

PAPER

[View Article Online](#)
[View Journal](#) | [View Issue](#)Cite this: *Nanoscale Adv.*, 2022, 4, 1345Ligand-assisted deposition of ultra-small Au nanodots on Fe₂O₃/reduced graphene oxide for flexible gas sensors†Jian Wang,^a Essalhi Fatima-Ezzahra,^a Jie Dai,^a Yanlei Liu,^a Chengjie Pei,^a Hai Li,^a Zhiwei Wang^{*ab} and Xiao Huang^{id} ^{*a}

The development of flexible room-temperature gas sensors is important in environmental monitoring and protection. In this contribution, by using 1-octadecanethiol (ODT) as a surface ligand, Au nanodots (NDs) with ultra-small size of ~1.7 nm were deposited on the surface of α -Fe₂O₃/reduced graphene oxide (rGO). The Au ND-ODT/ α -Fe₂O₃/rGO composite was fabricated into flexible gas sensors, which could detect NO₂ gas down to 200 ppb at room temperature. Compared with α -Fe₂O₃/rGO, Au ND-ODT/ α -Fe₂O₃/rGO showed enhanced sensing performance because of the beneficial effects of Au NDs, including facilitating the adsorption of NO₂ molecules and forming ohmic-like contact with rGO and α -Fe₂O₃. In addition, the sensing performance of the composite was also influenced by the surface ligands of the Au NDs. Ligands with less polar terminal groups were found to be beneficial to charge transfer in the sensing film. Moreover, Au ND-ODT/ α -Fe₂O₃/rGO-based flexible sensors showed negligible performance deterioration under moderately bent conditions, suggesting their potential to be used in portable and wearable devices.

Received 9th October 2021
Accepted 17th January 2022

DOI: 10.1039/d1na00734c

rsc.li/nanoscale-advances

1. Introduction

The fast technological and industrial development has led to increasingly serious air pollution. Among the several gaseous pollutants in air, nitrogen dioxide (NO₂), which is usually produced by fuel burning and vehicle exhausts,¹ can cause several pulmonary diseases such as pulmonary edema, tracheitis and pneumothorax, and is also the main cause for acid rain. Therefore, the development of highly sensitive and selective NO₂ gas sensors is important to environmental monitoring and protection.^{2,3} In addition, making gas sensors flexible can enable their integration into portable and wearable devices.^{4,5}

Metal oxides (MOXs), such as ZnO,^{6–8} NiO,^{9–11} Fe₂O₃,^{12–14} and In₂O₃ (ref. 15–17) have been widely used for detection of hazardous gases over the past few decades. For example, alpha-iron oxide (α -Fe₂O₃) is a commonly used sensing material for detection of acetone,¹⁸ H₂S¹⁹ and NO₂ (ref. 14) because of its low cost and simple production.²⁰ However, gas sensors based on MOXs normally require high operating temperatures due to

their poor conductivity and moderate surface activity at room temperature (RT), making it difficult to fabricate RT gas sensors with simple configurations towards flexible devices.

Hybridization of MOXs with conductive materials such as graphene derivatives^{21,22} and carbon nanotubes^{23,24} can improve their gas sensing performances. For instance, reduced graphene oxide (rGO), which possesses excellent electrical conductivity, large specific surface area, and good surface activity, has been widely utilized to composite with MOXs for gas sensing.^{25–27} Examples of MOX/rGO-based sensing materials include ZnO/rGO,²⁸ Fe₂O₃/rGO,²⁹ and CuO/rGO³⁰ for enhanced H₂S, NO₂, and acetone detection, respectively. Introducing noble metal nanostructures in sensing materials is another strategy to improve the gas sensing performance of MOX-based gas sensors. This is because, in addition to their good conductivity, noble metal nanomaterials can provide lower energy required for adsorption of gas molecules based on both experimental and theoretical investigations.³¹ For example, noble metals such as platinum (Pt),³² gold (Au),³³ silver (Ag)³⁴ and palladium (Pd)³⁵ have been used to improve the gas sensing response of MOX-based sensors. Besides, previous reports have suggested that the type of surface ligands can influence the surface activity of noble metal nanostructures.^{2,36} However, few studies have investigated the ligand effects of metal nanomaterials in gas sensing.

