Volume 10, Issue 3, 2020, 5610 - 5615 **ISSN 2069-5837**

Biointerface Research in Applied Chemistry

www.BiointerfaceResearch.com

https://doi.org/10.33263/BRIAC103.610615

Original Review Article **Open Access Journal**

Received: 04.03.2020 / Revised: 26.03.2020 / Accepted: 26.03.2020 / Published on-line: 29.03.2020

Nano metal oxides for sensing the VOC based gaseous pollutants

Farida A. Ali [1], Rasmita Nayak [2], Binita Nanda [2,*]

[1]Department of Electronics and Instrumentation Engineering, [2] Department of Chemistry, Institute of Technical Education and Research, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India

*corresponding author e-mail address: ***binitananda@soa.ac.in*** | Scopus ID 53980125400

ABSTRACT

The detection and monitoring of harmful toxic volatile organic compound (VOC) gases liberated from various domestic activities is necessary for environmental concern. In this regard, VOC sensors have taken greater demand in domestic environmental monitoring because of their low operating cost, cheap, reliable, low power consumption, improved energy efficiency and reduced emission. In this regard, metal oxide materials in their nano form show growing strength in many research laboratories and public health and so on with their effective chemical, physical, and electronic properties. Therefore, an attempt has been made to study the nano metal oxides for different toxic gases basing on overall research trend like, a good correlation between sensing materials and sensing properties to improve the sensitivity and selectivity of VOC sensors. This paper tries to accumulate the findings of different metal oxide semiconductor nanomaterials used in various types of VOC sensors.

Keywords: *Nano materials; metal oxide semiconductors; gaseous pollutants; sensor.*

1. INTRODUCTION

To support the life system on Earth there is atmosphere present, which constitutes of a complex dynamics of gaseous system. Thus, any unwanted chemical, particulates, organic or biological material causing damage to the living organism by damaging natural environment or atmosphere is called an air pollutant [1-4].

Air pollution is causing stratospheric ozone layer depletion causing life threats not only to human beings but also to the ecosystem of Earth. Besides this indoor air pollution and urban air quality are listed as two of the world's worst pollution problems [5-8].

There are different sources of pollutants present indoors and outdoors either naturally or due to human activities for different types of gaseous pollutants like Nitrogen oxide (NO_2) [9], carbon monoxide (CO), carbon dioxide (CO_2) [10], formaldehyde (HCHO) [11], methane (CH_4) [12], triethylamine (TEA) [13], Acetone (C_3H_6O) [14], sulphur oxide (SO_2), chlorofluorocarbon (CFCs), odours from garbage, sewage, industrial wastes etc. Amongst these pollutants volatile organic compounds (VOCs) are found more in air of our homes, schools and offices. Basically, it has been estimated that about 50-300 different types of VOCs are found. Some of the high volume of VOC emitting sources include a wide range of personal care products, vent gases during cooking, while making fire, painting the house, cutting the grass, using pesticides, surfactants used during cleaning cloths, dishes and floor etc, while cutting grass during gardening or simply during breathing too. Out of so many VOCs some are found to be highly toxic or carcinogenic in nature and some may have either short term or long term effect both on human health and also on the natural ecosystem. Therefore, extensive research is going on a wide variety of VOC sensors to monitor the indoor and outdoor air quality as it is becoming very essential for today's date.

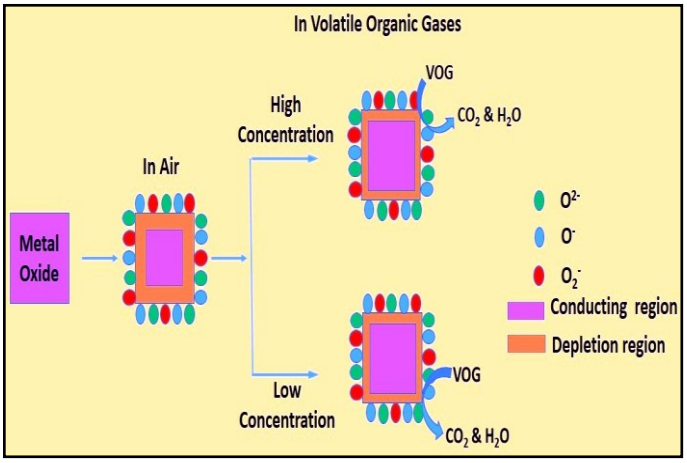
The word "**sensor**" finds its origin from the Latin word "**sentire**" which basically means '**to identify**' [15]. A sensor is a device that is capable of identifying a physical quantity and then converting it into a signal type that can be read by an observer or by an instrument. For accuracy purpose sensors are calibrated against known standards. Nowadays sensors are used everywhere like inside cars, machines, aeroplanes, homes, offices, robotics etc. A sensor is a device, which generates a functionally related output usually in the form of an electrical or optical signal corresponding to an input quantity [16, 17].

