A review on tin dioxide gas sensor: The role of the metal oxide doping, nanoparticles, and operating temperatures

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Abstract

Metal oxide gas sensors have many advantages over other solid-state gas monitoring devices, including low cost, ease of manufacture, and small design. However, the shape and structure of sensing materials have a considerable impact on the performance of such sensors, posing a significant challenge for gas sensing properties on materials or dense films to attain high-sensitivity characteristics. Various tin dioxide (SnO₂) nanostructures have been devised to increase gas sensing characteristics such as sensitivity, selectivity, and response time, among other characteristics. An overview of the most well-known techniques for synthesizing gas-sensing films, as well as the influence of doping with various metal oxides, nanoparticle size, and operating temperature on the gas-sensing properties of such films, is discussed in this work. The gas sensing mechanisms and the gas detection techniques are presented in detail. The metal oxide doped SnO₂ showed a strong response for SO₂ and NO₂ gases, whereas nanoparticle doping plays a crucial effect in increasing SnO₂ sensitivity towards H₂, H₂S, NO₂, CO, Ethanol, etc. Furthermore, the effect of operating temperature on SnO₂ response is discussed in this report. SnO₂ has a high sensitivity over a wide temperature range (100-350 °C).

Keywords: Thin films; review; SnO₂ nanoparticles; doping effect; operating temperature

Graphical abstract
1. Introduction

Nanoscience is described as the study of the properties of materials with nanometer-scale dimensions or the science concerned with tiny objects with dimensions ranging from a few nanometers to less than 100 nm [1]. Nanostructures metal oxides have a significant interest because of their size-dependent properties and their various applications [2]. Semiconductor oxides play a critical role in energy conservation and conversion applications, optoelectronics, memory applications, etc. [3–5]. One of the most critical types of semiconductors is the transparent conductive oxides (TCOs), which are composed of metal combined with oxygen, such as CdO, ZnO, and SnO$_2$ [6]. Such materials have two benefits; they are described by high electrical conductivity and optical transmittance. Despite the wide bandgap of these materials compared to the other semiconductors, the conduction band is full of free electrons. Thus, the transmittance spectrum within 400-1500 nm depends on the preparation conditions of the material.

Nanostructured semiconductors, such as SnO$_2$, ZnO, and TiO$_2$, can be used to detect a wide range of organic pollutants [7–11]. Tin (IV) Oxide (SnO$_2$) is an n-type transparent semiconductor with a wide bandgap of 3.6 eV at 300 K [12,13]. SnO$_2$ is used in a wide variety of applications, including photovoltaic devices [14–18], biological applications [19–23], solar cells [24–28], electrochemical applications [29–31], and gas sensors [32–37]. Due to its high sensitivity to reducing and oxidizing gases such as CO, H$_2$, and NO, tin oxide is commonly employed in gas sensor applications [38]. It was prepared by several techniques such as sol-gel, microwave-assisted and ultrasound-assisted methods, solvothermal, pulsed laser deposition, solid-state reaction, microemulsion, hydrothermal deposition, electron beam evaporation, sonochemical, sputtering, spray pyrolysis, sonication, vapor-liquid-solid synthesis [26,29,39–45]. It is an inorganic compound with a density of 6.99 g/cm$^3$, and the melting point is 1624.85 °C [46].

The rutile is the most common crystal structure of SnO$_2$. It has a tetragonal unit cell with P$4_{2}/mnm$ (136) space group [47], and the lattice constants are a=b= 4.73 Å and c=3.18 Å [48]. A single unit cell includes six atoms, two of which are Tin and four Oxygen. Each Sn atom is surrounded by six O atoms at the octahedron's vertices in this structure, whereas three Sn atoms surround each O atom at an equatorial triangle's vertex.

![Figure 1](image)

Figure 1(a) depicts the crystal structure of SnO$_2$. The particle size of SnO$_2$ nanostructures less than 20 nm with a surface area of 100-200 nm$^2$/g is particularly relevant in gas sensing applications. The structure of a SnO$_2$ thin film gas sensor is depicted in Figure 1(b). This review will highlight the most critical factors affecting the sensitivity of tin dioxide films and then compare the studied results from literature reviews to reach the optimal conditions for preparing tin oxide films as gas sensor devices.