In this work, a composite material, *i.e.* Au ND-ODT/ α -Fe₂O₃/rGO, containing ultra-small Au nanodots (NDs) functionalized with 1-octadecanethiol (ODT), α -Fe₂O₃ and rGO was prepared

^aInstitute of Advanced Materials (IAM), Nanjing Tech University (Nanjing Tech), 30 South Puzhu Road, Nanjing 211816, China. E-mail: iamxhuang@njtech.edu.cn

^bFrontiers Science Center for Flexible Electronics, Xi'an Institute of Flexible Electronics (IFE), Xi'an Institute of Biomedical Materials & Engineering, Northwestern Polytechnical University, 127 West Youyi Road, Xi'an 710072, China. E-mail: iamzwang@nwpu.edu.cn

† Electronic supplementary information (ESI) available: Fig. S1–S12. See DOI: 10.1039/d1na00734c

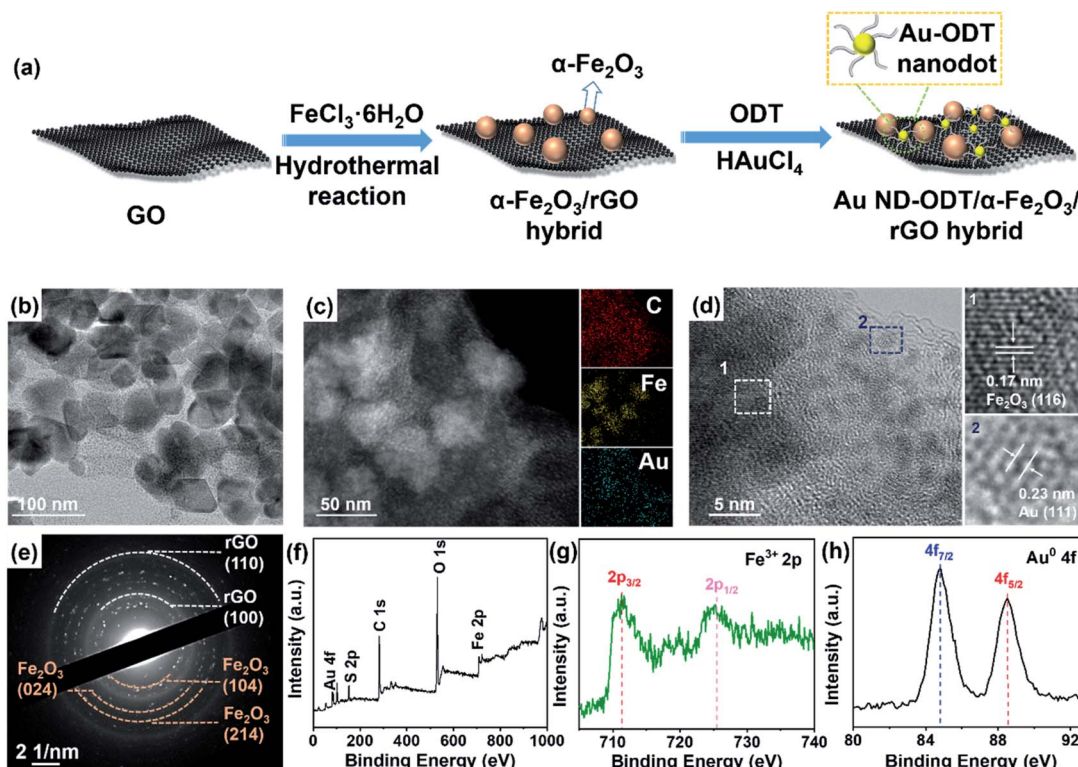


Fig. 1 (a) Schematic illustration of the preparation of Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ hybrids. (b) TEM image, (c) STEM image and EDX mapping, (d) HRTEM image, (e) SAED pattern, (f) XPS full scan spectrum, (g) high-resolution Fe 2p spectrum and (h) Au 4f spectrum of the Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ composite.