The sensitivity indicates how much the sensor's output changes when there is a small change measured in input quantity. Sensors that are capable of measuring very small changes have very high sensitivities. Demand for the variety of sensors and the capabilities of technological advancements allowing more and more sensors to be manufactured in different areas. Among all, gas sensing technology has received increasing attention and has become more significant because of its widespread and common applications on the detection and monitoring of flammable and toxic VOCs in domestic as well as in commercial and industrial environment. Thus, the detection of VOC gas molecules with conversion of their concentration information into electrical signals needs the use of sensing technologies in different fields. Among the different active sensing materials, metal oxides have shown effective results towards VOC sensing application. A lot of research studies have been done on VOC sensing applications with the help of metal oxides.

Therefore, in this paper effort has been made to gather findings of different researchers about different metal oxide semiconductor nano-materials used to detect few popular VOCs that are toxic in nature and the most popular pollutants available in and around human surroundings.

2. ROLE OF NANO METAL OXIDES IN VOC SENSING.

Nano metal oxides play a significant role in the gas sensing properties. Mostly the transition metals and their oxides from periodic table III-VI with electronic configuration (d0-d10) mainly exhibit the sensing property. The synthetic procedure used in the material science shows a remarkable change in the properties of nanomaterials and shows a better performance in different applications towards gas sensing. The properties are i) high surface-to-volume ratio facilitates more gas to adsorb onto the surface of nanomaterial for better sensing, ii) introducing defects in the nanomaterial, functionalization are more beneficial in the absorption of gas molecule, iii) proper charge transfer property because of semiconducting nature, iv) catalytic combustion or resistance modulation make nanomaterial suitable candidate for gas sensing.



Scheme 1. Schematic diagram VOC sensing mechanism.

The mechanism behind VOC sensing using metal oxide nanomaterials at a particular temperature is basically based on the phenomenon of adsorption of oxygen from the surrounding atmosphere. This process involves a change in density of the conducting electrons on the surface of the sensing element as shown in scheme 1. This change is due to series of chemical reactions as follows:

(i) Pre-adsorption of oxygen on the surface of metal-oxide semiconducting nanomaterial.
(ii) Adsorbs the specific VOC on test.
(iii) Reaction takes place between oxygen and the adsorbed VOC.
(iv) Desorption of reacted VOC on surface.

These steps of reactions generate three types of stable oxygen anions namely O_2^-, O^- and O^{2-} during the electron delivery process that takes place between the VOCs and the surface of the metal-oxide semiconductor nanomaterial. During the reaction with VOC under test, a conductivity increase means the adsorbed oxygen plays the role of acceptor whereas a conductivity decrease means the adsorbed oxygen playing the role of a donor. Thus, the gas sensing mechanism of metal-oxide semiconductor nanomaterials for VOC detection is quite complex to explain and is based on the resistance change due to the chemical and electronic interaction between the test gas and the material. This complexity occurs due to the various influencing parameters like chemical composition, adsorption ability, surface properties, catalytic effect, temperature, humidity and modified surface morphology etc.

3. DIFFERENT POLLUTANTS AND THEIR DETECTION

3.1. Formaldehyde (CH_2O).

Presence of CH_2O in indoor air within the range (0.2-50 ppm) may cause a serious health problem. The maximum exposure level of CH_2O is 80 ppb per 30 minute as the direction of world health organization (WHO). So, the early detection of CH_2O is highly necessary. In this regard, the development of nano based material plays a key role in the selective detection of CH_2O. Till date a handful of nano based metal oxides are used in the detection of CH_2O. The mechanism of CH_2O mainly depends on chemisorbed oxygen on the surface of the catalyst. The oxygen molecule present in air, first chemisorbed on the catalyst. Again this oxygen species (O_2^-) react with CH_2O and simultaneously releases of electrons to the catalyst. This leads to a decrease in electron depletion layer (ELD) thickness and thereby increasing the sensing efficiency. The mechanism was shown as follows:

$O_2 + 2e^- \rightarrow 2O^-$

$CH_2O + 2O^-_{(ads)} \rightarrow CO_2 + H_2O + 2e^-$

$CH_2O + O^-_{(ads)} \rightarrow CH_2O_2 + e^-$

Zhang *et al.* synthesized NiO doped SnO_2nanosphereand utilized the material for better sensing for CH_2Oat different temperature range 50^0C to 400^0C than neat SnO_2 and NiO. The selectivity of the material NiO doped SnO_2 was again compared with ethanol, acetone, methylbenzene, chloroform and 2-cholorophenol. It was seen that 50 ppm CH_2O showed enhanced sensing (26.03) at optimum temperature (100^0C). Chemisorbed oxygen plays an important role in sensing work.

In case of SnO_2 nanosphere, only half-backed monolayer of oxygen was chemisorbed whereas in-case of NiO-SnO_2, doping of NiO on the surface of SnO_2 easily aggregate and chemisorbed the full monolayer oxygen ions and oxidised to higher oxidation state [18]. Kim and his group prepared multi-heterogeneous oxides NiO/Fe_2O_3 loaded SnO_2 for formaldehyde detection.