2. Gas sensing mechanism

The detecting mechanism of metal-oxide gas sensors is based on species ionosorption on their surfaces, and the most significant ionosorbed species at ambient air are oxygen and water. The electrical and chemical activity of the O$_2$ vacancies on the surface of semiconductor oxides determines the sensing mechanism [49]. Two types of sensing reactions have been found in this mechanism. The first is the adsorb of charge-accepting molecules, such as oxygen or nitrogen dioxide, which extract the electrons from the conduction band at vacancy sites, decreasing the electrical conductance. Second, in an O$_2$ environment, oxygen molecules adsorbed on the surface react with gas molecules such as hydrogen or carbon dioxide, causing trapped electrons to be released and then injected back into the channel, increasing electrical conductivity [50]. The redox sensors' responses are categorized as oxidizing and reducing, which
is the basis for decreasing and increasing channel conductance. Equations 1 and 2 illustrate the oxidizing response of the sensor:

\[ NO + e^- \rightarrow NO^- \]  

While the reducing response of the sensor can be characterized by example:

\[ CO + O \rightarrow CO_2 + e^- \]  

The temperature at which semiconductor sensors operate should be low enough to avoid long-term alterations to the bulk material and high enough that gas reactions occur in the order of the desired response time[51,52]. In general, semiconductor sensors that operate in relatively high-temperature ranges show a significant change in electrical resistance, which increases the rate of chemical reaction to the surface and thus increases the charge transfer processes [53]. The essential principle of semiconductor sensors working is dependent mainly on the interaction between the reactive chemical species (e.g., \(OH^-, O^-, O_2^-, \) and \(H^+\)) and the gas molecules to be sensed. The primary elements affecting semiconductor sensitivity are the microstructure (surface to volume ratio), the size of the grains, the thickness of the sensor film, and the pore size of the oxide particle [54].

3. Gas Detection Techniques

The quantum mechanical analysis demonstrated that the periodic crystal lattice sites restricted by the semiconductor surfaces produce localized surface states. When the energy levels of semiconductor material are in the forbidden energy region, the surface states may inject/trap electric charge into the bulk crystal. The crystal's ionized donors or acceptors generate a countercharge on the surface due to the corresponding surface charge. The band bending in the crystal is compatible with the formation of a double charge layer, which has a net negative charge and a positive counteracting charge in bulk [55].

The exposure of semiconductor surfaces, such as SnO\(_2\) surface, to a gaseous atmosphere contributes to the development of more surface states as surrounding gases enhance the adsorption process occurring near the surface [56]. The principle of oxygen species adsorption, a component prevalent in most gas sensor applications, is illustrated in Figure 2a. The oxygen is adsorbed on the surface of the semiconductor when an electron is trapped from the conduction band, forming the oxygen ion \(O_2^-\). This electron capture is the same as occupying a surface state generated by localized adsorption (O\(_2\)) [57]. Since the Fermi level of the semiconductor is higher than the surface state energy level in the absence of oxygen, this mechanism is possible. The charge transfer results in developing a surface charge and thus the bending of the semiconductor's band structure, as illustrated in Figure 2b. The Fermi level is dropped until enough oxygen has been adsorbed to equalize the surface energy level with the semiconductor Fermi level, referred to as Fermi level pinning. The bending of the tape results in the depletion of free surface charge carriers, the formation of a charge carrier depletion region, and then a high ohmic electrons resistance [55].

![Figure 2](image.png)

**Figure 2** (a) The mechanism of SnO\(_2\) thin film gas sensor and (b1) Diagram of valance band, conduction band, and Fermi level (b2) band bending in case of oxygen species adsorption on a sensor surface.
4. Metal oxide doping effect