The oxidation states of the as-prepared Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ were investigated by X-ray photoelectron spectroscopy (XPS). The survey spectrum of the sample shows the presence of Au, Fe and C elements (Fig. 1f). The high-resolution Fe 2p spectrum shows a doublet at 711.7 and 725.6 eV, corresponding to the $2p_{3/2}$ and $2p_{1/2}$ bands of Fe^{3+} , respectively (Fig. 1g).⁴¹ Besides, in the Au 4f spectrum, two peaks at binding energies of 84.8 and 88.5 eV can be assigned to the Au $4f_{7/2}$ and $4f_{5/2}$ bands of Au^0 , respectively (Fig. 1h), indicating the successful photochemical reduction of Au^{3+} .⁴²

The as-prepared composites, namely, $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ and Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ were spin-coated onto interdigitated Ag electrodes which were inkjet-printed on flexible polyethylene terephthalate (PET) substrates (Fig. 2a) to prepare flexible gas sensors. The response–recovery curves of these gas sensors toward NO_2 were studied at RT in simulated air (20.9% O_2 , 79.1% N_2 , and 19% RH) with target gas concentrations increasing from 200 to 1000 ppb (Fig. 2b). All of the sensors showed decreased resistance upon NO_2 exposure, and the reduction in resistance (ΔR) increased with increasing NO_2 concentrations (Fig. 2b). The $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ and Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ sensors both exhibited fast response times (*e.g.*, about tens of seconds to 800 ppb NO_2) but slow recovery times (*e.g.*, more than 20 minutes to 800 ppb NO_2) (see Fig. S4 in the ESI†). This points to the strong interaction between the NO_2 molecules and the sensing material, leading to a slow desorption process.^{43–45} In our sensing materials, the rGO nanosheets and $\alpha\text{-Fe}_2\text{O}_3$ showed p-type and n-type

semiconducting properties, respectively, based on their ultraviolet photoelectron spectroscopy (UPS) and ultraviolet-visible (UV-vis) spectroscopy analysis results (see Fig. S5 and S6 in the ESI†).

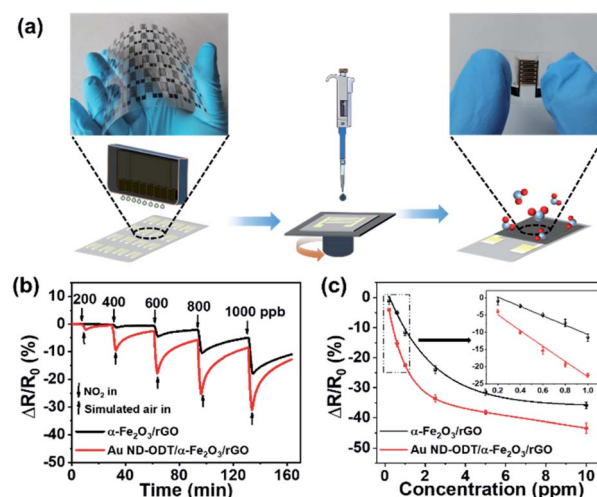


Fig. 2 (a) Schematic illustration of the preparation of the flexible NO_2 sensor, with photographs of the printed Ag electrode array and flexible gas sensor coated with Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$. (b) Dynamic response–recovery curves of $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ and Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ in response to NO_2 gas with different concentrations at RT. (c) Responses of $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ and Au ND-ODT/ $\alpha\text{-Fe}_2\text{O}_3/\text{rGO}$ sensors for NO_2 with different concentrations.

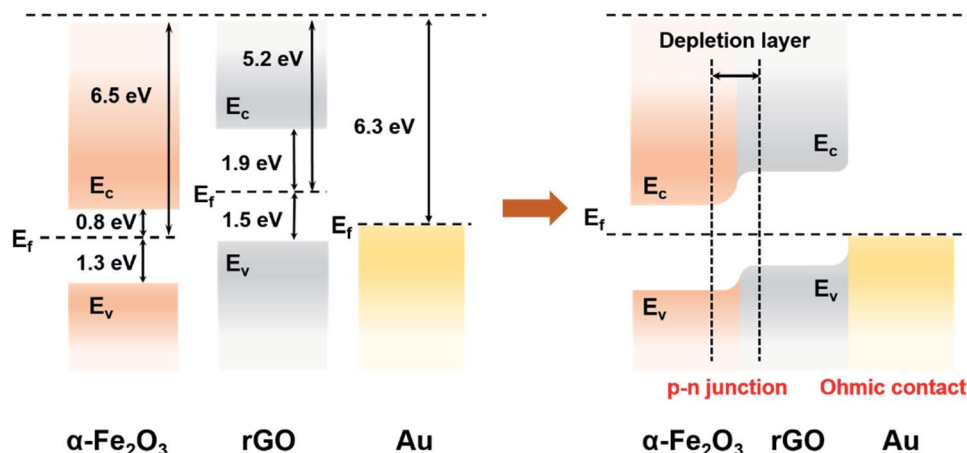


Fig. 3 Schematic of the band level diagram of the Au ND-ODT/ α -Fe₂O₃/rGO composite.

