Nanostructured WO$_3$/graphene composites for sensing NO$_x$ at room temperature

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WO$_3$ has emerged as an outstanding nanomaterial composite for gas sensing applications. In this paper, we report the synthesis of WO$_3$ using two different capping agents, namely, oxalic acid and citric acid, along with cetyltrimethyl ammonium bromide (CTAB). The effect of capping agent on the morphology of WO$_3$ material was investigated and presented. The WO$_3$ materials were characterized using X-ray diffraction analysis (XRD), field emission electron microscopy (FETEM), field emission scanning electron microscopy (FESEM), particle size distribution (PSD) analysis, and UV-visible spectroscopic analysis. WO$_3$ synthesized using oxalic acid exhibited orthorhombic phase with crystallite size of 10 nm, while WO$_3$ obtained using citric acid shows monoclinic phase with crystallite size of 20 nm. WO$_3$ obtained using both capping agents were used to study their gas sensing characteristics, particularly for NO$_2$ gas. The cross sensitivity towards interfering gases and organic vapors such as acetone, ethanol, methanol and triethylamine (TEA) was monitored and explained. Furthermore, the composites of WO$_3$ were prepared with graphene by physical mixing to improve the sensitivity, response and recovery time. The composites were tested for gas sensing at room temperature as well as at 50 °C and 100 °C. The results indicated that the citric acid-assisted WO$_3$ material exhibits better response towards NO$_2$ sensing when compared with oxalic acid-assisted WO$_3$. Moreover, the sensitivity of the WO$_3$/graphene nanocomposite was better than that of the pristine WO$_3$ material towards NO$_2$ gas. The WO$_3$ composite prepared using citric acid as capping agent and graphene exhibits sensing response and recovery time of 29 and 24 s, respectively.

1 Introduction

In power stations, the main component of the released exhaust gases is a mixture comprising 90% NO and NO$_2$ at different ranges of ppm levels. NO$_2$ has been the cause for calamities such as acid rain, smog and ozone depletion. The Threshold Limit Value (TLV) for NO and NO$_2$ estimated by environmental monitoring organizations is 3 and 25 ppm, respectively. Looking at these facts, many researchers tried to fabricate gas sensors using different sensing materials such as ZnO, SnO$_2$, WO$_3$, TiO$_2$, and Fe$_2$O$_3$. All these compounds have a non-stoichiometric structure and therefore, electrical conductivity is observed due to the presence of free electrons resulting from oxygen vacancies. When an oxidizing or reducing gas comes in contact with the semiconducting nanocompounds, their resistivity changes accordingly; hence, they can act as a sensor for the gas. Even though the same working mechanism exists for adsorption and desorption in all the above mentioned compounds such as ZnO, SnO$_2$, and WO$_3$, the operating temperature and voltage required by WO$_3$ for gas sensing is lower than that of the other compounds.

The nanostructured WO$_3$ powder with different morphologies have been synthesized by various methods such as hydrothermal method, acidification, atmospheric plasma spray method, solvothermal method, sol spin coating, template-directed wet chemical synthesis, thermal evaporation, and reactive DC magnetron sputtering. Meng et al. synthesized flower-like WO$_3$ nanostructure using citric acid as a capping agent, which exhibited sensing response towards ethanol at 250 °C. Su et al. also reported WO$_3$ nanoplates with square morphology using citric as well as tartaric acid. Wang et al. synthesized WO$_3$ nanorods with high crystallinity by hydrothermal method from ammonium meta-tungstate and citric acid. It was also reported that citric acid plays a major role in determining the morphology. With the increase in concentration of citric acid, there was growth observed along [202] and [220] crystallographic directions, resulting in the formation of nanorods. Patil et al. synthesized WO$_3$ nanorods using oxalic acid by the hydrothermal method, and the role of oxalic acid in synthesis was explained. Similarly You et al. synthesized oxalic acid-assisted WO$_3$ nanoparticles, which showed good response to NO$_2$ at 125 °C.
Considering the variations in morphologies yielded by two dicarboxylic acids, namely, citric and oxalic acid, with different experimental conditions, we selected these dicarboxylics for the synthesis of WO₃. Furthermore, the as-synthesized WO₃ was blended with graphene to increase its effective sensitivity. Thus, we achieved maximum sensitivity for WO₃ with lesser response and recovery time at room temperature for NO₂ when compared with WO₃ synthesized with earlier published literature.