Catalytic hetero-junction effect plays a crucial role in high gas sensing. Apart from hetero-junction property, loading of catalyst and operating temperature also plays an important role in high sensing of formaldehyde. Herein, the establishment of multi hetero-junction between NiO, SnO_2 and Fe_2O_3 (p-n junction between NiO and SnO_2 and n-n hetero-junction between SnO_2 and Fe_2O_3). The migration of e^-s from NiO to SnO_2 and again to Fe_2O_3decreased the EDL and increases the formaldehyde sensing of NiO/Fe_2O_3-SnO_2 composite [19].

Zhou and his team fabricated 3D hierarchical Co3O4 nanostructure by calcining Co5-based MOF microcrystals. As prepared Co_3O_4-350 shows the best sensing towards formaldehyde at low temperature (170^0C), the low detection limit of 10 ppm and 30 day stability.

Here, 3D nanostructure, high surface area, more active active sites, high porosity, shorter ionic diffusion lengths made the material more effective for formaldehyde sensing [20].

3.2. Methane (CH_4).

Methane is one of the most significant constituents of natural gas. It shows hazardous because it considered a

greenhouse and also flammable. Therefore it is necessary to detect CH_4 at lower concentration for warning purposes when it leaks and also to prevent hazards. Nowadays a handful of works have been done by the scientists and researchers. Nasresfahani *et al.* was synthesized Pd-doped SnO_2/PRGO and Pd-doped SnO_2/rGO and compared the methane sensing. The sensingperformance was evaluated from the concentration of methane gas which ranges between 800-16000 ppm at room temperature. In this regard Pd doped SnO_2/rGO shows the better result (9.8 % sensitivity) among all synthesized materials. This is because rGO nanosheets provide a favourable surface for nucleation and growth of nanoparticles and a conducting network that facilitate transfer of electron. High catalytic activities of Pd also play as an additive role which improves the methane sensitivity at a very low working temperature [21].

Microwave assisted spinel Co_3O_4 nanoparticles were fabricated by Shaalan and his team for methane sensing. Co_3O_4 is a p-type of semiconductor. As the holes are the major charge carriers in the p-type semiconductor, it dominates the passage of current through the boundary of semiconductor. Thus, there is a decrease in resistance occurs due to the formation of oxygen ions on the surface of the material by the trapping electrons. Again, during the mixing of CH_4 and O_2, the electrons come back to the material and increase the resistance because of electron-hole recombination [22].

3.3.Ethanol.

Ethanol is a reducing gas that used as the raw material for colors, antifreeze and formaldehyde. Direct methanol fuel cells (DMFC) are eco-friendly and considered as the important alternative fuel for automotive manufactures. However, 10 mL intake of methanol may cause total blindness and more than 30 mL, which may cause fatal diseases. So, the early detection of low concentration of methanol at low operating temperature is highly necessary.

Yang *et al*. adopted the hydrothermal method to synthesize SnO_2/Zn_2SnO_4 porous nanosphere for excellent ethanol gas sensing. The two main responsible factor for ethanol sensing are: i) porous structure and ii) the hetero-junction attained by SnO_2 and Zn_2SnO_4. High surface area provides a large active sites which are essential for gas adsorption and diffusion. More is the surface active sites more is the adsorption between the adsorbed oxygen and methanol and more is the sensing. The hetero-junction play a significant role in sensing performance because of different band gap energy and work function of SnO_2 and Zn_2SnO_4. Herein the conduction band edge potential of $Zn_2SnO_4$is higher than the conduction band edge potential of SnO_2 [23].

Cheng *et al.* were synthesized pure and Pd-doped α-Fe_2O_3 porous nanotubes (PNTs) by a facile electrospinning approach. the results reveal that, compared with pure α-Fe_2O_3, the 3.0 wt% Pd-doped α-Fe_2O_3 PNTs sensors exhibit superior performance in ethanol detection (at 240 °C). The highest sensitivity reaches 65.4 for 50 ppm ethanol and the detection limit is as low as 0.1 ppm. It is excellent selectivity, and good sensor towards ethanol [24].

3.4. Methanol.

Methanol is an essential substance in daily life and in the industry. It is also considered as a raw material for colors, antifreeze and formaldehyde. Though it has advantages, the dietary intake of 10 mL may result in total blindness and exceeds that quantity may cause fatal diseases. So, this is necessary to quick detect methanol gas of low concentration at low oprating temperature. Li and his group fabricated Sm_2O_3 doped ZnO/$SmFeO_3$ microsphere for the high performance in methanol sensing.

The composite show excellent behaviour toward very low concentration of methanol (5 ppm) sensing at very low operating temperature (195^0C) with 24 sec recovery time. Herein two main factors are responsible for methanol sensing are high surface area and p-n junction between ZnO (p-type) and $SmFeO_3$ (n-type).