Generally, NO₂, as an oxidizing gas, could extract electrons from sensing materials. This increased the concentration of holes in the p-type rGO, which was the main conducting matrix in the hybrid sensing material. The n-type α -Fe₂O₃ also lost electrons to NO₂, and because of its lower Fermi level than that of rGO (Fig. 3), its electron vacancies were compensated by extracting electrons from rGO. This further increased the hole concentration in rGO, thus decreasing the resistance of the sensing film.⁴⁶ Moreover, with the work functions, bandgaps and band level positions determined with UPS and UV-vis spectrometers (see Fig. S5 and S6 in the ESI†), we also studied the band alignment in the composite material as shown in Fig. 3. It can be seen that a p-n junction might form between rGO and α -Fe₂O₃, resulting in a charge neutral interface (the depletion layer). The adsorption of NO₂ molecules could narrow the width of the depletion layer and facilitate the charge transfer at the heterojunction, thus resulting in further decreased resistance of the sensing film.^{47–50}

The Au ND-ODT/ α -Fe₂O₃/rGO-based sensor showed an enhanced sensing performance as compared with the α -Fe₂O₃/rGO sensor, for example, with at least three times higher response at 200 ppb (Fig. 2c). Such an improvement might be attributed, in part, to the increased gas adsorption sites on the ultra-small Au NDs. Besides, due to the lower work function of Au NDs as compared to that of rGO, an ohmic contact might be established between them (Fig. 3), which favoured the charge transfer from rGO to Au NDs and finally to the NO₂ molecules, thus improving the sensitivity of the hybrid sensing material.^{51,52} Moreover, ohmic like contact might also form between α -Fe₂O₃ and Au NDs (see Fig. S7 in the ESI†), which enabled facile electron transfer across the Au/ α -Fe₂O₃ interface, leading to the formation of additional electron vacancies in α -Fe₂O₃ and thus an enhanced sensitivity. In addition, our Au ND-ODT/ α -Fe₂O₃/rGO-based sensor exhibits performance comparable to that of many previously reported RT NO₂ gas sensors (see Table S1 in the ESI†)^{53–61} and outperforms the recently reported rGO nanofiber,⁵⁴ Au-CuO⁵⁹ and MoS₂ (ref. 60) based sensors.

Since ODT molecules were used as the capping agent to prepare the ultra-small Au NDs, we also investigated the effect of surface ligands on the gas sensing performance by using another

type of thiol, *i.e.* 16-mercaptohexadecanoic acid (MHA), to prepare Au NDs (see Fig. S8 and S9 in the ESI†), and the resulting material was denoted as Au ND-MHA/ α -Fe₂O₃/rGO. Our results showed that the Au ND-ODT/ α -Fe₂O₃/rGO-based sensor outperformed the Au ND-MHA/ α -Fe₂O₃/rGO sensor (see Fig. S10 in the ESI†). This was mainly attributed to the different terminal groups of the two types of thiols (*i.e.* carboxylic acid groups in MHA and methyl groups in ODT), considering their similar alkane chain lengths. Compared to the less polar methyl groups of ODT molecules, the polar carboxylic acid groups of MHA possess higher electron withdrawing ability which could extract electrons from Au NDs,⁶² and hinder the charge transfer in the sensing film (Fig. 4). This was proved by the lower baseline resistance of the Au ND-ODT/ α -Fe₂O₃/rGO sensor compared to that of the Au ND-MHA/ α -Fe₂O₃/rGO sensor (see Fig. S10 in the ESI†).

