



Recent Advances of SnO₂-Based Sensors for Detecting Fault Characteristic Gases Extracted From Power Transformer Oil

Qingyan Zhang¹, Qu Zhou^{1,2*}, Zhaorui Lu¹, Zhijie Wei¹, Lingna Xu¹ and Yingang Gui¹

¹ College of Engineering and Technology, Southwest University, Chongqing, China, ² Electrical and Computer Engineering Department, Wayne State University, Detroit, MI, United States

OPEN ACCESS

Edited by:

Zhongchang Wang,
Laboratório Ibérico Internacional de
Nanotecnologia (INL), Portugal

Reviewed by:

Yiyi Zhang,
Guangxi University, China
Song Xiao,
Wuhan University, China

*Correspondence:

Qu Zhou
zhouqu@swu.edu.cn

Specialty section:

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

Received: 22 June 2018

Accepted: 30 July 2018

Published: 29 August 2018

Citation:

Zhang Q, Zhou Q, Lu Z, Wei Z, Xu L
and Gui Y (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

Tin oxide SnO₂-based gas sensors have been widely used for detecting typical fault characteristic gases extracted from power transformer oil, namely, H₂, CO, CO₂, CH₄, C₂H₂, C₂H₄, and C₂H₆, due to the remarkable advantages of high sensitivity, fast response, long-term stability, and so on. Herein, we present an overview of the recent significant improvement in fabrication and application of high performance SnO₂-based sensors for detecting these fault characteristic gases. Promising materials for the sensitive and selective detection of each kind of fault characteristic gas have been identified. Meanwhile, the corresponding sensing mechanisms of SnO₂-based gas sensors of these fault characteristic gases are comprehensively discussed. In the final section of this review, the major challenges and promising developments in this domain are also given.

Keywords: tin oxide, gas sensors, fault characteristic gases, power transformer oil, sensing properties, sensing mechanism

INTRODUCTION

Power transformers are one of the most important apparatuses in power systems, and their reliability is extremely vital to ensure the stable system operation (Zheng et al., 2018). Thermal and electrical faults in oil-filled power transformers may produce typical fault characteristic gases including hydrogen H₂ (David et al., 2018), carbon monoxide CO (Joseph, 1980; Uddin et al., 2016; Zhou et al., 2018b), carbon dioxide CO₂ (2015; Dan et al., 2016; Iwata et al., 2017; Zhang et al., 2017), methane CH₄ (Sedghi et al., 2010), acetylene C₂H₂ (Qi et al., 2008), ethylene C₂H₄, and ethane C₂H₆. These typical fault characteristic gases could be dissolved in transformer oil or accumulate as free gases if produced rapidly in large quantities. Therefore, detection and analysis of the species, quantities and generation rates of these fault gases presented in the fluid allow for the identification of power transformer fault types such as corona, sparking, overheating, and arcing.

During the past few decades, dissolved gas analysis has been developed to detect the latent faults of oil-immersed power transformers (Morais and Rolim, 2006; Zhan et al., 2015; Uddin et al., 2016; Gong et al., 2018). Gas sensing detection technology is the core of dissolved gas analysis. Different types of sensing technologies have been reported in previous studies for detecting typical fault characteristic gases extracted from transformer oil, such as metal oxide semiconductor gas sensors (Zhu and Zeng, 2017a; Chen et al., 2018), catalytic combustion sensors (Liu et al., 2011),

fuel cell sensors (Modjtahedi et al., 2016; Tonezzer et al., 2017), and optical sensors (Trieu-Vuong et al., 2016; Paliwal et al., 2017). Given the remarkable advantages of simple fabrication process, low maintenance cost, fast response and recovery, long service life, and so on, metal oxide semiconductor materials like SnO₂ (Choi et al., 2014; Zeng et al., 2014), ZnO (Zhou et al., 2017; Zhu and Zeng, 2017b; Zhu et al., 2017), TiO₂ (Zeng and Liu, 2010; Zhang et al., 2018b) and In₂O₃ (Cao et al., 2015) have received scientific and technological importance for many years and are widely used to detect these gases. Among them, as the most widely used gas-sensitive material, SnO₂ is currently the main sensing materials used in experimental research and commercial application for detecting typical fault characteristic gases extracted from power transformer oil (Zhang et al., 2010; Zhou et al., 2018a).

Herein, the first section of this review will briefly outline the preparation of the currently used SnO₂ sensing materials, the microstructure morphology, and doping modification of SnO₂ sensing materials for detecting typical fault characteristic gases extracted from power transformer oil. The second section addresses the main gas sensing mechanisms of SnO₂ gas sensors for these gases. The third section presents the conclusions, focusing on future challenges and potentialities associated with SnO₂-based gas sensors for detecting these typical fault characteristic gases.

SENSING PERFORMANCES OF SnO₂-BASED SENSORS TO FAULT CHARACTERISTIC GASES EXTRACTED FROM POWER TRANSFORMER OIL

For detecting and analyzing typical fault characteristic gases extracted from power transformer oil with SnO₂-based gas sensors, the most important concerns are the sensor sensitivity, selectivity, and repeatability (Fan et al., 2017). Combined with the research concerns mentioned above, this section briefly summarizes recent progress in the application of SnO₂ sensing materials to detect typical fault characteristic gases dissolved in transformer oil. The gas sensing performance of some modified SnO₂ gas sensors are listed in **Table 1**.