High surface area of $SmFeO_3$ (24 h) enhances the active sites which adsorb oxygen. This leads to releasing back of electrons to the semiconductor surface and decrease the conductivity. The reaction as follows:

$$CH_3OH + 3O^{n-} \rightarrow CO_2 + H_2O + 3ne^-$$

Secondly, the formation of p-n heterojuction between ZnO and $SmFeO_3$, the transfer of electron and hole takes place through the interface as long they balance the Fermi level. Methanol reacts with the adsorbed oxygen on the surface of ZnO, releasing electron back. $CH_3OH + O^- \rightarrow HCHO + H_2O + e^-$

$$HCHO + O^- \rightarrow CO_2 + H_2O + e^-$$

Again, on the surface of $SmFeO_3$, the hole react with the adsorbed oxygen

$$CH_3OH + h^+ + O^- \rightarrow HCHO + H_2O$$

$$HCHO + h^+ + O^- \rightarrow CO_2 + H_2O + e^-$$

That mean the two different type of metal oxide can easily reactive with oxidative and reductive gases leading to high methanol sensing [25].

3.5. Acetone.

Acetone is good for some synthetic fibres and it is water miscible, can be used in common cleaning purpose. Acetone poisoning occurs when there's more acetone in your body than your liver can break down. When exposed to the air, it quickly evaporates and remains highly flammable. Acetone is dangerous to use around an open flame.

He prolonged exposure to acetone i.e. more than 173 ppm is highly toxic and cause serious threat to human health. As per the literature survey, the excelled gas of a healthy man is less than 0.8 ppm and in case of diabetic person is more than 1.8 ppm. So, sensing acetone is the best way to diagnose as compared to other testing. Thus it is highly necessary to prepare a suitable material that can easily sense acetone at a lower concentration. Wu *et al.* synthesized $ZnFe_2O_4$/rGO for acetone sensing (10 ppm) at the operating temperature (150^0C-225^0C).

When adsorbed oxygen on the surface of $ZnFe_2O_4$ surface capture electrons in the CB to form O2- and O-. This results in the increase in resistance because of electron depletion layer. When acetone is exposed to the surface of $ZnFe_2O_4$, O_2^- and O^- react acetone at the grain boundary of $ZnFe_2O_4$. At this time again electrons are released back to CB.

$$O_{2(gas)} \rightarrow O_{2(ads)}$$

$$ZnFe_2O_4/rGO + O_{2\,(ads)} + e^- \rightarrow O_2^-$$

$$ZnFe_2O_4/rGO + O_2^- + e^- \rightarrow 2O^-$$

$$CH_3COCH_3 + 8O^- \rightarrow CO_2 + H_2O + 8e^-$$

Again, the enhancement of sensing of acetone occurred due to 2D-rGO nanosheet by the improvement of electron mobility

inside the composite, forming a heterojunction structure in the composite. [26].

Xu and his team fabricated hollow Pt functionalized tungsten oxide ($W_{18}O_{49}$) for acetone sensing. The combined effect of porous shell and properties of Pt enhances the sensing performances 20 times more than pure $W_{18}O_{49}$. The enhanced sensing properties mainly due to two factors, one is spreading of Ptnano particle over the surface of $W_{18}O_{49}$ and the second one is the lower work function of $W_{18}O_{49}$. The spillage of Pt onto the surface of $W_{18}O_{49}$ dissociates the O-H, CH, O-O= bond, so more oxygenated species are available on the surface of composite, which trap more electrons. More acetone molecule adsorbed on the surface, which reacts with the adsorbed oxygen. As the work function of $W_{18}O_{49}$ (4.6eV) is less than Pt (5.65 eV), the electron flows from $W_{18}O_{49}$to Pt nanoparticle till the Fermi level equalized, decreasing the electron depletion layer and simultaneously increasing the scottky barrier height at the interface of p-n junction ($W_{18}O_{49}$ and PtO_x).

This results in increase the resistance and therby the sensing performance. Apart from these properties, the high surface are, hollow sphere provides a better active sites for gas diffusion and inhibits the excellent gas sensing [27].

3.6. Triethylamine (TEA).

TEA is a colourless volatile liquid widely used in chemical industries. It is also highly explosive. The maximum consumption limit of TEA is 10 ppm or less. Higher to this concentration level, it causes headache, lungs problem etc. Various traditional methods are used for TEA detection such as gel chromatography and gas tube detection. But these methods are tedious and also costly. To avoid these problems, sensing is the best way to detect very low concentration of TEA gas at the faster rate. In this regard, porous metal oxides are the best option to use as the sensing material. Highly effective SnO_2 hallow microfiber was prepared by Zhou and his co-workers for TEA sensing.