The selectivity of Au ND-ODT/ α -Fe₂O₃/rGO-based sensors was studied by comparing their responses to NO₂ with other

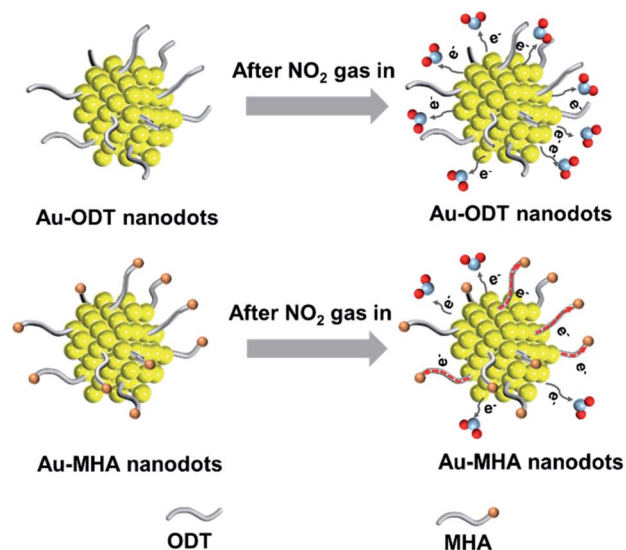


Fig. 4 Schematic illustration of the effect of surface ligands of Au NDs on gas sensing.



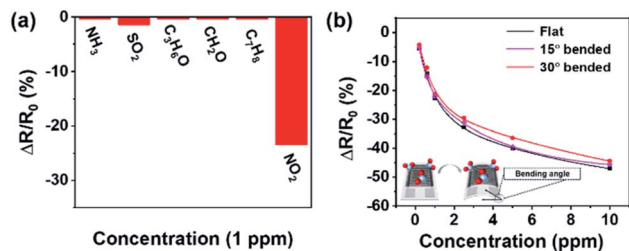


Fig. 5 (a) Responses of the Au ND-ODT/ α -Fe₂O₃/rGO sensor to 1 ppm of NH₃, SO₂, C₃H₆O, CH₂O, C₇H₈ and NO₂. (b) Comparison of the responses of a typical Au ND-ODT/ α -Fe₂O₃/rGO sensor to NO₂ under flat and different bent conditions.

gases including NH₃, SO₂, acetone, formaldehyde and methylbenzene. The responses to the other gases were at least 8 times lower than that to NO₂, indicating the good selectivity of the hybrid sensing material (Fig. 5a). Lastly, we demonstrated that our sensors on flexible substrates can work under bent conditions. As shown in Fig. 5b, a typical gas sensor showed similar sensing responses under the flat and bent conditions at bending angles of 15° and 30°, and negligible performance change even after the device was bent 300 times (see Fig. S11 in the ESI†). This can be due to the good mechanical strength, flexibility and film-forming ability of rGO sheets, which could help to avoid the loss of contact points under moderately bent conditions. However, at larger bending angles, e.g. 45° and 60°, the loss of contact points in the sensing film might occur, causing performance deterioration (see Fig. S12 in the ESI†).

4. Conclusion

In summary, the Au ND-ODT/ α -Fe₂O₃/rGO composite was successfully prepared, which was utilized for NO₂ sensing. The sensor could detect NO₂ with concentrations down to 200 ppb at RT in simulated air, and showed improved sensing performance as compared with α -Fe₂O₃/rGO because of the advantageous effects of Au NDs. Besides, the surface ligands on Au NDs also influenced the sensing performance, that is, less polar terminal groups of the ligands favored charge transfer in the sensing film. Flexible gas sensors based on Au ND-ODT/ α -Fe₂O₃/rGO exhibited well-maintained sensing responses under moderately bent conditions, indicating their potential applications in portable and wearable electronic devices.

Conflicts of interest

The authors declare no competing interests.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (grant no.: 51832001), the Fundamental Research Funds for the Central Universities of China, the Young 1000 Talents Global Recruitment Program of China, the Joint Research Funds of Department of Science & Technology of Shaanxi Province and Northwestern Polytechnical University

(grant no.: 2020GXLH-Z-026 and 2020GXLH-Z-027), and the China Postdoctoral Science Foundation (grant no.: 2021M692618).