F. Ren et al. first reported that an excellent gas-sensitive performance of CuO/SnO$_2$ based sensor to BTEX belongs to the addition of catalyst CuO [58]. The highly sensitive, low-temperature, operated nitrogen dioxide (NO$_2$) gas sensor was fabricated using SnO$_2$ thin film doped with CuO. Sonker et al. stated that CuO/SnO$_2$ has a higher sensitivity than undoped SnO$_2$ [59]. Also, Zhou showed that p-type metal oxide (CuO) doped SnO$_2$ gas sensing thin films have high sensitive H$_2$S [60]. The CuO/SnO$_2$ thin film is confirmed to be a promising thin-film in gas sensor devices because the metal oxide catalyst increases the surface area. Punit Tyagi has studied the thin films' growth, especially SnO$_2$ thin films with high electrical resistivity, employing the NiO as a catalyst has combined on the surface of SnO$_2$ thin film with dotted nanoclusters and a continuous layer to enhance the response properties. The sensing response improved around 56 observed at a lower temperature for the NiO dotted cluster/SnO$_2$ sensor. Anjali Sharma has studied the structure of gas sensors based on RF sputtered SnO$_2$ thin film [61]. Various catalysts like In$_2$O$_3$, Al$_2$O$_3$, WO$_3$, CuO, NiO, and TeO$_2$ in nanoclusters structure have been deposited on the surface of SnO$_2$ to enhance the speed of response and recovery of the sensor and their effect on sensing response properties against NO$_2$ gas. According to D. Xue et al., the results of gas sensing demonstrate that the WO$_3$-SnO$_2$ nanocomposites have superior methane sensing properties compared to pure SnO$_2$ [62]. Punit Tyagi has presented the SO$_2$ gas sensing feature of SnO$_2$ thin film prepared using the RF sputtering method [63].

Various catalysts (MgO and V$_2$O$_5$) with nanoclusters form having a diameter of 600 μm have been loaded on the surface of SnO$_2$ for SO$_2$ gas detection. Both catalysts have incorporated with SnO$_2$ film, leading to high selectivity towards SO$_2$ gas at lower temperatures. J. Y. Choi and T. S. Oh described the sensor response of La$_2$O$_3$-doped SnO$_2$ to 10–75 ppm CO gas [64]. The La$_2$O$_3$-doped SnO$_2$ showed significantly improved CO sensitivity. Using the hydrothermal technique, S. Yan et al. prepared CeO$_2$-SnO$_2$ 2-Dimensions nanosheets of equal size and little rhombus nanopores [65]. For the CeO$_2$-SnO$_2$ sensor, the response toward 100 ppm ethanol was 44, and it was larger two times than that of the pure SnO$_2$ sensor. In addition, the results showed that the CeO$_2$-SnO$_2$ nanosheets improved the characteristics of the gas sensing and the response and recovery time become shorter due to the effect of the CeO$_2$-doping and the porous structure.

Kuang-Chung Lee et al. studied the behavior of CO gas sensing of the PdO-decorated sensors by depositing the PdO nanoparticles on SnO$_2$ thin films via reactive sputter deposition [66]. For the PdO-decorated sensor, the sensor signal is larger than three times that of the pure SnO$_2$ sensor. Z. Tianshu et al. presented the CdO doping effect on conductance, microstructure, and gas-sensing characteristics of SnO$_2$-based sensors [67]. The 10 mol.% Cd-doped SnO$_2$-based sensor reveals the outstanding performance of ethanol-sensing, like a great sensitivity, is 275 for 100 ppm C$_2$H$_5$OH, great selectivity over CO, H$_2$, and i-C$_3$H$_7$OH and a fast response rate of about 12 seconds for 90% response time. A comparison of the most common doping material summarizing its gas concentration and sensitivity is presented in Table (1).