Sensing mechanism of hollow SnO_2microfibres is mainly due to the presence of oxidative radicals (O_2^-, O^-, and O^{2-}) and formation of electron depletion layer on the surface of the material. Other than that, unique structural characteristics such as the small grain boundary of SnO_2, large active sites, 1D carbon morphology and hollow porous structure contribute the outstanding response to TEA sensing having concentration 100 ppm at operating temperature 270^0C [28]. Song *et al.* synthesized Au decorated porous α-Fe_2O_3nanorod for very low ppm level detection of Triethyl amine sensor. As selectivity is the most important character for gas sensor, Au/α-Fe_2O_3 exhibit the highest response towards 50 ppm of TEA at 40^0C as compared to neat α-Fe_2O_3. High response is mainly based on the bond energy. As bond energy of C-N (305 KJ/mol) is weakest among all other bonds, TEA is most unstable. For this reason the bond breaks easily lead to the high activity of TEA and response increases. When TEA is exposed on the surface of Au/ α-Fe_2O_3, there is an oxidation and reduction reaction occur between TEA and $O^{\delta-}$ asper the reaction:

$$N(C_2H_5)_3 + O^{\delta-} (O^{2-}, O^-, O_2^-) \rightarrow N_2 + H_2O + CO_2 + e^-$$

In addition, the decoration of gold on the surface of α-Fe_2O_3 leads to extraction of more number of electrons from the conduction band of α-Fe_2O_3. High extent of chemisorbed oxygen adsorption capacity on the surface of Au/α-Fe_2O_3 results in the high response by accelerating the reaction between the oxygen species and the reducing gas. This leads to decrease in recovery time of Au/ α-Fe_2O_3 sensors [29]. In addition, few other nano materials used in the sensing of various types ofVOCs at different concentratin and operating temperature are summerised in the Table 1.

Table 1. Different other materials utilized in the sensing of VOCs.

Sl. No.	Nanomaterials used	Type of VOCs	Concentration and operating temperature	References
1.	$CdIn_2O_4$ Nano porous thin film	formaldehyde	100 ppm, 100^0C	30
2.	SnO_2 hollow microspheres	formaldehyde	200 ppm, 300^0C	31
3.	Au nanoparticle modified ZnO	formaldehyde	10 ppb	32
4.	Co_3O_4 derived from Co5-Based MOF Microcrystals	formaldehyde	10 ppm, 175^0C	33
5.	ZnONanostructures	methane	200µL/L, 275^0C	34
6.	Ordered Mesoporous In_2O_3	methane	600^0C	35
7.	SnO_2@rGOPANI	methane	100-10000 ppm, room temperature	36
9.	Pd-doped α-Fe_2O_3 porous nanotubes (PNTs)	ethanol	50 ppm, 240^0C	24
10.	TiO_2nanoflower	methanol	100 ppm, 200^0C	37
11.	2D nanosheet assembled pdZnOmicroflowers	acetone	200 ppm, 370^0C	38
13.	NiO/ZnO hybrid	acetone	200 ppm, 260^0C	39
14.	ZnO/$ZnFe_2O_4$hollow spheres	acetone	50 pm, 280^0C	40
15.	$ZnFe_2O_4$-graphene quantumdots	acetone	10ppm, at room temperature	41
16.	1 wt% RGO-$CdFe_2O_4$	Acetone	10 ppm, 270^0C	42
17.	SnO_2hollow microfiber	triethylamine	100ppm, 270 ^{0}C	43
18.	α- Fe_2O_3 microrod	triethylamine	500ppm, 275^0C	44
19.	TiO_2/SnO_2nanosheet	triethylamine	50 ppm, 260 ^{0}C	45
20.	CuO sphere	triethylamine	100 ppm, 230^0C	46

4. CONCLUSIONS

This paper addresses the detection and monitoring of harmful volatile organic compounds liberated mostly from household activities. Because of the adverse effects of these gaseous pollutants on human health and also on the surrounding environment, VOC sensors have been taken up for greater demand in environmental and also domestic monitoring. This paper is an

attempt to study few well known VOC sensors based on metal oxide semiconductor nano materials.

