J., Ruan, S. P., et al. (2019). Fe₂O₃ nanoparticles-decorated MoO₃ nanobelts for enhanced chemiresistive gas sensing. *J. Alloy. Compd.* 782, 672–678. doi: 10.1016/j.jallcom.2018.12.258
- Sau, S., Chakraborty, S., Das, T., and Pal, M. (2019). Ethanol sensing properties of nanocrystalline α -MoO₃. *Front. Mater.* 6:285. doi: 10.3389/fmats.2019.00285
- Shen, J. L., Guo, S. J., Chen, C., Sun, L., Wen, S. P., Chen, Y., et al. (2017). Synthesis of Ni-doped-MoO₃ nanolamella and their improved gas sensing properties. *Sens. Actuat. B Chem.* 252, 757–763. doi: 10.1016/j.snb.2017.06.040
- Shen, S. K., Zhang, X. F., Cheng, X. L., Xu, Y. M., Gao, S., Zhao, H., et al. (2019). Oxygen-vacancy-enriched porous α -MoO₃ nanosheets for trimethylamine sensing. *ACS Appl. Nano Mater.* 2, 8016–8026. doi: 10.1021/acsanm.9b02072
- Sui, L. L., Xu, Y. M., Zhang, X. F., Cheng, X. L., Gao, S., Zhao, H., et al. (2015). Construction of three-dimensional flower-like-MoO₃ with hierarchical structure for highly selective triethylamine sensor. *Sens. Actuat. B Chem.* 208, 406–414. doi: 10.1016/j.snb.2014.10.138
- Wang, J. X., Zhou, Q., Lu, Z. R., Wei, Z. J., and Zeng, W. (2019a). Gas sensing performances and mechanism at atomic level of Au-MoS₂ microspheres. *Appl. Surf. Sci.* 490, 124–136. doi: 10.1016/j.apsusc.2019.06.075
- Wang, J. X., Zhou, Q., Lu, Z. R., Wei, Z. J., and Zeng, W. (2019b). The novel 2D honeycomb-like NiO nanoplates assembled by nanosheet arrays with excellent gas sensing performance. *Mater. Lett.* 255:26523. doi: 10.1016/j.matlet.2019.12.6523
- Wang, J. X., Zhou, Q., and Zeng, W. (2019c). Competitive adsorption of SF₆ decompositions on Ni-doped ZnO (100) surface: computational and experimental study. *Appl. Surf. Sci.* 479, 185–197. doi: 10.1016/j.apsusc.2019.01.255
- Wang, L. W., Wang, S. P., Fu, H., Wang, Y. H., and Yu, K. F. (2018). Synthesis of Au nanoparticles functionalized 1D α -MoO₃ nanobelts and their gas sensing properties. *NANO: Brief Rep. Rev.* 13:1850115. doi: 10.1142/S1793292018501151
- Wang, S. Q., Xie, J., Hu, J. D., Qin, H. Y., and Cao, Y. L. (2020). Fe-doped α -MoO₃ nanoarrays: Facile solid-state synthesis and excellent xylene-sensing performance. *Appl. Surf. Sci.* 512:145722. doi: 10.1016/j.apsusc.2020.145722
- Wei, Q., Song, P., Li, Z. Q., Yang, Z. X., and Wang, Q. (2019). Enhanced triethylamine sensing performance of MoO₃ nanobelts by RuO₂ nanoparticles decoration. *Vacuum* 162, 85–91. doi: 10.1016/j.vacuum.2019.01.028
- Wei, Z. J., Zhou, Q., Wang, J. X., Lu, Z. R., Xu, L. N., and Zeng, W. (2019). Hydrothermal synthesis of SnO₂ nanoneedle-anchored NiO microsphere and its gas sensing performances. *Nanomaterials* 9:1015. doi: 10.3390/nano9071015
- Wei, Z. J., Zhou, Q., and Zeng, W. (2020). Hierarchical WO₃-NiO microflower for high sensitivity detection of SF₆ decomposition byproduct H₂S. *Nanotechnology* 31:215701. doi: 10.1088/1361-6528/ab73bd
- Xia, Y. C., Wu, C. S., Zhao, N. Y., and Zhang, H. (2016). Spongy MoO₃ hierarchical nanostructures for excellent performance ethanol sensor. *Mater. Lett.* 171, 117–120. doi: 10.1016/j.matlet.2015.12.159
- Xiao, S. H., Liu, B., Zhou, R., Liu, Z. W., Li, Q. H., and Wang, T. H. (2018). Room-temperature H₂ sensing interfered by CO based on interfacial effects in palladium-tungsten oxide nanoparticles. *Sens. Actuat. B Chem.* 254, 966–972. doi: 10.1016/j.snb.2017.07.169
- Xu, K., Wei, W. Y., Sun, Y., Lu, W. H., Yu, T., Yang, Y., et al. (2019). Design of NiCo₂O₄ porous nanosheets/ α -MoO₃ nanorods heterostructures for ppb-level ethanol detection. *Powder Technol.* 345, 633–642. doi: 10.1016/j.powtec.2019.01.051
- Yan, H. H., Song, P., Zhang, S., Zhang, J., Yang, Z. X., and Wang, Q. (2016). Au nanoparticles modified MoO₃ nanosheets with their enhanced properties for gas sensing. *Sens. Actuat. B Chem.* 236, 201–207. doi: 10.1016/j.snb.2016.05.139
- Yang, S. A., Liu, Y. L., Chen, T., Jin, W., Yang, T. Q., Cao, M. C., et al. (2017). Zn doped MoO₃ nanobelts and the enhanced gas sensing properties to ethanol. *Appl. Surf. Sci.* 393, 377–384. doi: 10.1016/j.apsusc.2016.10.021
- Yang, S. A., Liu, Y. L., Chen, W., Jin, W., Zhou, J., Zhang, H., et al. (2016). High sensitivity and good selectivity of ultralong MoO₃ nanobelts for trimethylamine gas. *Sens. Actuat. B Chem.* 226, 478–485. doi: 10.1016/j.snb.2015.12.005
- Yang, S. L., Wang, Z., Hu, Y. M., Cai, Y. X., Huang, R., Li, X. X., et al. (2018). Defect-original room-temperature hydrogen sensing of MoO₃ nanoribbon: experimental and theoretical studies. *Sens. Actuat. B Chem.* 260, 21–32. doi: 10.1016/j.snb.2017.12.166
- Zhang, D. Z., Jiang, C. X., and Wu, J. F. (2018). Layer-by-layer assembled In₂O₃ nanocubes/flower-like MoS₂ nanofilm for room temperature formaldehyde sensing. *Sens. Actuat. B Chem.* 273, 176–184. doi: 10.1016/j.snb.2018.06.044
- Zhang, F. D., Dong, X., Cheng, X. L., Xu, Y. M., Zhang, X. F., and Huo, L. H. (2019). Enhanced gas-sensing properties for trimethylamine at low temperature based on MoO₃/Bi₂MO₃O₁₂ hollow microspheres. *ACS Appl. Mater. Interfaces* 11, 11755–11762. doi: 10.1021/acsami.8b22132
- Zhang, J., Song, P., Li, J., Yang, Z. X., and Wang, Q. (2017). Template-assisted synthesis of hierarchical MoO₃ microboxes and their high