**Table 1** Comparison of the most common doping material summarizing gas type, gas concentration, and the sensitivity

<table>
<thead>
<tr>
<th>Doping material</th>
<th>Gas</th>
<th>Gas Concentration ppm</th>
<th>Sensitivity%</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuO</td>
<td>BTEX</td>
<td>50</td>
<td>6 times higher than pure</td>
<td>[58]</td>
</tr>
<tr>
<td></td>
<td>NO$_2$</td>
<td>20</td>
<td>Highest response $1.83 \times 10^2$</td>
<td>[59]</td>
</tr>
<tr>
<td></td>
<td>H$_2$S</td>
<td>-</td>
<td>Highest responses 438</td>
<td>[60]</td>
</tr>
<tr>
<td>WO$_3$</td>
<td>methane</td>
<td>500</td>
<td>2.3 times higher than pure</td>
<td>[62]</td>
</tr>
<tr>
<td>NiO</td>
<td>SO$_2$</td>
<td>500</td>
<td>Highest response ~ 56</td>
<td>[63]</td>
</tr>
<tr>
<td>La$_2$O$_3$</td>
<td>CO</td>
<td>50</td>
<td>Highest response 59.0</td>
<td>[64]</td>
</tr>
<tr>
<td>CeO$_2$</td>
<td>Ethanol</td>
<td>100</td>
<td>2 times higher than pure</td>
<td>[65]</td>
</tr>
<tr>
<td>PdO</td>
<td>CO</td>
<td>2000</td>
<td>1.6 times higher than pure</td>
<td>[66]</td>
</tr>
<tr>
<td>CdO</td>
<td>H$_2$</td>
<td>1000</td>
<td>Highest response at 98</td>
<td>[67]</td>
</tr>
<tr>
<td>NiO</td>
<td>SO$_2$</td>
<td>500</td>
<td>Maximum response ~ 56</td>
<td>[68]</td>
</tr>
<tr>
<td>WO$_3$</td>
<td>NO$_2$</td>
<td>10</td>
<td>Highest response $5.4 \times 10^4$</td>
<td>[69]</td>
</tr>
<tr>
<td>MgO, V$_2$O$_5$</td>
<td>SO$_2$</td>
<td>5000</td>
<td>317,166</td>
<td>[70]</td>
</tr>
</tbody>
</table>
5. Nanoparticles effect

P. Sun et al. synthesized the hierarchical Cd-doped and undoped SnO$_2$ nanostructures using the hydrothermal method’s inexpensive and friendly environment [71]. The 3.0 wt.% Cd-doped SnO$_2$ based sensor exhibit outstanding selectivity toward H$_2$S. S. Rani reported the gas sensing properties of sol-gel-derived Fe-doped nanocrystalline SnO$_2$ thin films [72]. The films with 2% Fe content showed a high response and excellent selectivity for CO compared to other gases. Yanbai Shen et al. synthesized SnO$_2$ nanowires using a thermal evaporation method with a tetragonal structure [73]. The outcomes showed that the doping by Pd led to enhancing the sensor’s response and decreased the operating temperature, which maximized the sensor’s response. K. Hu et al. prepared Pd-doped SnO$_2$ nanofibers by magnetron and electrospinning sputtering [74]. The manufactured material showed a response of about 53 for 500 ppm hydrogen at the temperature of 130°C, which is an essential enhancement compared with sensors untreated with plasma. J. Kaur prepared different kinds of thin films, indium-doped and undoped SnO$_2$ thin films with various values of doping concentrations by using the sol-gel spin coating technique on glass substrates [75].

At a low temperature, the indium doping improves the selectivity and sensor response towards NO$_2$ gas and prevents the agglomeration of particles, which is responsible for lowering the sensor response and stability in the range of particle size. As well, A. Salehi studied the dependence of the SnO$_2$ sensitivity on indium concentration by chemical vapor deposition [76]. The sensitivity of indium-doped SnO$_2$ is four times higher than the undoped sensor, which can be obtained for 1000 ppm methanol. M. D’Arienzo et al. carried out a one-pot synthesis of SnO$_2$ and Pt–doped SnO$_2$ inverted opal thin films, which can be used for gas sensing [77]. The electrical sensitivity values under an atmosphere of CO/Air showed that the response of pure SnO$_2$ films is lower than Pt-doped films; also, the response of the sol–gel films is lower than inverted opal films. P. Ivanov used a valuable, thick-film technique to manufacture robust, small, and sensitive semiconductor metal oxide sensors to reveal traces of ethanol vapors in the air [78]. The alteration in resistance of the Pt-doped sensors is from two to fifty-times larger than the alteration in the mercantile sensor. The material of Pt-doped SnO$_2$ is more sensitive, less resistant, and has a faster response to ethanol than that of pure SnO$_2$.