T_{oper} , temperature at which the best sensor performance, usually in terms of the highest response toward target gas, could be obtained.

S , gas sensing response of a SnO₂-based sensor to target gas, which is defined as $S = R_a/R_g$ for reducing gas and $S = R_g/R_a$ for oxidizing gas (where R_a and R_g are the resistance of the sensor in air and in the test gas, respectively).

It is known that the metal oxide semiconductor SnO₂ is a promising material for sensing the typical fault characteristic gases extracted from power transformer oil. Nevertheless, the sensing performance of the proposed sensors considerably depends on the preparation method and surface structure of the sensing materials and the dopants. The structure of modern SnO₂ gas sensors could be classified into two main types including thick/thin films and nanoparticles. The preparation methods of the sensing materials mainly include the hydrothermal method,

the sol-gel method, the electrospinning technique, chemical vapor deposition and so on. Different preparation methods could affect the morphology of the sensing materials and further change their gas sensing properties (Long et al., 2018; Zhang et al., 2018a; Zhou et al., 2018c). Noble metals or metal oxide doped on SnO₂-based sensors can play an important role in accelerating the sensing process and improving the gas sensor performances.

In power transformers, H₂ is generated from the thermal decomposition of oil at high temperatures, which is a serious problem for transformer oil (Uddin et al., 2016). Various high-efficacy and workable SnO₂-based sensors have been recently introduced for detecting H₂. It can be seen from the data in **Table 1** that various metal particles such as Co (Liu et al., 2010), Au (Yin and Tao, 2017), and Pd (Nguyen et al., 2017) have been added to SnO₂-based sensors to enhance H₂ gas sensing performance. Among them, the Au-loaded SnO₂ sensor can detect H₂ down to 1 ppm, which is a good property for detecting low concentrations of H₂ dissolved in transformer oil (Yin and Tao, 2017). K. Inyawilert reported that a SnO₂ sensing film with an optimal Rh-doping level of 0.2 wt% exhibited an ultra-high response of 22,170 and a short response time of 6 s toward 30,000 ppm H₂ at an optimum operating temperature of 300°C. In addition, the proposed Rh-doped SnO₂ sensor displayed good H₂ selectivity against NO₂, SO₂, C₂H₄, C₃H₆O, CH₄, H₂S, and CO (Inyawilert et al., 2017). Except for nanoparticles embedded in the metal oxide matrix, the morphology of the SnO₂ materials could be applied to improve the H₂ sensing properties, and low dimensional nanostructures have attracted increasing attention. Nguyen Kien et al. introduced the on-chip growth of SnO₂ nanowire-based gas sensors to detect low concentrations of H₂ gas, which responded with 2.6 for 20 ppm H₂ gas at 400°C (Nguyen et al., 2017). Taken together, these findings suggest that the Au-loaded SnO₂ gas sensor is the most promising candidate for detecting low concentration H₂ extracted from power transformer oil.

The insulating paper, pressboard and wood blocks in power transformers contain a large number of anhydroglucose rings as well as weak C-O molecular bonds and glycosidic bonds that are thermally less stable than the hydrocarbon bonds in oil. These bonds could decompose to CO and CO₂ at lower temperatures when potential faults occur. As shown in **Table 1**, Pt-doped SnO₂ thick film (Chen et al., 2018), ZnO-SnO₂ nanoparticles (Chen et al., 2015), and Au-doped SnO₂ yolk-shell nanospheres (Wang et al., 2013) could be potential candidates for CO sensors. Among them, Wang et al. compared the gas sensing properties of Au@SnO₂ yolk-shell nanospheres with that of hollow SnO₂ nanospheres. The sensor fabricated with the Au@SnO₂ yolk-shell nanospheres showed lower operating temperature (210°C), lower detection limit (5 ppm), faster response (0.3 s), and better selectivity to CO gas (Wang et al., 2013), which could be attributed to the catalytic effect of Au and enhanced electron depletion at the surface of the Au@SnO₂ yolk-shell nanospheres. Moreover, SnO₂ loaded with Pd nanoparticles may be another kind of promising material for CO gas sensing (Zhou et al., 2018d). Yuasa et al. prepared PdO-loaded SnO₂ nanoparticles by the reverse micelle method and reported that the 0.1 mol% PdO-loaded SnO₂ sensor exhibited a high gas response value of 320

TABLE 1 | Comparison of the representative SnO₂ based sensors for fault characteristic gases extracted from power transformer oil.