References

- W. Huang, X. Zhuang, F. S. Melkonyan, B. Wang, L. Zeng, G. Wang, S. Han, M. J. Bedzyk, J. Yu, T. J. Marks and A. Facchetti, *Adv. Mater.*, 2017, **29**, 1701706.
- Q. Sun, J. Wang, X. Wang, J. Dai, X. Wang, H. Fan, Z. Wang, H. Li, X. Huang and W. Huang, *Nanoscale*, 2020, **12**, 16987–16994.
- H. Wang, W. P. Lustig and J. Li, *Chem. Soc. Rev.*, 2018, **47**, 4729–4756.
- J. Dai, O. Ogbeide, N. Macadam, Q. Sun, W. Yu, Y. Li, B. L. Su, T. Hasan, X. Huang and W. Huang, *Chem. Soc. Rev.*, 2020, **49**, 1756–1789.
- S. Ota, A. Ando and D. Chiba, *Nat. Electron.*, 2018, **1**, 124–129.
- H. Kim, Y. Pak, Y. Jeong, W. Kim, J. Kim and G. Y. Jung, *Sens. Actuators, B*, 2018, **262**, 460–468.
- G. Namgung, Q. T. H. Ta, W. Yang and J. S. Noh, *ACS Appl. Mater. Interfaces*, 2019, **11**, 1411–1419.
- H. Yuan, S. Aljneibi, J. Yuan, Y. Wang, H. Liu, J. Fang, C. Tang, X. Yan, H. Cai, Y. Gu, S. J. Pennycook, J. Tao and D. Zhao, *Adv. Mater.*, 2019, **31**, e1807161.
- P. Li, C. Cao, Q. Shen, B. Bai, H. Jin, J. Yu, W. Chen and W. Song, *Sens. Actuators, B*, 2021, **339**, 129886.
- S. Y. Yi, Y. G. Song, J. Y. Park, J. M. Suh, G. S. Kim, Y. S. Shim, J. M. Yuk, S. Kim, H. W. Jang, B. K. Ju and C. Y. Kang, *ACS Appl. Mater. Interfaces*, 2019, **11**, 7529–7538.
- L. Sui, T. Yu, D. Zhao, X. Cheng, X. Zhang, P. Wang, Y. Xu, S. Gao, H. Zhao, Y. Gao and L. Huo, *J. Hazard. Mater.*, 2020, **385**, 121570.
- H. Fu, Q. Wang, J. Ding, Y. Zhu, M. Zhang, C. Yang and S. Wang, *Sens. Actuators, B*, 2020, **303**, 127186.
- R. Ahmad, M. S. Ahn and Y. B. Hahn, *Adv. Mater. Interfaces*, 2017, **4**, 1700691.
- C. Hua, Y. Shang, Y. Wang, J. Xu, Y. Zhang, X. Li and A. Cao, *Appl. Surf. Sci.*, 2017, **405**, 405–411.
- Z. Wang, C. Hou, Q. De, F. Gu and D. Han, *ACS Sens.*, 2018, **3**, 468–475.
- L. Jun, Q. Chen, W. Fu, Y. Yang, W. Zhu and J. Zhang, *ACS Appl. Mater. Interfaces*, 2020, **12**, 38425–38434.
- X. Liu, K. Zhao, X. Sun, C. Zhang, X. Duan, P. Hou, G. Zhao, S. Zhang, H. Yang, R. Cao and X. Xu, *Sens. Actuators, B*, 2019, **285**, 1–10.
- S. Zhang, M. Yang, K. Liang, A. Turak, B. Zhang, D. Meng, C. Wang, F. Qu, W. Cheng and M. Yang, *Sens. Actuators, B*, 2019, **290**, 59–67.
- Y. Guo, X. Tian, X. Wang and J. Sun, *Sens. Actuators, B*, 2019, **293**, 136–143.
- B. Zhang, J. Liu, X. Cui, Y. Wang, Y. Gao, P. Sun, F. Liu, K. Shimanoe, N. Yamazoe and G. Lu, *Sens. Actuators, B*, 2017, **241**, 904–914.
- G. Bae, I. S. Jeon, M. Jang, W. Song, S. Myung, J. Lim, S. S. Lee, H. K. Jung, C. Y. Park and K. S. An, *ACS Appl. Mater. Interfaces*, 2019, **11**, 16830–16837.