K. Y. Dong et al. fabricated nanofibers oxide gas sensors considered sensing materials on micro platforms by employing the micromachining technique [79]. The results showed that the responses of 0.08 wt.% Pt doped SnO$_2$ are more significant than that of pure SnO$_2$ nanofibers to 4–20 ppm H$_2$S. X. Kou et al. prepared pure SnO$_2$ nanofibers and 1–5 mol% Co-doped SnO$_2$ nanofibers using an electrospinning technique [80]. Their results revealed that the maximum response to 100 ppm ethanol was for 3 mol.% Co-doped SnO$_2$ nanofibers, about 40.1, four times greater than pure SnO$_2$ one. Using the spin-coating method, Kou Chang et al. prepared pure SnO$_2$ thin film and several thin films of 1–10 mol% Co-doped SnO$_2$ thin [80]. The result showed that the most response properties were for the sample of 1 mol% Co-doped SnO$_2$ thin film at a temperature of 225°C, where the response was 59.04 with a response time of 7s toward 2000 ppm H$_2$gas. The improved H$_2$ gas sensing properties are due to the smaller grain size and the formation of p-n heterojunction. Y. Guan et al. used a one-step hydrothermal route to prepare pure SnO$_2$ and Zn-doped SnO$_2$ hierarchical architectures [81]. The sensor-based on S3 (Zn$_2^+/Sn^{4+}$=0.056) at the temperature of 213°C exhibited outstanding selectivity toward ethanol with a response of about 14.4 to 100 ppm, more than three times larger than the pure SnO$_2$ sensor. X. Ding prepared Zn-doped SnO$_2$ nanorods clusters for different sizes by modifying the concentration of Zn$^{2+}$ in the solution by employing a facile hydrothermal method [82]. The morphology-composition-performance is the more the doping ratio of Zn, the longer the length of nanorods, and the larger the response to methanol, which is essential for the synthesis and the design of gas sensors with excellent performance.

P. S. Kolhe deposited SnO$_2$ based thin films on glass substrates with doped ratios 1.5, 3.0, and 4.5 mol% of Ag by employing the spray pyrolysis method [83]. A critical response (~1.38) with a short recovery and response time (110 s, 46 s) towards 450 ppm H$_2$S at a temperature of 100°C can be observed for the sample with 3 mol.% Ag-doped SnO$_2$ film. X. Lian et al. have used the hydrothermal technique to manufacture pure and Ce-doped with 3, 5, and 7 wt.% SnO$_2$ nanoparticles. The outcomes have shown that the nanoparticles had formed of SnO$_2$ and Ce atoms had doped into the SnO$_2$ substrates, for 5 wt.% SnO$_2$/Ce, it has a greater specific surface area around 173.53 m$^2$/g. Significantly, the performance of the SnO$_2$/Ce sensor has enhanced contrasted to pure SnO$_2$ and showed the highest response, which is about 50.5 for 50 ppm, and good acetone selectivity at a temperature of 270°C. A. I. Khudiar and A. M. Ouﬁ doped SnO$_2$ thin films with Al thin films with concentrations of 0, 1, 3, and 5% via the RF plasma sputtering technique [84]. The results show that the increase the doping levels to 3%, the response increases; however, for a doping concentration of 5%, the response decreases. Perfect properties of hydrogen sensing were obtained, such as good selectivity, fast response time, high response, and short recovery time. These results give good evidence that the additive enhances the gas sensor’s performance. Y. Wu et al. synthesized single-crystal nanobelts of SnO$_2$ and La-SnO$_2$ (SnO$_2$:NBs, La-SnO$_2$:NBs) using thermal evaporation [85]. It found that at a concentration of 100 ppm, the single La-SnO$_2$ NB sensor had a high sensitivity of 8.76 toward ethanediol at an operating temperature of 230°C.
C. M. Hung et al. synthesized ZnO-SnO$_2$ nanofibers doped with Au crystals by electrospinning technique for improving the performance of H$_2$S gas sensing [86]. Depending on the optimal doping concentration of Au, the gas sensitivity to H$_2$S is enhanced by around 700%. X. Kou et al. reported the effect of doping of Ru on the gas sensing characteristics of SnO$_2$ nanofibers for acetone detection [87]. The outcomes exhibit that the response to 100 ppm acetone of 2 mol% Ru-doped SnO$_2$ nanofibers is 118.8, larger than that of pure SnO$_2$. L. Du et al. synthesized undoped SnO$_2$ and Ga-doped porous micro flowers (SPMs) by a facile hydrothermal technique [88]. The sensor of 3 wt.% Ga-doped SPM shows a weak detection limit of 3.0/0.1 ppm and enhanced sensitivity of 95.8/50 ppm to formaldehyde at a temperature of 230 °C, which is greater than that of the pure SPM sensor at 21.2/50 ppm. Z. Jiang et al. synthesized a set of Eu-doped and undoped SnO$_2$ nanofibers by a simple electrospinning method and subsequent calcination treatment [89]. Eu-doped SnO$_2$ nanofibers show important improved sensing properties with short response and recovery time, considerable response value, and excellent selectivity to acetone vapor. Particularly, the sensor is based on 2 mol.% Eu-doped SnO$_2$ nanofibers demonstrate the highest response (32.2 for 100 ppm), which was two times greater than the pure SnO$_2$ sensor.