Target gas	Sensing material	Synthesis method	Morphology	Detection range (ppm)	T _{oper.} (°C)	S/ppm	Selectivity	References
H ₂	1 wt% Co-doped SnO ₂	Electrospinning	Nanofibers	100–25,000	330	24/100	H ₂ > CO	Liu et al., 2010
	1 mol% Au-doped SnO ₂	Sol-gel	Nanoparticles	1–5,000	400	48/5,000	H ₂ > CO	Yin and Tao, 2017
	Pd-decorated SnO ₂	Chemical vapor deposition	Nanowires	10–100	350	7.1/100	H ₂ > CO ₂	Nguyen et al., 2017
CO	1.5% Pd-doped SnO ₂	Co-precipitation	Thick-film	100–1,000	260	6.59/400	–	Chen et al., 2018
	ZnO–SnO ₂ nanoparticles	Typical hydrothermal	Nanoparticles	40–160	300	13/100	–	Chen et al., 2015
	Au@SnO ₂	Hydrothermal deposition	Yolk–shell nanospheres	5–100	210	30/50	CO > H ₂ > C ₂ H ₄ > CO ₂	Wang et al., 2013
CO ₂	LaFeO ₃ /SnO ₂	Sol-gel	Thick film	–	250	2.72/4,000	–	Zhang et al., 2017
	LaOCl-doped SnO ₂	One-step electrospinning	Nanofibers	100–20,000	300	3.7/1,000	–	Xiong et al., 2017
CH ₄	20 mol% Pt–SnO ₂	Electrospinning	Nanofibers	1–1,000	350	1.11/1	–	Lu et al., 2018
	Pt–SnO ₂	Wet chemical	Thin film	1000–10,000	400	1.55/1,000	–	Min and Choi, 2005
C ₂ H ₂	Sm ₂ O ₃ -doped SnO ₂	Sol-gel	Nanoparticles	1–5,000	180	63.8/1,000	C ₂ H ₂ > CO > CH ₄ > H ₂	Qi et al., 2008
	rGO-Loaded SnO ₂	Hydrothermal	Nanoparticles	0.5–500	180	12.4/50	C ₂ H ₂ > CH ₄ > H ₂ > CO > CO ₂	Jin et al., 2017
C ₂ H ₄	silicalite-1 layer coated on SnO ₂	Ultrasonic spray pyrolysis technique	Thin film	2–70	350	2.21/8	–	Jadsadapattarakul et al., 2010
	SnO ₂	R.F. magnetron sputtering	Thin film	10–100	300	10.43/100	–	Ahn et al., 2010
C ₂ H ₆	5 wt% Pd-doped SnO ₂	Hydrothermal	Nanoparticles	5–100	400	5.89/100	–	Chen et al., 2013a

to 200 ppm CO gas (Yuasa et al., 2009). Chen et al. synthesized Pd-doped SnO₂ nanoparticles using a co-precipitation method, and the 1.5 wt% PdO decorated SnO₂ presented the largest gas-sensitive response of 6.59 at 260°C in 400 ppm CO atmosphere (Chen et al., 2018). Another study reported that Pd-modified nanocrystalline SnO₂ displayed a fairly high and reversible CO response (2–100 ppm) at room temperature (Marikutsa et al., 2010). Yin et al. prepared Pd-loaded and Fe-doped SnO₂ by the sol-gel method. The composite with 10 mol% Fe and 0.2 mol% Pd had the highest sensitivity and selectivity to CO in the range of 200–3,000 ppm at 350°C, and the response value to 2,000 ppm CO was increased 13 times compared with pure SnO₂ (Yin and Guo, 2014). Therefore, Pd is a highly effective catalyst for improving the sensing performance of SnO₂-based sensors to CO gas (Xiong et al., 2017).

Due to their high chemical stability, conventional binary metal oxides have very low sensitivity to chemically inert gases such as CO₂ (Korotcenkov and Cho, 2017). However, it was reported that La-doped SnO₂ nanocomposites can be used for CO₂ sensing (Kim et al., 2000). And the 8% LaOCl-SnO₂ nanofibers exhibited

an optimal response of 3.7 toward 1,000 ppm CO₂ at 300°C with response/recovery times of 24/92 s (Xiong et al., 2017). Karthik et al. reported the sensing properties of tin oxide (SnO₂) and zinc oxide (ZnO) thin films deposited onto macroporous silicon (PS) substrates to CO₂ and found that the obtained SnO₂/PS films showed the highest sensing response of 19 to 15 ppm CO₂ gas (Karthik et al., 2018).

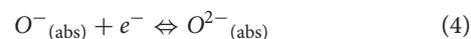
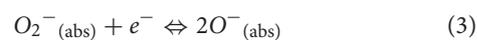
For hydrocarbons, namely, CH₄, C₂H₂, C₂H₄, and C₂H₆, when high energy discharge occurs, such as arcing, in transformer oil, the content of C₂H₂ is relatively high. At low temperature thermal faults ($T < 300^{\circ}\text{C}$), the contents of CH₄ and C₂H₆ tend to be high. C₂H₄ is the main content of hydrocarbon while at high temperature thermal faults ($T > 300^{\circ}\text{C}$) (Fan et al., 2017). For detecting these hydrocarbons, an online monitoring system based on a SnO₂-based gas chromatographic detector for assessing the running condition of a power transformer was developed (Fan et al., 2017). Qi et al. fabricated a C₂H₂ sensor based on 6 wt% Sm₂O₃-doped SnO₂, whose gas response to 1,000 ppm C₂H₂ could reach 63.8, 16.8 times larger than that of pure SnO₂ (Qi et al., 2008).

Moreover, Jin et al. reported that reduced graphene oxide (rGO)-loaded SnO₂ hybrid nanocomposite showed high sensor response (12.4 toward 50 ppm), fast response-recovery time (54 and 23 s), low detection limit (1.3 ppm), good linearity, excellent selectivity and long-term stability to C₂H₂ (Jin et al., 2017). These results indicated that rGO would be an effective addition to enhance the sensing properties of SnO₂-based sensors to C₂H₂ and make a contribution to developing a ppm-level gas sensor for on-line monitoring of C₂H₂ gas extracted from transformer oil.