- 22 S. S. Niyol, M. Budde, A. Papadogianni, M. Heilmann, H. M. Moghaddam, C. M. Aldao, G. Ligorio, E. J. W. List Kratochvil, J. M. J. Lopes, N. Barsan, O. Bierwagen and F. Schipani, *Sens. Actuators, B*, 2020, **325**, 128797.
- 23 M. Sinha, S. Neogi, R. Mahapatra, S. Krishnamurthy and R. Ghosh, *Sens. Actuators, B*, 2021, **336**, 129729.
- 24 V. S. Bhati, M. Kumar and R. Banerjee, *J. Mater. Chem. C*, 2021, **9**, 8776–8808.
- 25 O. C. Compton and S. T. Nguyen, *Small*, 2010, **6**, 711–723.
- 26 C. Chang, W. Chen, Y. Chen, Y. Chen, Y. Chen, F. Ding, C. Fan, H. Jin Fan, Z. Fan, C. Gong, Y. Gong, Q. He, X. Hong, S. Hu, W. Hu, W. Huang, Y. Huang, W. Ji, D. Li, L.-J. Li, Q. Li, L. Lin, C. Ling, M. Liu, N. Liu, Z. Liu, K. Ping Loh, J. Ma, F. Miao, H. Peng, M. Shao, L. Song, S. Su, S. Sun, C. Tan, Z. Tang, D. Wang, H. Wang, J. Wang, X. Wang, X. Wang, A. T. S. Wee, Z. Wei, Y. Wu, Z.-S. Wu, J. Xiong, Q. Xiong, W. Xu, P. Yin, H. Zeng, Z. Zeng, T. Zhai, H. Zhang, H. Zhang, Q. Zhang, T. Zhang, X. Zhang, L.-D. Zhao, M. Zhao, W. Zhao, Y. Zhao, K.-G. Zhou, X. Zhou, Y. Zhou, H. Zhu, H. Zhang and Z. Liu, *Acta Phys.-Chim. Sin.*, 2021, **37**, 2108017.
- 27 K. Yang, X. Wang, H. Li, B. Chen, X. Zhang, S. Li, N. Wang, H. Zhang, X. Huang and W. Huang, *Nanoscale*, 2017, **9**, 5102–5109.
- 28 T. K. Dang, N. T. Son, N. T. Lanh, P. H. Phuoc, N. N. Viet, L. V. Thong, C. M. Hung, N. V. Duy, N. D. Hoa and N. V. Hieu, *J. Alloys Compd.*, 2021, **879**, 160457.
- 29 H. Zhang, L. Yu, Q. Li, Y. Du and S. Ruan, *Sens. Actuators, B*, 2017, **241**, 109–115.
- 30 M. Liu, Z. Wang, P. Song, Z. Yang and Q. Wang, *Sens. Actuators, B*, 2021, **340**, 129946.
- 31 V. Montes Garcia, M. A. Squillaci, M. Diez Castellnou, Q. K. Ong, F. Stellacci and P. Samori, *Chem. Soc. Rev.*, 2021, **50**, 1269–1304.
- 32 R. Jolly Bose, N. Illyasukutty, K. S. Tan, R. S. Rawat, M. Vadakke Matham, H. Kohler and V. P. Mahadevan Pillai, *Appl. Surf. Sci.*, 2018, **440**, 320–330.
- 33 J. Ma, X. Xiao, Y. Zou, Y. Ren, X. Zhou, X. Yang, X. Cheng and Y. Deng, *Small*, 2019, **15**, e1904240.
- 34 Q. A. Drmosh, Y. A. Al Wajih, I. O. Alade, A. K. Mohamedkhair, M. Qamar, A. S. Hakeem and Z. H. Yamani, *Sens. Actuators, B*, 2021, **338**, 129851.
- 35 Y. Wang, X. Meng, M. Yao, G. Sun and Z. Zhang, *Ceram. Int.*, 2019, **45**, 13150–13157.
- 36 J. S. Kim, H. W. Yoo, H. O. Choi and H. T. Jung, *Nano Lett.*, 2014, **14**, 5941–5947.
- 37 Y. Zhou, Q. Bao, L. A. L. Tang, Y. Zhong and K. P. Loh, *Chem. Mater.*, 2009, **21**, 2950–2956.
- 38 X. Huang, X. Zhou, S. Wu, Y. Wei, X. Qi, J. Zhang, F. Boey and H. Zhang, *Small*, 2010, **6**, 513–516.
- 39 K. O'Connell and J. R. Regalbuto, *Catal. Lett.*, 2015, **145**, 777–783.
- 40 A. Weibel, R. Bouchet, F. Boulc and P. Knauth, *Chem. Mater.*, 2005, **17**, 2378–2385.