Inderan et al. fabricated an ethanol gas sensor using a hydrothermal technique with an improved sensor response using Ni-doped SnO$_2$ nanorods [90]. They demonstrated that the average length and diameter of the pure SnO$_2$ are 150 nm and 25 nm, respectively, while they were 35 nm and 6 nm for the 5.0Ni:SnO$_2$ nanorods; they are four times smaller than pure SnO$_2$ nanorods. They investigated that the high response of the 5.0Ni:SnO$_2$ nanorod sensor is due to the particle’s dimensions, which leads to an increase in the charge depletion layer thickness and the existence of oxygen vacancies in the SnO$_2$ nanorods lattice elements. A comparison of the most common nanoparticle doping material summarizing its Gas Concentration and sensitivity is presented in Table (2).

**Table 2** Comparison of the most common nanoparticle doping material summarizing gas type, gas concentration, and the sensitivity

<table>
<thead>
<tr>
<th>Nanoparticle</th>
<th>Gas</th>
<th>Gas Concentration ppm</th>
<th>Sensitivity%</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>H$_2$S</td>
<td>10-31</td>
<td>22 times higher than pure</td>
<td>[71]</td>
</tr>
<tr>
<td>Fe</td>
<td>NH$_3$, CO, C$_2$H$_5$OH</td>
<td>1000</td>
<td>46,120, 84</td>
<td>[72]</td>
</tr>
<tr>
<td>Pd</td>
<td>H$_2$</td>
<td>1000</td>
<td>Highest response 253</td>
<td>[73]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>Highest response 53.0</td>
<td>[74]</td>
</tr>
<tr>
<td>In</td>
<td>NO$_2$</td>
<td>500</td>
<td>Highest response 7200</td>
<td>[75]</td>
</tr>
<tr>
<td></td>
<td>H$_2$</td>
<td>1000</td>
<td>4 times higher than pure</td>
<td>[76]</td>
</tr>
<tr>
<td>Pt</td>
<td>CO</td>
<td>580</td>
<td>One time higher than pure</td>
<td>[77]</td>
</tr>
<tr>
<td></td>
<td>Ethanol</td>
<td>1-1000</td>
<td>2.55 times higher than pure</td>
<td>[78]</td>
</tr>
<tr>
<td></td>
<td>H$_2$S</td>
<td>4-20</td>
<td>25.9-40.6 times higher than pure</td>
<td>[79]</td>
</tr>
<tr>
<td>Co</td>
<td>Ethanol</td>
<td>100</td>
<td>40.1</td>
<td>[80]</td>
</tr>
<tr>
<td>Zn</td>
<td>Ethanol</td>
<td>100</td>
<td>3.2 times higher than pure</td>
<td>[81]</td>
</tr>
<tr>
<td></td>
<td>Methanol</td>
<td>100</td>
<td>Highest response 50.8</td>
<td>[82]</td>
</tr>
<tr>
<td>Ag</td>
<td>H$_2$S</td>
<td>450</td>
<td>Highest response 1.38</td>
<td>[83]</td>
</tr>
<tr>
<td>Al</td>
<td>H$_2$</td>
<td>50-500</td>
<td>3 times higher than pure</td>
<td>[84]</td>
</tr>
<tr>
<td>La</td>
<td>Ethanol</td>
<td>100</td>
<td>Highest response 8.67</td>
<td>[85]</td>
</tr>
<tr>
<td>Au</td>
<td>H$_2$S</td>
<td>0.1-1</td>
<td>700</td>
<td>[86]</td>
</tr>
<tr>
<td>Ru</td>
<td>Acetone</td>
<td>100</td>
<td>12 times higher than pure</td>
<td>[87]</td>
</tr>
<tr>
<td>Ga</td>
<td>Formaldehyde</td>
<td>0.1-3.0</td>
<td>4.5 times higher than pure</td>
<td>[88]</td>
</tr>
<tr>
<td>Eu</td>
<td>Acetone vapor</td>
<td>100</td>
<td>2 times higher than pure</td>
<td>[89]</td>
</tr>
<tr>
<td>Ni</td>
<td>Ethanol</td>
<td>1000</td>
<td>13 times higher than pure</td>
<td>[90]</td>
</tr>
<tr>
<td>Co</td>
<td>H$_2$</td>
<td>2000</td>
<td>Highest response 59.04</td>
<td>[91]</td>
</tr>
<tr>
<td>Ce</td>
<td>Acetone</td>
<td>50</td>
<td>Highest response 50.5</td>
<td>[92]</td>
</tr>
</tbody>
</table>
6. Operating temperature effect