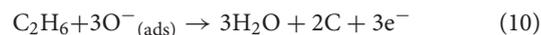
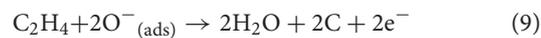
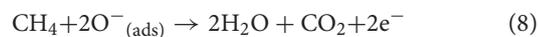
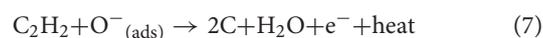
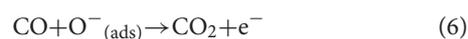
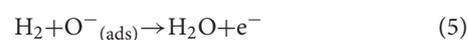
Sensors for CH₄ detection have also been widely studied and are partly summarized in **Table 1**. The 20 mol% Pt-SnO₂ nanofibers exhibited excellent CH₄ sensing properties over a temperature range of 100–350°C, and an obvious response of 1.11 to 1 ppm CH₄ was measured at 350°C (Lu et al., 2018). Koeck et al. found a device prepared by ultra-long single crystalline SnO₂-nanowires, which was able to detect a few ppm of CO and CH₄ at the operating temperature of 200–250°C (Koeck et al., 2009). Chen et al. successfully synthesized Co-doped SnO₂ nanofibers via an electrospinning method and reported that the Co-doped SnO₂ nanofiber sensor exhibited a high response of 30.28 toward 50 ppm CH₄ at 300°C (Chen et al., 2013b). For C₂H₄ and C₂H₆ detection, only a few sensors including SnO₂ thin films and Pd-doped SnO₂ nanoparticles are found to be effective. Jadsadapattarakul et al. reported that the sensing response, response and recovery time of SnO₂ thin film sensors for selective detecting of C₂H₄ gas could be improved by coating a layer of [010] highly preferred-orientation silicalite-1 polycrystals (Jadsadapattarakul et al., 2010). Ahn et al. obtained SnO₂ thin films by R.F. magnetron sputtering to fabricate high performance C₂H₄ gas sensors (Ahn et al., 2010). Chen et al. discovered that the 5 wt% Pd-doped SnO₂ sensor could detect C₂H₆ at 400°C, and the sensor exhibited the largest gas-sensitive response of 5.89 toward 100 ppm C₂H₆ (Chen et al., 2013a).

SENSING MECHANISMS OF SnO₂-BASED SENSORS TO FAULT CHARACTERISTIC GASES EXTRACTED FROM POWER TRANSFORMER OIL

It is well agreed that the sensing mechanism of SnO₂ gas sensors is the change in conductivity of the metal oxide layer caused by the interaction with the surrounding atmosphere (Duc er e et al., 2012; Zeng et al., 2013; Korotcenkov and Cho, 2017). When exposed to air, oxygen molecules would be adsorbed on the surface of the SnO₂ nanostructures and capture electrons from the conduction band of SnO₂ to generate chemisorbed oxygen species (O⁻, O²⁻, and O₂⁻, depending on temperatures) (Shahabuddin et al., 2017). At low temperatures (below 150°C), oxygen molecules exist in the form of molecular ions O₂⁻, which would change to atomic ions O⁻ (150–400°C) and O²⁻ (more than 400°C) as temperatures rising (Punginsang et al., 2017). The chemical adsorption process can be explained by the following reactions:



As the electrons transfer from the conduction band of SnO₂ to the chemisorbed oxygen, the electron concentration and electrical conductivity of the SnO₂ film decrease. When the SnO₂ film is exposed to typical fault characteristic gases, the reducing gas would react with the chemisorbed oxygen species, thereby releasing electrons back to the conduction band with increasing electrical conductivity. The sensing mechanisms of the SnO₂ sensor sensing these fault gases can be explained from the following reaction paths, where O⁻ is taken as an example (Samerjai et al., 2012).



Dopants added to SnO₂-based gas sensors can accelerate the reaction process mentioned above and improve the sensing performance of gas sensors. The doped catalysts can enhance the sensing performance of a sensor in two ways, namely, chemical sensitization and electronic sensitization (Lin et al., 2017). The high surface area structures such as porous structures and hollow structures could accelerate gas diffusion on the material surface and then shorten the response time.

On the other hand, to understand the sensing mechanism of SnO₂-based materials at the atomic and quantum levels, based on the framework of Density Function Theory (DFT), Li et al. established a SnO₂ surface model, gas molecular models and adsorption models. A first principles calculation using the Cambridge Sequential Total Energy Package (CASTEP) program was performed, and the total energies, electronic structures and adsorption properties were investigated in detail. Theoretical calculations provided a qualitative explanation of the sensing properties of the fabricated SnO₂-based sensor to various fault characteristic gases (CH₄, C₂H₆, C₂H₄, and C₂H₂) extracted from power transformers (Li et al., 2017). Zeng et al. performed a first principles calculation to investigate how H₂ gas interacts with the SnO₂ (110) surface and the effect of metallic ions on the gas response of SnO₂. Based on the theoretical calculation, it was reported that the Pd-doped SnO₂ (110) surface could adsorb more H₂ gas and receive larger electrons from adsorbed H₂ molecules (Zeng et al., 2011). Other research involving a

possible CO sensing mechanism for Pd-doped SnO₂ sensors was investigated with first principles calculations (Chen et al., 2018), and the theoretical results demonstrated that CO molecules can grab O from the pre-adsorbed oxygen on the Pd⁴ cluster or the PdO cluster on the SnO₂ (110) surface. These processes may play an important role in CO sensing for Pd-doped SnO₂ (Chen et al., 2018). In particular, theoretical calculations indicated that CO₂ molecules cannot be adsorbed onto the stoichiometric SnO₂ (110) surface or SnO₂ (110) surface pre-adsorbed by O₂⁻ and O⁻ in dry air. However in wet air, CO₂ could react with O of pre-adsorbed OH⁻, bringing about the formation of carbonates containing (CO₃)²⁻ and the dissociation/movement of surface OH⁻ groups, accompanying the release of electrons from CO₂ to the SnO₂ surface (Wang et al., 2016).