2 Experimental

All the chemicals used in the experiment are of AR grade.

2.1 Synthesis of nanostructured WO₃

Sodium tungstate dihydrate was dissolved in water to form 20 mL 3 mM solution. To this solution, 2 M HCl was added dropwise to form a pale yellow precipitate. The precipitate was centrifuged and dissolved in 1 M citric acid solution. To the above solution, 4.5 mM CTAB was added and the resultant mixture was diluted to 40 mL. The reaction mixture was further transferred to a Teflon-lined stainless steel autoclave and heated at 180 °C for 12 h in an oven. The autoclave was naturally cooled to room temperature. The intermediate products were collected after centrifugation (5000 rpm) and dried at 80 °C for 4 h. The as-prepared precursors were sintered at 600 °C for 2 h to obtain the final oxides. WO₃ obtained using citric acid is labelled as PA1. Similar experiment was conducted to synthesize WO₃ using oxalic acid instead of citric acid. WO₃ obtained using oxalic acid is labelled as PA2.

2.2 Synthesis of WO₃/graphene nanocomposite

The nanocomposite of WO₃ and graphene was prepared using a physical mixture method. Initially, 1% graphene was taken in 10 mL ethanol and sonicated for 20 min. To this solution, the as-synthesized WO₃ powder was added and further sonicated for 1 h. The resultant WO₃/graphene nanocomposite solution was allowed to evaporate at room temperature to form a paste, which was then applied on the substrate.

2.3 Physicochemical characterization

The crystalline structures of the resultant powders were characterized by XRD on a Rigaku Miniflex diffractometer using CuKα radiation (λ = 1.5405 Å; nickel filter). The crystallite size was estimated using the Scherrer’s formula. Optical absorption spectrum was recorded on a Hitachi UV-Visible Spectrophotometer (model U-3210). Morphological studies were conducted using FE-SEM (Hitachi Model 5890). FETEM analysis was performed using an FETEM analyzer (JEOL JEM 220 ks model). PSD analysis was conducting via a dynamic light scattering method using a submicron particle size analyzer, PSS-Nicomp-380 (Santa Barbara, California, USA).

2.4 Gas sensing characterization

The gas sensing measurements were performed for WO₃ and WO₃/graphene nanocomposite products. Planar interdigitated electrode arrays are a commonly used electrode configuration for conductimetric sensing applications. The electrodes were fabricated in-house using a thick film paste. The design of the interdigitated electrode structure is illustrated in Fig. 1a. At one end of the structure, there is a set of interdigitated electrodes that occupy an area of 8 × 8 mm. The width of the digits is 1 mm and the space between them is 0.5 mm. Alumina substrate (0.6 mm thick and 10 × 10 mm area) was used for the fabrication of interdigitated electrodes. Screen-printing technique was used for the printing of the electrode pattern on the substrate. Silver paste was screen-printed on the substrate. The thickness of the silver pattern was 8 μm. The gas sensing measurements were performed using a set-up (shown in Fig. 1c) as reported earlier. It essentially consists of a circular platform with a place for mounting the substrate and sensing material. The platform was covered with a glass dome to house it in inert atmosphere and to protect it from other gaseous disturbances. The process conducted was as follows. Initially, 25 mg each of the WO₃ (WO₃ prepared using oxalic acid and citric acid) were taken in a mortar and pestle. Then, 0.5 mL ethanol was added to form a paste. The semi-liquid paste was then drop casted on an alumina substrate with silver electrodes patterned on it. The substrate was then dried at 60 °C for 1 h.