The operating temperature affects the sensitivity by increasing the chemical reaction speed between the components of the adsorbed oxygen and the gas molecules. At low temperatures, the sensor's response is determined by the speed of the chemical reactions, while the gas diffusion speed on the surface, at high temperatures. D. L. Kamble synthesized NO₂ gas sensor of nanocrystalline SnO₂ using different spray solution concentrations \([93]\). The prepared sensor achieved the responsibility of 556 when exposed to 40 ppm of NO₂ at an operating temperature of 150 °C with a response and recovery times of were 100-46 seconds and 48-224, respectively. Z. Ying synthesized nanowhiskers SnO₂ of mass production by evaporating Sn as powders at a temperature of 800 °C \([94]\). The SnO₂ nanowhiskers revealed that at a temperature of 300 °C, the sensitivity of ethanol gas was from 23 to 50 ppm. A. Alhadi et al. prepared SnO₂ nanoparticles by employing an inexpensive hydrothermal technique \([95]\). The pure SnO₂ nanoparticles sensor has excellent selectivity for 100 ppm ethanol at a temperature of 180 °C and the great response of about 27 s, and a weak detection of 5 ppm. In addition, it has a recovery time of about 2 s and a response time of about 4 s. The distinguish sensing characteristics of the SnO₂ sensor make it a suitable sensor for ethanol detection. G. D. Khuspe et al. synthesized SnO₂ nanostructure via an inexpensive sol-gel spin coating technique using the solvent m-cresol \([96]\). SnO₂ demonstrated the highest response (19%) of good stability, 77.90% toward 100 ppm NO₂ at an operating temperature of 200 °C. The recovery and response times (20 min and 7 sec) were also observed with the same operating parameters. Y. Shen formed SnO₂ nanowires on oxidized Si substrates by the thermal evaporation technique of Sn grains at 900 °C \([73]\). The sensitivity increased as the H₂ concentration increased, and the highest sensitivity (118) was observed for a 2wt.% Pt-doped SnO₂ sample when exposed to 1000 ppm H₂ at 100 °C.

Table 3 Comparison of the most common nanoparticle doping material summarizing its gas concentration, sensitivity, and temperature

<table>
<thead>
<tr>
<th>Doping material</th>
<th>Gas</th>
<th>Gas Concentration ppm</th>
<th>Sensitivity%</th>
<th>Temperature°C</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>NO₂</td>
<td>40</td>
<td>Highest response at 556</td>
<td>150</td>
<td>[93]</td>
</tr>
<tr>
<td>-</td>
<td>Ethanol</td>
<td>50</td>
<td>Highest response at 23</td>
<td>300</td>
<td>[94]</td>
</tr>
<tr>
<td>-</td>
<td>Ethanol</td>
<td>100</td>
<td>Highest response at 27</td>
<td>180</td>
<td>[95]</td>
</tr>
<tr>
<td>Pd</td>
<td>LPG</td>
<td>5000</td>
<td>72%</td>
<td>350</td>
<td>[97]</td>
</tr>
<tr>
<td>Cu</td>
<td>H₂S</td>
<td>10</td>
<td>Highest response at 2500</td>
<td>100</td>
<td>[98]</td>
</tr>
<tr>
<td></td>
<td>H₂S</td>
<td>100</td>
<td>1 time higher than pure</td>
<td>180</td>
<td>[99]</td>
</tr>
<tr>
<td>In</td>
<td>H₂</td>
<td>500-3000</td>
<td>7%</td>
<td>200</td>
<td>[100]</td>
</tr>
<tr>
<td>Co</td>
<td>H₂</td>
<td>100</td>
<td>Highest response at 24</td>
<td>330</td>
<td>[101]</td>
</tr>
<tr>
<td>-</td>
<td>NO₂</td>
<td>100</td>
<td>19%</td>
<td>200</td>
<td>[102]</td>
</tr>
<tr>
<td>Pt</td>
<td>H₂</td>
<td>1000</td>
<td>118</td>
<td>100</td>
<td>[103]</td>
</tr>
</tbody>
</table>