CONCLUSION AND PERSPECTIVE

In this mini-review, SnO₂-based gas sensors for detecting typical fault characteristic gases extracted from power transformer oil have been briefly summarized. The analysis shows that the detection performances of SnO₂-based gas sensors can be obviously enhanced with dopant addition or increasing the surface area of the sensing materials. Despite achieving good results, there is still much room for further development. First of all, due to the cross-sensitivity between these fault characteristic gases, selectivity is a large challenge for developing high performance SnO₂-based sensors to detect these gases independently. In the future, to promote engineering

applications, a combination of SnO₂-based gas sensors and gas chromatography should be further studied for multi-component detection of these gases. For further development of the gas-sensing performances, the high surface area structures such as hollow and hierarchical nanostructures could be prepared to obtain more active sites for gas diffusion, and different types of dopant elements should be examined. Furthermore, the gas sensing mechanisms are still imperfect and controversial, which cannot effectively guide development of novel SnO₂-based sensors and limit the prevailing application of these sensors to fault characteristic gases extracted from power transformer oil. Further research should focus on determining a satisfying mechanism model of SnO₂-based sensors to provide a guide for future work.

AUTHOR CONTRIBUTIONS

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

ACKNOWLEDGMENTS

This work has been supported in part by the National Natural Science Foundation of China (Nos. 51507144, 5127785), the China Postdoctoral Science Foundation Project (Nos. 2015M580771, 2016T90832), and the Chongqing Science and Technology Commission (CSTC) (No. cstc2016jcyjA0400).

REFERENCES

- Ahn, H., Noh, J. H., Kim, S.-B., Overfelt, R. A., Yoon, Y. S., and Kim, D.-J. (2010). Effect of annealing and argon-to-oxygen ratio on sputtered SnO₂ thin film sensor for ethylene gas detection. *Mater. Chem. Phys.* 124, 563–568. doi: 10.1016/j.matchemphys.2010.07.012
- Cao, Y., Zhao, J., Zou, X., Jin, P.-P., Chen, H., Gao, R., et al. (2015). Synthesis of porous In₂O₃ microspheres as a sensitive material for early warning of hydrocarbon explosions. *RSC Adv.* 5, 5424–5431. doi: 10.1039/C4RA13763A
- Chen, W., Li, Q., Xu, L., and Zeng, W. (2015). Gas sensing properties of ZnO-SnO₂ nanostructures. *J. Nanosci. Nanotechnol.* 15, 1245–1252. doi: 10.1166/jnn.2015.9061
- Chen, W., Zhou, Q., Gao, T., Su, X., and Wan, F. (2013a). Pd-doped SnO₂-based sensor detecting characteristic fault hydrocarbon gases in transformer oil. *J. Nanomater.* 2013:127345. doi: 10.1155/2013/127345
- Chen, W., Zhou, Q., Xu, L., Wan, F., Peng, S., and Zeng, W. (2013b). Improved methane sensing properties of Co-doped SnO₂ electrospun nanofibers. *J. Nanomater.* 2013:173232. doi: 10.1155/2013/173232
- Chen, Y., Qin, H., and Hu, J. (2018). CO sensing properties and mechanism of Pd doped SnO₂ thick-films. *Appl. Surf. Sci.* 428, 207–217. doi: 10.1016/j.apsusc.2017.08.205
- Choi, S. W., Katoch, A., Kim, J. H., and Kim, S. S. (2014). Prominent reducing gas-sensing performances of n-SnO₂ nanowires by local creation of p-n heterojunctions by functionalization with p-Cr₂O₃ nanoparticles. *ACS Appl. Mater. Inter.* 6, 17723–17729. doi: 10.1021/am504164j
- Dan, D. W., Yan, P. C., Zhong, X. L., Ling, L., Chang, M. S., Hong, W. Q., et al. (2016). CO₂-sensing properties and mechanism of nano-SnO₂ thick-film sensor. *Sens. Actuat. B* 227, 73–84. doi: 10.1016/j.snb.2015.12.025
- David, E. M., Gugu, H. M., Peter, R. M., Baban, P. D., Fransciuous, R. C., Hendrik, C. S., et al. (2018). Ultra-high sensitive and selective H₂ gas sensor manifested by interface of n-n heterostructure of CeO₂-SnO₂ nanoparticles. *Sens. Actuat. B* 254, 984–995. doi: 10.1016/j.snb.2017.07.093
- Ducéré, J.-M., Hemeryck, A., Esteve, A., Rouhani, M. D., Landa, G., Menini, P., et al. (2012). A computational chemist approach to gas sensors: modeling the response of SnO₂ to CO, O₂, and H₂O Gases. *J. Comput. Chem.* 33, 247–258. doi: 10.1002/jcc.21959
- Fan, J., Wang, F., Sun, Q., Bin, F., Ye, H., and Liu, Y. (2017). An online monitoring system for oil immersed power transformer based on SnO₂ GC detector with a new quantification approach. *IEEE Sens. J.* 17, 6662–6671. doi: 10.1109/JSEN.2017.2734072
- Gong, Z., Chen, K., Yang, Y., Zhou, X., and Yu, Q. (2018). Photoacoustic spectroscopy based multi-gas detection using high-sensitivity fiber-optic low-frequency acoustic sensor. *Sens. Actuat. B* 260, 357–363. doi: 10.1016/j.snb.2018.01.005
- Inyawilert, K., Wisitsoraat, A., Tuantranont, A., Phanichphant, S., and Liewhiran, C. (2017). Ultra-sensitive and highly selective H₂ sensors based on FSP-made Rh-substituted SnO₂ sensing films. *Sens. Actuat. B* 240, 1141–1152. doi: 10.1016/j.snb.2016.09.094
- Iwata, T., Matsuda, K., Takahashi, K., and Sawada, K. (2017). CO₂ sensing characteristics of a La₂O₃/SnO₂ stacked structure with micromachined hotplates. *Sensors* 17:2156. doi: 10.3390/s17092156
- Jadsadapattarakul, D., Thanachayanont, C., Nukeaw, J., and Sooknoi, T. (2010). Improved selectivity, response time and recovery time by 010 highly preferred-orientation silicalite-1 layer coated on SnO₂ thin film sensor for selective ethylene gas detection. *Sens. Actuat. B* 144, 73–80. doi: 10.1016/j.snb.2009.10.035
- Jin, L., Chen, W., Zhang, H., Xiao, G., Yu, C., and Zhou, Q. (2017). Characterization of reduced graphene oxide (rGO)-loaded SnO₂ nanocomposite and applications in C₂H₂ gas detection. *Appl. Sci.* 7:19. doi: 10.3390/app7010019