The WO₃-coated substrate was kept inside the dome and a provision was made to inject the gas in the dome. For measuring the change in resistance, a Digital Multimeter (Keithley model 7510) was used.
3 Results and discussion

The particulate properties of the nanostructured WO₃ were studied via XRD, FESEM, FT-TEM, UV-visible spectroscopy and PSD. The diffraction patterns of the WO₃ products obtained using citric acid and oxalic acid as capping agents exhibited sharp crystalline peaks. The diffraction pattern of WO₃ obtained using citric acid perfectly matches with the JCPDS card no. 05-0363, confirming the formation of the monoclinic phase (Fig. 2a). The prominent peaks were observed at 2θ values of 23.37, 23.90, 26.35, 28.44, 33.88, 41.48, 44.68, 45.61, 49.75, 51.65, 54.76, 55.70, and 62.12 corresponding to (001), (020), (200), (120), (111), (021), (220), (121), (221), (003), (040), (140), (022), (041), (−240), (−420), and (−340) diffraction planes, respectively. The lattice parameters match with the standard values, with \( a = 7.3410 \), \( b = 7.5700 \), and \( c = 7.7541 \), and are in accordance with the literature. The mean crystalline size calculated is around 10 nm. No other impurity peaks were observed in both the XRD patterns.

Similarly, XRD pattern of the WO₃ product obtained using oxalic acid (Fig. 2b) matches with the JCPDS card no. 01-071-0131, depicting the orthorhombic phase. The major diffraction peaks are observed at 2θ values of 23.37, 23.90, 26.35, 28.44, 33.88, 41.48, 44.68, 45.61, 49.75, 51.65, 54.76, 55.70, and 62.12 corresponding to (020), (200), (120), (112), (220), (222), (132), (312), (140), (303), (214), (420), and (314) diffraction planes, respectively. The lattice parameters match with the standard values, with \( a = 7.3410 \), \( b = 7.5700 \), and \( c = 7.7541 \), and are in accordance with the literature. The mean crystalline size calculated is around 10 nm. No other impurity peaks were observed in both the XRD patterns.

The optical absorption spectra of WO₃ obtained using citric acid and oxalic acid as capping agents are as shown in Fig. 3c. It could be observed that there is a change in the optical absorption spectrum after addition of graphene. The band located at 250 nm is due to the \( π−π^* \) transition of graphene. The SEM and FESEM photomicrographs obtained using citric acid and oxalic acid-assisted WO₃ are presented in Fig. 4. It can be observed that the citric acid-assisted WO₃ product consists of a mixture of nanoparticles as well as rod-like structures. The rod-like structures were presumably formed by the agglomeration of nanoparticles and can be evidenced by FT-TEM analysis. The diameter of the nanorods is 90 nm and length is a few microns.
In case of WO₃ obtained using oxalic acid, clusters of nanoparticles are observed (Fig. 4b). The size of the nanoparticles is around 20–30 nm. The nanoparticles are intact and form an island of clusters all over.

The FESEM photomicrographs of WO₃ (obtained using citric acid) and graphene composite are presented in Fig. 4c. It can be observed that the composite consists of WO₃ nanoparticles well-wrapped with graphene sheets. The interface of WO₃ and graphene can also be clearly seen.

Closer observations on morphological characterization were performed using FETEM analysis. The corresponding FETEM images are displayed in Fig. 5. The WO₃ product obtained using citric acid shows spherical nanoparticles with size of around 60–70 nm, and were agglomerated to form rod-like structures (Fig. 5a). Fig. 5b illustrates the clusters of 10 to 20 nanoparticles with size varying from 20–50 nm. All these results are in accordance with the SEM observations. The inset shown in Fig. 5 is a clear crystallite diffraction pattern for both the products.

The chemical reaction mechanism for the formation of WO₃ using citric acid and oxalic acid is explained below. In the initial stage, sodium tungstate reacts with HCl to form tungstic acid and sodium chloride.

\[
\text{Na}_2\text{WO}_4 + 2\text{HCl} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{WO}_4 + 2\text{NaCl} + \text{H}_2\text{O} \tag{1}
\]

In case of citric acid-assisted WO₃, the initially obtained precipitate was redissolved in 1 M citric acid solution. The probable reaction is given below:

\[
\text{H}_3\text{WO}_4 + \text{C}_6\text{H}_5\text{O}_7 + \text{H}_2\text{O} \rightarrow \text{WO}_3 + \text{C}_6\text{H}_5\text{O}_7 + 2\text{H}_2\text{O} \tag{2}
\]

Thus, WO₃ formation takes place, and the growth of WO₃ is controlled by citric acid. Citric acid acts as a shape modifier. The growth of the particles is controlled in citric acid by the coating of citric ions on the particles of WO₃. However, after heating at 600 °C, the one directional growth accelerated, resulting in formation of the nanorods of WO₃.