- gas-sensing performance. *Sens. Actuat. B Chem.* 249, 458–466. doi: 10.1016/j.snb.2017.04.137
- Zhang, J., Song, P., Li, Z. Q., Zhang, S., Yang, Z. X., and Wang, Q. (2016). Enhanced trimethylamine sensing performance of single-crystal MoO₃ nanobelts decorated with Au nanoparticles. *J. Alloy. Compd.* 685, 1024–1033. doi: 10.1016/j.jallcom.2016.06.257
- Zhang, Q. Y., Zhou, Q., Lu, Z. R., Wei, Z. J., Xu, L. N., et al. (2018). Recent advances of SnO₂-based sensors for detecting fault characteristic gases extracted from power transformer oil. *Front. Chem.* 6:364. doi: 10.3389/fchem.2018.00364
- Zhou, Q., Chen, W. G., Xu, L. N., Kumar, R., Gui, Y. G., Zhao, Z. Y., et al. (2018a). Highly sensitive carbon monoxide (CO) gas sensors based on Ni and Zn doped SnO₂ nanomaterials. *Ceram. Int.* 44, 4392–4399. doi: 10.1016/j.ceramint.2017.12.038
- Zhou, Q., Umar, A., Sodki, E., Amine, A., Xu, L. N., and Gui, Y. G. (2018b). Fabrication and characterization of highly sensitive and selective sensors based on porous NiO nanodisks. *Sens. Actuat. B Chem.* 259, 604–615. doi: 10.1016/j.snb.2017.12.050
- Zhou, Q., Xu, L. N., Umar, A., Chen, W. G., and Kumar, R. (2018c). Pt nanoparticles decorated SnO₂ nanoneedles for efficient CO gas sensing applications. *Sens. Actuat. B Chem.* 256, 656–664. doi: 10.1016/j.snb.2017.09.206
- Zhou, Q., Zeng, W., Chen, W. G., Xu, L. N., Kumar, R., and Umar, A. (2019). High sensitive and low-concentration sulfur dioxide (SO₂) gas sensor application of heterostructure NiO-ZnO nanodisks. *Sens. Actuat. B Chem.* 298:126870. doi: 10.1016/j.snb.2019.126870
- Zhou, Q., Zhang, Q. Y., Liu, H. C., Hong, C. X., Wu, G. L., Peng, S. D., et al. (2017). Research on gas sensing properties of orthorhombic molybdenum oxide based sensor to hydrogen sulfide. *J. Nanoelectr. Optoelectr.* 12, 1072–1076. doi: 10.1166/jno.2017.2119
- Zhu, L., Zeng, W., Li, Y. Q., and Yang, J. D. (2019). Enhanced ethanol gas-sensing property based on hollow MoO₃ microcages. *Phys. E* 106, 170–175. doi: 10.1016/j.physe.2018.10.038
- Zhu, L., Zeng, W., Li, Y. Q., and Zhang, H. (2018). Novel hollow MoO₃ cage structure and its gas sensing property. *Mater. Lett.* 229, 269–271. doi: 10.1016/j.matlet.2018.07.054

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

Copyright © 2020 Wang, Zhou, Peng, Xu and Zeng. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.