- Joseph, J. K. (1980). Transformer fault diagnosis by dissolved-gas analysis. *IEEE Trans. Ind. Appl.* IA-16, 777–782. doi: 10.1109/TIA.1980.4503871
- Karthik, T. V. K., Martinez, L., and Agarwal, V. (2018). Porous silicon ZnO/SnO₂ structures for CO₂ detection. *J. Alloy Compd.* 731, 853–863. doi: 10.1016/j.jallcom.2017.10.070
- Kim, D. H., Yoon, J. Y., Park, H. C., and Kim, K. H. (2000). CO₂-sensing characteristics of SnO₂ thick film by coating lanthanum oxide. *Sens. Actuat. B* 62, 61–66. doi: 10.1016/S0925-4005(99)00305-6
- Koeck, A., Tischner, A., Maier, T., Kast, M., Edtmaier, C., Gspan, C., et al. (2009). Atmospheric pressure fabrication of SnO₂-nanowires for highly sensitive CO and CH₄ detection. *Sens. Actuat. B* 138, 160–167. doi: 10.1016/j.snb.2009.02.055
- Korotcenkov, G., and Cho, B. K. (2017). Metal oxide composites in conductometric gas sensors: achievements and challenges. *Sens. Actuat. B* 244, 182–210. doi: 10.1016/j.snb.2016.12.117
- Li, Z., Jin, L., Liu, B., Shen, Z., Peng, S., and Zhou, Q. (2017). Experiment and simulation study of nano-SnO₂ for dissolved fault gases analysis of power transformer. *Sci. Adv. Mater.* 9, 1888–1894. doi: 10.1166/sam.2017.3243
- Lin, T., Lv, X., Li, S., and Wang, Q. (2017). The morphologies of the semiconductor oxides and their gas-sensing properties. *Sensors* 17:2779. doi: 10.3390/s17122779
- Liu, F., Zhang, Y., Yu, Y., Xu, J., Sun, J., and Lu, G. (2011). Enhanced sensing performance of catalytic combustion methane sensor by using Pd nanorod/gamma-Al₂O₃. *Sens. Actuat. B* 160, 1091–1097. doi: 10.1016/j.snb.2011.09.032
- Liu, L., Guo, C., Li, S., Wang, L., Dong, Q., and Li, W. (2010). Improved H₂ sensing properties of Co-doped SnO₂ nanofibers. *Sens. Actuat. B* 150, 806–810. doi: 10.1016/j.snb.2010.07.022
- Long, H. W., Zeng, W., Wang, H., Qian, M. M., Liang, Y. H., and Wang, Z. C. (2018). Self-assembled biomolecular 1D nanostructures for aqueous sodium-ion battery. *Adv. Sci.* 5:1700634. doi: 10.1002/advs.201700634
- Lu, W., Ding, D., Xue, Q., Du, Y., Xiong, Y., Zhang, J., et al. (2018). Great enhancement of CH₄ sensitivity of SnO₂ based nanofibers by heterogeneous sensitization and catalytic effect. *Sens. Actuat. B* 254, 393–401. doi: 10.1016/j.snb.2017.07.128
- Marikutsa, A. V., Rumyantseva, M. N., Yashina, L. V., and Gaskov, A. M. (2010). Role of surface hydroxyl groups in promoting room temperature CO sensing by Pd-modified nanocrystalline SnO₂. *J. Solid State Chem.* 183, 2389–2399. doi: 10.1016/j.jssc.2010.07.017
- Min, B.-K., and Choi, S.-D. (2005). Undoped and 0.1wt.% Ca-doped Pt-catalyzed SnO₂ sensors for CH₄ detection. *Sens. Actuat. B* 108, 119–124. doi: 10.1016/j.snb.2004.12.112
- Modjtahedi, A., Amirfazli, A., and Farhad, S. (2016). Low catalyst loaded ethanol gas fuel cell sensor. *Sens. Actuat. B* 234, 70–79. doi: 10.1016/j.snb.2016.04.108
- Morais, D. R., and Rolim, J. G. (2006). A hybrid tool for detection of incipient faults in transformers based on the dissolved gas analysis of insulating oil. *IEEE Trans. Power. Deliv.* 21, 673–680. doi: 10.1109/TPWRD.2005.864044
- Nguyen, K., Hung, C. M., Ngoc, T. M., Thanh Le, D. T., Nguyen, D. H., Nguyen Van, D., et al. (2017). Low-temperature prototype hydrogen sensors using Pd-decorated SnO₂ nanowires for exhaled breath applications. *Sens. Actuat. B* 253, 156–163. doi: 10.1016/j.snb.2017.06.141
- Paliwal, A., Sharma, A., Tomar, M., and Gupta, V. (2017). Carbon monoxide (CO) optical gas sensor based on ZnO thin films. *Sens. Actuat. B* 250, 679–685. doi: 10.1016/j.snb.2017.05.064
- Punginsang, M., Wisitsoraat, A., Sriprachubwong, C., Phokharatkul, D., Tuantranont, A., Phanichphant, S., et al. (2017). Roles of cobalt doping on ethanol-sensing mechanisms of flame-spray-made SnO₂ nanoparticles-electrolytically exfoliated graphene interfaces. *Appl. Surf. Sci.* 425, 351–366. doi: 10.1016/j.apsusc.2017.06.265
- Qi, Q., Tong, Z., Xue, J. Z., Hui, T. F., Li, L., Rui, W., et al. (2008). Electrical response of Sm₂O₃-doped SnO₂ to C₂H₂ and effect of humidity interference. *Sens. Actuat. B* 134, 36–42. doi: 10.1016/j.snb.2008.04.011
- Samerjai, T., Tamaekong, N., Wetchakun, K., Kruefu, V., Liwhiran, C., Siriwong, C., et al. (2012). Flame-spray-made metal-loaded semiconducting metal oxides thick films for flammable gas sensing. *Sens. Actuat. B* 171, 43–61. doi: 10.1016/j.snb.2012.05.052