The reaction with oxalic acid can be presented as follows:

\[
\text{H}_2\text{WO}_4 + \text{C}_2\text{H}_2\text{O}_4 + \text{H}_2\text{O} \rightarrow \text{WO}_3 + \text{C}_2\text{H}_2\text{O}_4 + 2\text{H}_2\text{O} \tag{3}
\]

Oxalic acid is a well-known chelating agent that can combine with WO₄²⁻ ions and form WO₃·OC₂H₄. Subsequent chelating forms WO₃ after calcination at 600 °C. Thus, WO₃ formed after calcinations at 600 °C exhibit distinct crystal growth. The WO₃ nanocrystals formed are unidirectional and in the form of clusters.

### 3.1 Sensing characterization

Gas sensing measurements were performed to check the sensitivities using various gases such as NOₓ, acetone, ethanol, methanol, and TEA.

The sensitivity was calculated using the formula:

\[
\text{Sensitivity} = \frac{R_g}{R_a} - 1, \text{ for oxidizing gases;}
\]
\[
\text{Sensitivity} = \frac{R_a}{R_g} - 1, \text{ for reducing gases;}
\]

where \(R_a\) is resistance in air and \(R_g\) is resistance in gas.

The effect of morphologies of two different samples and the effect of graphene on the sensitivity of the gas sensing was studied. Due to its small band gap, WO₃ shows a sensing property of WO₃. The sensitivity of both the WO₃ samples was studied at room temperature for different gases such as NOₓ, acetone, ethanol, methanol, and TEA. As shown in the Fig. 6, the WO₃ product sensitivity obtained using citric and oxalic acid is the highest towards NOₓ as compared with other gases.

WO₃ obtained using citric acid has higher sensitivity than WO₃ obtained using oxalic acid. In case of the product obtained using oxalic acid, even though the sensitivity for NOₓ is more, there is hardly any difference between the sensitivities of the five gases studied, as shown in Fig. 6.

To compare the sensitivity towards NOₓ, both the products were exposed to different concentrations of NOₓ, and the results...
are presented in Fig. 7. The concentration of NO₂ was varied from 200 ppm to 1000 ppm in steps of 200 ppm. At 200 ppm the response of both the products towards NO₂ is comparatively similar. However, as the concentration changes from 200 ppm to 500 ppm, the response of citric acid-assisted WO₃ increases linearly up to 1000 ppm compared with oxalic acid-assisted WO₃, which increases linearly up to 400 ppm and drops thereafter. Thus, the overall response of WO₃ obtained using citric acid towards NO₂ was found to be better and higher when compared with oxalic acid-assisted WO₃.

We can depict from the above study that the morphology of the material and band gap affects the sensing response considerably. It is further opined that smaller the band gap, higher would be the response at room temperature. Particle size also plays an important role. As shown in Fig. 7(a & b), it could be observed that oxalic acid-assisted WO₃ has slightly greater response at lower concentration of NO₂ than the citric acid-assisted WO₃, which can be attributed to the smaller particle size of oxalic acid-assisted WO₃. As the overall sensitivity and response of WO₃ obtained using citric acid is higher than that of the other product, the citric acid-assisted WO₃ was selected for further studies.

The NO₂ gas sensing experiment was performed with the citric acid-assisted WO₃ at different temperatures namely, at room temperature, 50 °C and 100 °C (Fig. 8). For these three temperatures, the sensitivity towards NO₂ was found to increase with the increase in concentration of NO₂.

As the temperature increases, the resistance of the material decreases and therefore, the change in resistance (ΔR) decreases, resulting in reduction in the sensitivity at higher temperature. Thus, the maximum sensitivity was observed at room temperature. Furthermore, to increase the sensitivity, graphene was introduced.