5. REFERENCES

1. Rossi, A.; Vila, Y.; Barsotti, F.; Sani, L.; Ceccarelli, P.; Lanzetta, M. Embedded smart sensor device in construction site machinery. *Comput. Ind* **2019**, *108,* 12-20. https://doi.org/10.1016/j.compind.2019.02.008.
2. Park, S.J.; Lee, S.H.; Seol, M.L.; Jeon, S.B.; Bae, H.; Kim, D.; Cho, G.H.; Choi, Y.K. Self-sustainable wind speed sensor system with omni-directional wind based triboelectric generator. *Nano Energy* **2019**, *55*, 115-121, https://doi.org/10.1016/j.nanoen.2018.10.063.
3. Pan, T.; Cao, W.; Wang, M. Opt. TiO2 thin film temperature sensor monitored by smartphone. *Fiber Technol* **2018**, *45*, 359-362. https://doi.org/10.1016/j.yofte.2018.08.017.
4. Yenuganti, S.; Zhang, H.; Zhang, C. Langasite Crystal Based Pressure Sensor With Temperature Compensation. *Sensor Actuat A: Phys* **2018**, *281*, 108-116, https://doi.org/10.1016/j.sna.2018.07.012.
5. Qi, P.; Zhang, T.; Shao, J.; Yang, B.; Fei, T.; Wang, R. A QCM humidity sensor constructed by graphene quantum dots and chitosan composites. *Sensor Actuat A: Phys* **2019**, *287*, 93-101, https://doi.org/10.1016/j.sna.2019.01.009.
6. Bekhtin, Y.S.; Babayan, P.V.; Strotov, V.V. Onboard FPGA-based Fast Estimation of Point Object Coordinates for Linear IR-sensor. *Microprocessors Microsy* **2017**, *51,* 99-105, https://doi.org/10.1016/j.micpro.2017.04.009.
7. Sertel, B.C.; Sonmez, N.A.; Kaya, M.D.; Ozcelik, S. Development of MgO:TiO2 thin films for gas sensor applications. *Ceram. Int* **2019**, *45,* 2917-2921, https://doi.org/10.1016/j.ceramint.2018.11.079.
8. Liu, X.; Zhao, K.; Sun, X.; Zhang, C.; Duan, X.; Hou, P.; Zhao, G.; Zhang, S.; Yang, H.; Cao, R.; Xu, X. Rational design of sensitivity enhanced and stability improved TEA gas sensor assembled with Pd nanoparticles-functionalized In2O3 composites. *Sensor Actuat B: Chem* **2019**, *285*, 1-10, https://doi.org/10.1016/j.snb.2019.01.029.
9. Hoon Kim, T.; Hasani, A.; Quyet Van, L.; Kim, Y.; Yun Park, S.; Gyoung Lee, M.; Sohn, W.; Phan Nguyen, T.; Soon Choi, K.; Young Kim, S.; Won Jang, H.; NO2 sensing properties of porous Au-incorporated tungsten oxide thin films prepared by solution process. *Sensors and actuators: B. Chemical* **2019**, *286*, 512-520, https://doi.org/10.1016/j.snb.2019.02.009.
10. Zandi, A.; Gilani, A.; Fard, H.G.; Koohsorkhi, J. An optimized resistive CNT-based gas sensor with a novel configuration by top electrical contact. *Diam. Relat. Mater* **2019**, *93*, 224-232. https://doi.org/10.1016/j.diamond.2019.01.020.
11. Kumar, M.; Bhatt, V.; Kumar, A.; Yun, J.H. Nano lily-buds garden like ZnO nanostructures based gas sensor for H2 detection. *Mater. Let* **2019**, *240*, 13-16, https://doi.org/10.1016/j.matlet.2018.12.113.
12. Diniz, M.O.; Golin, A.F.; Santos, M.C.; Bianchi, R.F.; Guerra, E.M. Improving performance of polymer-based ammonia gas sensor using POMA/ V2O5 hybrid films. *Org. Electron* **2019**, *67*, 215-221. https://doi.org/10.1016/j.orgel.2019.01.039.
13. Ayesh, A.I.; Ahmed, R.E.; Rashid, M.A.; Alarrouqi, R.A.; Saleh, B.; Abdulrehman, T.; Haik, Y.; Sulaiti, L.A. Selective gas sensors using graphene and CuO nanorods. *Sensor Actuat. A Phys* **2018,** *283,* 107-112, https://doi.org/10.1016/j.sna.2018.09.068.
14. Dey, A. Semiconductor metal oxide gas sensors: A review. *Mater. Sci. Eng. B* **2018**, *229,* 206-217, https://doi.org/10.1016/j.mseb.2017.12.036.