- Sedghi, S. M., Mortazavi, Y., and Khodadadi, A. (2010). Low temperature CO and CH₄ dual selective gas sensor using SnO₂ quantum dots prepared by sonochemical method. *Sens. Actuat. B* 145, 7–12. doi: 10.1016/j.snb.2009.11.002
- Shahabuddin, M., Umar, A., Tomar, M., and Gupta, V. (2017). Custom designed metal anchored SnO₂ sensor for H₂ detection. *Int. J. Hydrogen Energ.* 42, 4597–4609. doi: 10.1016/j.ijhydene.2016.12.054
- Tonezzer, M., Thi Thanh Le, D., Quang Huy, T., Van Hieu, N., and Iannotta, S. (2017). Selective hydrogen sensor for liquefied petroleum gas steam reforming fuel cell systems. *Int. J. Hydrogen Energ.* 42, 740–748. doi: 10.1016/j.ijhydene.2016.11.102
- Trieu-Vuong, D., Choi, I.-Y., Son, Y.-S., and Kim, J.-C. (2016). A review on non-dispersive infrared gas sensors: improvement of sensor detection limit and interference correction. *Sens. Actuat. B* 231, 529–538. doi: 10.1016/j.snb.2016.03.040
- Uddin, A. S. M. I., Yaqoob, U., and Chung, G.-S. (2016). Dissolved hydrogen gas analysis in transformer oil using Pd catalyst decorated on ZnO nanorod array. *Sens. Actuat. B* 226, 90–95. doi: 10.1016/j.snb.2015.11.110
- Wang, D., Chen, Y., Liu, Z., Li, L., Shi, C., Qin, H., et al. (2016). CO₂-sensing properties and mechanism of nano-SnO₂ thick-film sensor. *Sens. Actuat. B* 227, 73–84. doi: 10.1016/j.snb.2015.12.025
- Wang, L., Dou, H., Lou, Z., and Zhang, T. (2013). Encapsulated nanoreactors (Au@SnO₂): a new sensing material for chemical sensors. *Nanoscale* 5, 2686–2691. doi: 10.1039/c2nr33088a
- Xiong, Y., Xue, Q., Ling, C., Lu, W., Ding, D., Zhu, L., et al. (2017). Effective CO₂ detection based on LaOCl-doped SnO₂ nanofibers: insight into the role of oxygen in carrier gas. *Sens. Actuat. B* 241, 725–734. doi: 10.1016/j.snb.2016.10.143
- Yin, X.-T., and Guo, X.-M. (2014). Selectivity and sensitivity of Pd-loaded and Fe-doped SnO₂ sensor for CO detection. *Sens. Actuat. B* 200, 213–218. doi: 10.1016/j.snb.2014.04.026
- Yin, X.-T., and Tao, L. (2017). Fabrication and gas sensing properties of Au-loaded SnO₂ composite nanoparticles for low concentration hydrogen. *J. Alloy Compd.* 727, 254–259. doi: 10.1016/j.jallcom.2017.08.122
- Yuasa, M., Masaki, T., Kida, T., Shimanoe, K., and Yamazoe, N. (2009). Nano-sized PdO loaded SnO₂ nanoparticles by reverse micelle method for highly sensitive CO gas sensor. *Sens. Actuat. B* 136, 99–104. doi: 10.1016/j.snb.2008.11.022
- Zeng, W., He, Q., Pan, K., and Wang, Y. (2013). Synthesis of multifarious hierarchical flower-like SnO₂ and their gas-sensing properties. *Phys. E* 54, 313–318. doi: 10.1016/j.physe.2013.07.014
- Zeng, W., Li, Y., Miao, B., Lin, L., and Wang, Z. (2014). Recognition of carbon monoxide with SnO₂/Ti thick-film sensor and its gas-sensing mechanism. *Sens. Actuat. B* 191, 1–8. doi: 10.1016/j.snb.2013.09.092
- Zeng, W., Liu, T., Liu, D., and Han, E. (2011). Hydrogen sensing and mechanism of M-doped SnO₂ (M=Cr³⁺, Cu²⁺ and Pd²⁺) nanocomposite. *Sens. Actuat. B* 160, 455–462. doi: 10.1016/j.snb.2011.08.008
- Zeng, W., and Liu, T. M. (2010). Hydrogen sensing characteristics and mechanism of nanosize TiO₂ dope with metallic ions. *Phys. B* 405, 564–568. doi: 10.1016/j.physb.2009.09.066
- Zhan, W., Goulart, A. E., Falahi, M., and Rondla, P. (2015). Development of a low-cost self-diagnostic module for oil-immersed forced-air cooling transformers. *IEEE Trans. Power. Deliv.* 30, 129–137. doi: 10.1109/TPWRD.2014.2341454
- Zhang, H., Li, Z., Liu, L., Xu, X., Wang, Z., and Wang, W. (2010). Enhancement of hydrogen monitoring properties based on Pd-SnO₂ composite nanofibers. *Sens. Actuat. B* 147, 111–115. doi: 10.1016/j.snb.2010.01.056
- Zhang, W., Xie, C., Zhang, G., Zhang, J., Zhang, S., and Zeng, D. (2017). Porous LaFeO₃/SnO₂ nanocomposite film for CO₂ detection with high sensitivity. *Mater. Chem. Phys.* 186, 228–236. doi: 10.1016/j.matchemphys.2016.10.048
- Zhang, Y. X., Zeng, W., and Li, Y. Q. (2018a). The hydrothermal synthesis of 3D hierarchical porous MoS₂ microspheres assembled by nanosheets with excellent gas sensing properties. *J. Alloy Compd.* 749, 355–362. doi: 10.1016/j.jallcom.2018.03.307
- Zhang, Y. X., Zeng, W., Ye, H., and Li, Y. Q. (2018b). Enhanced carbon monoxide sensing properties of TiO₂ with exposed (001) facet: a combined first-principle and experimental study. *Appl. Surf. Sci.* 442, 507–516. doi: 10.1016/j.apsusc.2018.02.036
- Zheng, H., Zhang, Y., Liu, J., Wei, H., Zhao, J., and Liao, R. (2018). A novel model based on wavelet LS-SVM integrated improved PSO algorithm for forecasting