- 41 F. Qu, X. Zhou, B. Zhang, S. Zhang, C. Jiang, S. Ruan and M. Yang, *J. Alloys Compd.*, 2019, **782**, 672–678.
- 42 P. Li, H. Zhan, S. Tian, J. Wang, X. Wang, Z. Zhu, J. Dai, Y. Dai, Z. Wang, C. Zhang, X. Huang and W. Huang, *ACS Appl. Mater. Interfaces*, 2019, **11**, 13624–13631.
- 43 H. Y. Lee, Y. C. Heish and C. T. Lee, *J. Alloys Compd.*, 2019, **773**, 950–954.
- 44 J. Hu, C. Zou, Y. Su, M. Li, X. Ye, B. Cai, E. S. W. Kong, Z. Yang and Y. Zhang, *Sens. Actuators, B*, 2018, **270**, 119–129.
- 45 B. I. Adamu, A. Falak, Y. Tian, X. Tan, X. Meng, P. Chen, H. Wang and W. Chu, *ACS Appl. Mater. Interfaces*, 2020, **12**, 8411–8421.
- 46 B. Zhang, G. Liu, M. Cheng, Y. Gao, L. Zhao, S. Li, F. Liu, X. Yan, T. Zhang, P. Sun and G. Lu, *Sens. Actuators, B*, 2018, **261**, 252–263.
- 47 S. Zhao, Y. Shen, F. Hao, C. Kang, B. Cui, D. Wei and F. Meng, *Appl. Surf. Sci.*, 2021, **538**, 148140.
- 48 M. Shafiei, J. Bradford, H. Khan, C. Piloto, W. Wlodarski, Y. Li and N. Motta, *Appl. Surf. Sci.*, 2018, **462**, 330–336.
- 49 X. Jiang, H. Tai, Z. Ye, Z. Yuan, C. Liu, Y. Su and Y. Jiang, *Mater. Lett.*, 2017, **186**, 49–52.
- 50 X. Wang, Y. Liu, J. Dai, Q. Chen, X. Huang and W. Huang, *Chem.-Eur. J.*, 2020, **26**, 3870–3876.
- 51 X. Wang, Z. Wang, J. Zhang, X. Wang, Z. Zhang, J. Wang, Z. Zhu, Z. Li, Y. Liu, X. Hu, J. Qiu, G. Hu, B. Chen, N. Wang, Q. He, J. Chen, J. Yan, W. Zhang, T. Hasan, S. Li, H. Li, H. Zhang, Q. Wang, X. Huang and W. Huang, *Nat. Commun.*, 2018, **9**, 3611.
- 52 J. Bao, S. Zeng, J. Dai, X. Wang, Q. Liu, H. Li, X. Huang and W. Huang, *Chem. Commun.*, 2021, **57**, 5590–5593.
- 53 H. J. Park, W. J. Kim, H. K. Lee, D. S. Lee, J. H. Shin, Y. Jun and Y. J. Yun, *Sens. Actuators, B*, 2018, **257**, 846–852.
- 54 J. Zha, Z. Yuan, Z. Zhou, Y. Li, J. Zhao, Z. Zeng, L. Zhen, H. Tai, C. Tan and H. Zhang, *Small Struct.*, 2021, **2**, 2100067.
- 55 Jyoti and G. D. Varma, *J. Alloys Compd.*, 2019, **806**, 1469–1480.
- 56 S. Li, Z. Wang, X. Wang, F. Sun, K. Gao, N. Hao, Z. Zhang, Z. Ma, H. Li, X. Huang and W. Huang, *Nano Res.*, 2017, **10**, 1710–1719.
- 57 M. Reddeppa, N. T. KimPhung, G. Murali, K. S. Pasupuleti, B. G. Park, I. In and M. D. Kim, *Sens. Actuators, B*, 2021, **329**, 129175.
- 58 M. S. Choi, H. G. Na, J. H. Bang, A. Mirzaei, S. Han, H. Y. Lee, S. S. Kim, H. W. Kim and C. Jin, *Sens. Actuators, B*, 2021, **326**, 128801.
- 59 X. Chen, S. Zhao, P. Zhou, B. Cui, W. Liu, D. Wei and Y. Shen, *Sens. Actuators, B*, 2021, **328**, 129070.
- 60 R. Kumar, N. Goel and M. Kumar, *ACS Sens.*, 2017, **2**, 1744–1752.
- 61 B. Liu, X. Liu, Z. Yuan, Y. Jiang, Y. Su, J. Ma and H. Tai, *Sens. Actuators, B*, 2019, **295**, 86–92.
- 62 N. D. K. Tu, J. Choi, C. R. Park and H. Kim, *Chem. Mater.*, 2015, **27**, 7362–7369.