15. Haiduk, Y.S.; Khort, A.A.; Lapchuk, N.M.; Savitsky, A.A. Study of WO3–In2O3 nanocomposites for highly sensitive CO and NO2 gas sensors. *J. solid state chem* **2019**, 273, 25-31, https://doi.org/10.1016/j.jssc.2019.02.023.
16. Li, G.; Cheng, Z.; Xiang, Q.; Yan, L.; Wang, X.; Xu, J. Bimetal PdAu decorated SnO2 nanosheets based gas sensor with temperature-dependent dual selectivity for detecting formaldehyde and acetone. *Sensor Actuat. B Chem* **2019**, *283*, 590-601, https://doi.org/10.1016/j.snb.2018.09.117.
17. Yong, Y.; Cui, H.; Zhou, Q.; Su, X.; Kuang, Y.; Li, X. Ultrathin nanowire based on icosahedral W@Au12 and application as NO gas sensor. *J. phys chem. Solids* **2019**, *127,* 68-75, https://doi.org/10.1016/j.jpcs.2018.12.008.
18. Zhang, G.; Han, X.; Bian, W.; Zhana, J.; Ma, X. Facile synthesis and high formaldehyde-sensing performance of NiO–SnO2 hybrid nanospheres. *RSC Adv* **2016**, *6*, 3919-3926, https://doi.org/10.1039/c5ra21063a.
19. Jeong, Y.J.; Kim, D.; Jang, J.; Kang, J.Y.; Kim, R.; Kim, I. Bio-Inspired Heterogeneous Sensitization of Bimetal Oxides on SnO2 Scaffold for Unparalleled Formaldehyde Detection. *Chem Comm* **2013***, 00*, 1-3, https://doi.org/10.1039/C8CC09882D.
20. Zhou, W.; Wu, Y.P.; Zhao, J.; Dong, W.W.; Qiao, X.Q.; Hou, D.F.; Bu, X.; Li, D.S. Efficient Gas-Sensing for Formaldehyde with 3D Hierarchical Co3O4 Derived from Co5 Based MOF Microcrystals. *Inorg. Chem 2017*, 56, 14111-14117, https://doi.org/10.1021/acs.inorgchem.7b02254.
21. Nasresfahani, S.; Sheikhi, M.H.; Tohidi, M.; Zarifkar, A. Methane gas sensing properties of Pd-doped SnO2/reduced graphene oxide synthesized by a facile hydrothermal route. *Mater. Res. Bull* **2017**, *89,* 161-169. http://dx.doi.org/doi:10.1016/j.materresbull.2017.01.032.
22. Shaalan, N.M.; Rashad, M.; Moharramc, A.H.; bdel-Rahim, M.A.A. Promising methane gas sensor synthesized by microwave-assisted Co3O4 nanoparticles. *Mater. Sci. Semicond Process* **2016**, *46*, 1–5, http://dx.doi.org/10.1016/j.mssp.2016.01.020.
23. Yang, X.; Li, H.; Li, T.; Li, Z.; Wu, W.; Zhou, C.; Sun, P.; Liu, Yan, F.X.; Gao, Y.; Liang, X. Lu, G. Highly efficient ethanol gas sensor based on hierarchical SnO2/Zn2SnO4 porous spheres. *Sensor Actuat. B. Chem* **2018**, *282,* 339-346, https://doi.org/10.1016/j.snb.2018.11.070.
24. Cheng, Y.; Guo, H.; Wang, Y.; Zhao, Y.; Li, Y.; Liu, L.; Li, H.; Duan, H. Low cost fabrication of highly sensitive ethanol sensor based on Pd-doped α-Fe2O3 porous nanotubes. *Mater. Res. Bull* **2018**, *105,* 21-27, https://doi.org/10.1016/j.materresbull.2018.04.025.
25. Li, K.; Wu, Y.; Chen, M.; Rong, Q.; Zhu, Z.; Liu, Q.; Zhang, J. High Methanol Gas-Sensing Performance of Sm2O3/ZnO/SmFeO3 Microspheres Synthesized Via a Hydrothermal Method. *Nanoscale Res. Lett* **2019**, *14,* 1-13, https://doi.org/10.1186/s11671-019-2890-5.
26. Wu, K.; Luo, Y.; Li, Y.; Zhang, C. Synthesis and acetone sensing properties of ZnFe2O4/rGO gas sensors. *Beilstein J. Nanotechnol* **2019**, *10,* 2516–2526, https://doi.org/10.3762/bjnano.10.242.
27. Xu, Y.; Lou, C.; Zheng, L.; Zheng, W.; Liua, X.; Kumar, M.; Zhang, J. Highly sensitive and selective detection of acetone based on platinum sensitized porous tungsten oxide nanospheres. *Sensor Actuat B Chem* **2020**, *307,* 1-9, https://doi.org/10.1016/j.snb.2019.127616.