- of dissolved gas contents in power transformers. *Electr. Power Syst. Res.* 155, 196–205. doi: 10.1016/j.epsr.2017.10.010
- Zhou, Q., Chen, W., Xu, L., Kumar, R., Gui, Y., Zhao, Z., 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., Hong, C. X., Yao, Y., Ibrahim, A. M., Xu, L. N., Kumar, R., et al. (2017). Fabrication and characterization of highly sensitive acetone chemical sensor based on ZnO nanoballs. *Materials* 10:E799. doi: 10.3390/ma10070799
- Zhou, Q., Lu, Z., Wei, Z., Xu, L., Gui, Y., and Chen, W. (2018b). Hydrothermal synthesis of hierarchical ultrathin NiO nanoflakes for high-performance CH₄ sensing. *Front. Chem.* 6:194. doi: 10.3389/fchem.2018.00194
- Zhou, Q., Umar, A., Sodki, E. M., Amine, A., Xu, L., Gui, Y., et al. (2018c). Fabrication and characterization of highly sensitive and selective sensors based on porous NiO nanodisks. *Sens. Actuat. B* 259, 604–615. doi: 10.1016/j.snb.2017.12.050
- Zhou, Q., Xu, L. N., Umar, A., Chen, W. G., and Kumar, R. (2018d). Pt nanoparticles decorated SnO₂ nanoneedles for efficient CO gas sensing applications. *Sens. Actuat. B* 256, 656–664. doi: 10.1016/j.snb.2017.09.206
- Zhu, L., Li, Y., and Zeng, W. (2017). Enhanced ethanol sensing and mechanism of Cr-doped ZnO nanorods: experimental and computational study. *Ceram. Int.* 43, 14873–14879. doi: 10.1016/j.ceramint.2017.08.003
- Zhu, L., and Zeng, W. (2017a). A novel coral rock-like ZnO and its gas sensing. *Mater. Lett.* 209, 244–246. doi: 10.1016/j.matlet.2017.08.020
- Zhu, L., and Zeng, W. (2017b). Room-temperature gas sensing of ZnO-based gas sensor: a review. *Sens. Actuat. A* 267, 242–261. doi: 10.1016/j.sna.2017.10.021

Conflict of Interest Statement: 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 © 2018 Zhang, Zhou, Lu, Wei, Xu and Gui. 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.