A gas sensing experiment in the concentration range of 10–200 ppm of NO₂ was performed for citric acid-assisted WO₃ and graphene nanocomposite at room temperature and compared with pristine WO₃ obtained using citric and oxalic acid (depicted in Fig. 9). As the concentration of gas increases in the range between 10 and 200 ppm, the sensitivity of WO₃/graphene composite was found to be linearly increasing. However, in case of pristine WO₃, the increase in sensitivity with respect to concentration is not clearly linear.

The response time and recovery time of the sensing material is also a crucial aspect. The composite was found to have a minimum response time of 29 s and recovery time of 24 s, as depicted from the graph (Fig. 10). The response and recovery time of the composite was compared with the reported literature. Qin et al. reported the NO₂ sensing response of solvothermally prepared WO₃ nanowire and nanosheets. Their sensor worked at 200 °C and the response time and recovery time achieved were 19 s and 112 s, respectively. You et al. reported more sensitive square-like geometrical WO₃ sheets, exhibiting NO₂ response at 150 °C with a response time of 300 s and recovery time of 30 s. You et al. tested the sensing response and recovery time for spherical WO₃ nanoparticles at 125 °C. The response time observed was 180 s, while the recovery time was 90 s. Xia et al. synthesized ultrathin ZnO nanorods/reduced graphene oxide mesoporous nanocomposites for high-performance room-temperature NO₂ sensors, showing response time of 75 s and recovery time of 132 s. Bai et al. doped WO₃ nanoparticles with Sb, Cd and Ce to enhance the temperature sensitivity of the material. They have also concluded that lowering the band gap of the material may result in an increase in its response towards NO₂ at room temperature. Hence, compared with the above

Fig. 8 NO₂ sensing response of WO₃ obtained using citric acid at different temperatures (RT, 50 °C and 100 °C) as a function of increase in concentration of NO₂.

Fig. 9 Comparison of sensitivity of pristine WO₃ (obtained using citric acid and oxalic acid) and WO₃/graphene composite at room temperature.

Fig. 10 NO₂ gas sensing response of WO₃ and WO₃/graphene nanocomposite at room temperature, 50 °C, and 100 °C.
mentioned reports, the composite of WO₃ and graphene prepared in the present study shows a very good response and recovery time at room temperature. WO₃ is generally immobilized on graphene, and the electrons generated are quickly transported to the surface due to graphene. Hence, graphene works as an electron transporter and shows good response. This can be attributed to its efficient functioning at room temperature. The mechanism of sensing is as follows. WO₃ is an n-type semiconductor in which electrons are majority charge carriers responsible for sensing the gas molecules. NO₂ is an oxidizing gas. When NO₂ is adsorbed on the active sites of WO₃, it increases the surface area, and (iii) specific capturing and migration of electrons from WO₃ to graphene due to the Schottky barrier at the interface of graphene and WO₃. The gas sensing experiments of the composite were also performed at specific time intervals to check its stability and reproducibility and the results were found to be consistent.

4 Conclusions

WO₃ nanocomposites for sensing at room temperature were successfully synthesized by citric acid and oxalic acid. Nanorod structures caused by agglomeration of spherical particles were observed in citric acid-assisted WO₃, whereas a uniformly distributed spherical structure was observed in oxalic acid-assisted WO₃. The sensitivity of citric acid-assisted WO₃ was higher at room temperature and it increases drastically when mixed with graphene. The composite of graphene and WO₃ nanorods prepared by the physical mixture method showed a 29 s response time and 24 s recovery time at room temperature for 10 ppm. The increase in concentration of NO₂ resulted in a linear increase in sensitivity for 10, 25, 50, 100 and 200 ppm of NO₂ compared with the published study on WO₃ sensors, indicating that both the response time and recovery time were better. We can also depict from this study that the morphology of the material and band gap affects the sensitivity response considerably. The overall results indicate that a room temperature NO₂ sensor could be fabricated using graphene and WO₃ nanocomposite with better response and recovery time. Further studies to use the findings of this research to fabricate a NO₂ sensing device based on citric acid-assisted WO₃ are in progress.

Conflicts of interest

There is no conflict of interest.

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References