28. Zou, Y.H.; Chen, S.; Sun, S.; Liu, J. Q.; Che, Y. K.; Zhang, Highly Efficient Gas Sensor Using a Hollow SnO2 Microfiber for Triethylamine Detection. *Nanohybrid. Mater. Sci. Semicond. Process* **2018**, *88,* 139-147, https://doi.org/10.1021/acssensors.7b00276.
29. Song, X.; Xu, Q.; Zhang, T.; Song, B.; Li, C.; Cao, B. Room-temperature, high selectivity and low-ppm-level triethylamine sensor assembled with Au decahedrons-decorated porous -Fe2O3 nanorods directly grown on flat substrate. *Sensor Actuat B Chem* **2018**, *268,* 170-181. https://doi.org/10.1016/j.snb.2018.04.096.
30. Wang, Z.; Zou, T.; Xing, X.; Zhao, R.; Wang, Z.; Yang, Y.; Wang, Y. CdIn2O4 nanoporous thin film gas-sensor for formaldehyde detection. *Physica E Low Dimens. Syst. Nanostruct* **2018**, *103,* 18-24, https://doi.org/10.1016/j.physe.2018.05.018.
31. Yang, J.; Wang, S.; Dong, R.; Zhang, L.; Zhu, Z.; Gao, X. One-pot synthesis of SnO2 hollow microspheres and their formaldehyde sensor application. *Mater. Lett* **2016,** *184*, 9-12, https://doi.org/10.1016/j.matlet.2016.08.007.
32. Chung, F.C.; Zhu, Z.; Luo, P.Y.; Wu, R.J.; Wei, L. Au@ZnO core–shell structure for gaseous formaldehyde sensing at room temperature. *Sensor Actuat B Chem* **2014**, 199, 314-319, https://doi.org/10.1016/j.snb.2014.04.004.
33. Zhou, W.; Wu, Y.P.; Zhao, J.; Dong, W.W.; Qiao, X.Q.; Hou, D.F.; Bu, X.; Li, D.S. Efficient Gas-Sensing for Formaldehyde with 3D Hierarchical Co3O4 Derived from Co5 Based MOF Microcrystals. *Inorg. Chem* **2017**, *56,* 14111-14117, https://doi.org/10.1021/acs.inorgchem.7b02254.
34. Zhou, Q.; Chen, W.; Xu, L.; Peng, S. Hydrothermal Synthesis of Various Hierarchical ZnO Nanostructures and Their Methane Sensing Properties. *Sensors* **2013**, *13,* 6171-6182, https://doi.org/10.3390/s130506171.
35. Waitz, T.; Wagner, T.; Sauerwald, T.; Kohl, C.D.; Tiemann, M. Ordered Mesoporous In2O3: Synthesis by Structure Replication and Application as a Methane Gas Sensor. *Adv. Funct. Mater* **2009**, *19*, 653–661, https://doi.org/10.1002/adfm.200801458.
36. Navazani, S.; Shokuhfar, A.; Hassanisadi, M.; Carlo, A.D.; Shahcheraghi, N. Fabrication and characterization of a sensitive, room temperature methane sensor based on SnO2@reduced graphene oxide-polyaniline ternary nanohybrid. *Mater. Sci. Semicond. Process* **2018**, *88,* 139-147, https://doi.org/10.1016/j.mssp.2018.08.006.
37. Song, L.; Lukianov, A.; Butenko, D.; Li, H.; Zhang, J.; Feng, M.; Liu, L.; Chen, D.; Klyui, N.I. *Nanoscale Res. Lett* **2019**, *14,* 1-11. https://doi.org/10.1186/s11671-019-2911-4.
38. Zhang, Y.H.; Cai, X.L.; Song, L.Z.; Feng, F.Y.; Ding, J.Y.; Gong, F.L. 2D nanosheet-assembled PdeZnO microflowers for acetone sensor with enhanced performances. *J. Phys. Chem. Solid* **2019**, *124,* 330-335, https://doi.org/10.1016/j.jpcs.2018.09.006.
39. Zhang, R.; Shi, J.; Zhou, T.; Tu, J.; Zhang, T. A yolk-double-shelled heterostructure-based sensor for acetone detecting application. *J. Colloid Interface Sci* **2019,** *539*, 490–496, https://doi.org/10.1016/j.jcis.2018.12.096.
40. Zhang, R.; Zhang, T.; Zhou, T.; Lou, Z.; Deng, J.; Wang, L. Fast and real-time acetone gas sensor using hybrid ZnFe2O4/ZnO hollow spheres. *RSC Adv.* **2016**, *6*, 66738–66744, https://doi.org/10.1039/c6ra12201a.
41. Chu, X.; Dai, P.; Liang, S.; Bhattacharya, A.; Dong, Y.; Epifani, M. The acetone sensing properties of ZnFe2O4-graphene quantum dots (GQDs) nanocomposites at room temperature. *Phys. E (Amsterdam, Neth.)* **2019**, *106*, 326–333, https://doi.org/10.1016/j.physe.2018.08.003.
42. Kaur, J.; Anand, K.; Kaur, A.; Singh, R.C. Sensitive and selective acetone sensor based on Gd doped WO3/reduced graphene oxide nanocomposite. *Sens. Actuators B* **2018**, *258*, 1022–1035, https://doi.org/10.1016/j.snb.2017.11.159.
43. Zou, Y.H.; Chen, S.; Sun, J.; Liu, J.Q.; Che, Y.K.; Liu, X.H.; Zhang, J.; Yang, D.J. Highly Efficient Gas Sensor Using a Hollow SnO2 Microfiber for Triethylamine Detection. *ACS Sens* **2017,** *7,* 897–902, https://doi.org/10.1021/acssensors.7b00276.
44. Sun, G.; Chen, H.L.; Li, Y.W.; Ma, G.Z.; Zhang, S.S.; Jia, T.K.; Cao, J.L.; Wang, X.D.; Bala, H.; Zhang, Z.Y. Synthesis and triethylamine sensing properties of mesoporous α-Fe2O3 microrods. *Mater. Lett* **2016**, *178,* 213–216, https://doi.org/10.1016/j.matlet.2016.04.209.
45. Xu, H.Y.; Ju, D.X.; Li, W.R.; Zhang, J.; Wang, J.Q.; Cao, B.Q. Superior triethylamine-sensing properties based on TiO2/SnO2 n-n heterojunction nanosheets directly grown on ceramic tubes. *Sens. Actuators B* **2016**, *228*, 634–642, https://doi.org/10.1016/j.snb.2016.01.059.
46. Wu, Y.P.; Zhou, W.; Dong, W.W.; Zhao, J.; Qiao, X.Q.; Hou, D.F.; Li, D.S.; Zhang, Q.C.; Feng, P.Y. Temperature-controlled synthesis of porous CuO particles with different morphologies for highly sensitive detection of triethylamine. *Cryst. Growth Des* **2017**, *17,* 2158–2165, https://doi.org/10.1021/acs.cgd.7b00102.

6. ACKNOWLEDGEMENTS

Authors are thankful to the management SOA (deemed to be University) for constant encouragement.