J. K. Srivastava analyzed the sensitivity, response, recovery time, and sensing mechanism of Pd-doped thick SnO₂ film for LPG detection \([97]\). The sensor doped with 1% palladium revealed the highest sensitivity of 72% at an operating temperature of 350 °C for 0.5% LPG concentration. C. M. Ghimbeu presented the possibility of electrostatic sprayed SnO₂ and SnO₂ doped with Cu films for NO₂, SO₂, and H₂S detection \([98]\). The doping significantly improves the sensing properties of SnO₂ films. Cu-doped SnO₂ films had a higher response against low H₂S concentrations (10ppm) at temperatures of 100°C. S. Zhang fabricated undoped and Cu-doped SnO₂ thin films with extensive specific surface areas via a self-assembled soft template combined with simple physical co-sputtering deposition \([99]\). The sensitivity of the undoped SnO₂ sensor is lesser than the Cu-doped SnO₂ porous sensor, with a recovery time ~ 42.4 sec and a response time ~10.1sec to 100 ppm of H₂S at a temperature of 180 °C. A. Salehi used Indium doping to improve the SnO₂ gas sensor selectivity \([100]\). Both Indium-doped and undoped SnO₂ gas sensors were manufactured with various deposition methods. At various temperatures, ranging from 50 °C to 300 °C. The sensitivity change was measured for the sensors induced by selective gases of the hydrogen and wood smoke at concentrations ranging from 500 to 3000 ppm. The peaks of sensitivity of the samples show several values for selective gases with a response time of approximately 0.5 sec. L. Liu synthesized Pure and Co-doped SnO₂ nanofibers using an electrospinning technique \([101]\). Co-doped SnO₂...
nanofibers reveal enhancing H$_2$ sensing characteristics. From the samples for pure and Co-doped SnO$_2$ nanofibers, it was found that 1 wt.% of Co-doped SnO$_2$ nanofibers exhibit the greatest response with a fast recovery and response times. When the sensor was exposed to 100 ppm H$_2$ at 330 °C, the recovery time was 3 sec, and the response time was 2 sec, while the response was up to 24. A comparison of the most common nanoparticle doping material summarizing its Gas concentration, sensitivity, and temperature is presented in Table (3).

7. Conclusion

This paper reviews the effect of metal oxide doping, nanoparticles, and operating temperature on SnO$_2$ gas sensing characteristics towards numerous gases. Metal oxide catalyst increases the thin film’s surface area, indicating that it can be used as a gas sensor. Doped/coated SnO$_2$ containing nanoclusters of various catalysts, such as In$_2$O$_3$, WO$_3$, Cu, O, NiO and TeO$_2$, enhances the sensor response and recovery time and its sensitivity to a variety of gases. Doping SnO$_2$ with various semiconductors results in porous nanostructures that increase gas sensing features and shorten the response time and recovery time. The initial factor influencing particle dimensions (crystallite size and grain size), hence the thickness of the charge depletion layer and the presence of oxygen vacancies in the sensor lattice components, is doping with nanoparticles. Doping with nanoparticles at low temperatures improves the sensor’s specific characteristics and response. The particle accumulation is responsible for lowering sensor response and stabilizing the particle size range. According to the reviews, Tin oxide is commonly employed in gas sensor applications due to its high sensitivity to reducing and oxidizing gases.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this document.

References

Table planar study their Particle Size at Different Current.


