Nanostructured Tin Oxide Films: Physical Synthesis, Characterization, and Gas Sensing Properties

*S. M. Ingole^a, S. T. Navale^b, Y. H. Navale^a, D. K. Bandgar^a, F. J. Stadler^b, R. S. Mane^e,
N. S. Ramgir^c, S. K. Gupta^c, D. K. Aswal^d, V.B. Patil^{a*}*

*^aFunctional Materials Research Laboratory, School of Physical Sciences, Solapur University,
Solapur-413255, (MS) India (*Email. drvbpatil@gmail.com)*

*^bCollege of Materials Science and Engineering, Shenzhen Key Laboratory of Polymer Science
and Technology, Shenzhen University, Shenzhen 518060, P. R. China*

^cTechnical Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai, India.

^dNational Physical Laboratory, New Delhi, India.

^eSchool of Physical Sciences, SRTM University, Nanded, (MS), India.

Abstract

Nanostructured tin oxide (SnO₂) films are synthesized using physical method i.e. thermal evaporation and are further characterized with X-ray diffraction, X-ray photoelectron spectroscopy, scanning electron microscopy, transmission electron microscopy, and atomic force microscopy measurement techniques for confirming its structure and morphology. The chemiresistive properties of SnO₂ films are studied towards different oxidizing and reducing gases where these films have demonstrated considerable selectivity towards oxidizing nitrogen dioxide (NO₂) gas with a maximum response of 403% to 100 ppm @200° C, and fast response and recovery times of 4 s and 210 s, respectively, than other test gases. In addition, SnO₂ films are enabling to detect as low as 1 ppm NO₂ gas concentration @200° C with 23% response enhancement. Chemiresistive performances of SnO₂ films are carried out in the range of 1-100 ppm and reported. Finally, plausible adsorption and desorption reaction mechanism of NO₂ gas molecules with SnO₂ film surface has been thoroughly discussed by means of an impedance spectroscopy analysis.

Keywords: Thermal evaporation; Tin oxide, Structure and morphology; NO₂ sensor; Impedance spectroscopy.

1. Introduction

Field of gas sensors is increasing extensively in which the use of metal oxide semiconductors is unavoidable [1-3]. These gas sensors have undergone through various developments as they demonstrate an inadequate sensing performance in terms of selectivity, sensitivity, stability, response time, and cost [1-4]. Sensors based on metal oxide usually reveal high response at working temperatures above 300° C [4-6]. Basically, an ideal sensor material must be responsive at lower operating temperatures and should have high selectivity towards target gas. The process of gas sensing mainly includes three steps; first one is the dynamic process of adsorption and/or reactions of gases on the sensor surface, second one is the accumulation or depletion process of surface charges by the adsorbents, and third is the change of electrical resistance of the sensing material which is an indicator of the gas sensing activity [7]. The density of adsorbents depends on the surface temperature [8]. Solid state gas sensors are extensively useful in detecting toxic, harmful, and combustible gases of various concentrations [9–11], which are classified according to their sensing mechanism types such as semiconductor gas sensors, solid electrolyte gas sensors, and catalytic combustion gas sensors etc. [12]. Out of these sensors, metal oxide semiconductor-based gas sensors have broadly been used in numerous applications such as domestic security and safety, environmental monitoring, health care, defense, food industry, and medical [13-15]. Metal oxides like titanium oxide, tin oxide (SnO_2), zinc oxide, tungsten oxide, indium oxide, and copper oxide have extensively been envisaged in gas sensing application [16–18]. Among the variety of metal oxides, SnO_2 is one of the most popular materials so far envisaged in gas sensing application owing to its high crystallinity, tunable morphology, and chemical/thermal stability. So far, SnO_2 -based gas sensors are being employed for sensing of different gas species such as nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), ethanol ($\text{C}_2\text{H}_5\text{OH}$), carbon monoxide (CO), and methanol (CH_3OH) [19- 23]. Out of these gases, NO_2 is highly reactive oxidant, toxic, and corrosive gas can be produced from the combustion of engine and thermal power station sources. The NO_2 gas causes respiratory system and an impairing in the lung function with long-term exposure [24, 25]. Therefore, it is a need to develop a highly sensitive gas sensor for easily detecting NO_2 gas at it's an early stage.

As far as synthesis of SnO_2 concern, several physical and chemical methods such as hydrothermal [26], sol–gel [27], ultrasonic spray pyrolysis [28], chemical vapor deposition [29], pulsed laser deposition [30], sputtering [31], and thermal evaporation etc., have been used in

literature [32, 33]. Thermal evaporation (efficient and cost-effective physical synthesis route) is simple, flexible, and effective in producing nanoparticles (NPs) of various dimensions. As per the literature survey, it is inferred that little efforts have been attempted in preparing SnO₂ NPs by thermal evaporation method. There are few reports where semiconducting metal oxide thin films of pure and modified SnO₂ with suitable catalysts are used for the detection of NO₂ gas. The reported operating temperatures and detection limits of NO₂ are quite high [34–45].

In the present work, we report on the synthesis of SnO₂ films by thermal evaporation method without the use of any catalyst, which when used in sensor application reveals an enhanced response to NO₂. An improved rate of adsorption and desorption of target gas on the sensor surface is evidenced. The *as-synthesized* SnO₂ films are characterized by X-ray powder diffraction (XRD), X-ray photoelectron spectroscopy (XPS), scanning electron microscope (SEM), energy dispersive X-ray analysis (EDAX), atomic force microscopy (AFM), transmission electron microscopy (TEM), and contact angle (CA) measurement techniques. The responses of SnO₂ film towards NO₂, Cl₂, H₂S, CH₃OH, and NH₃ gases were tested for different operating temperatures and reported herein. The gas sensing parameters, of SnO₂ film with other gases, such as gas selectivity, response, reproducibility, and stability are systematically studied and reported. An interaction of NO₂ gas molecules with SnO₂ NPs film surface is explained on the basis of impedance spectroscopy results.

2. Experimental details

The SnO₂ films, composed of NPs, were prepared by high vacuum thermal coating unit (IHVU) onto the glass substrates. For synthesis of SnO₂ films, highly pure Sn powder (99.99% Aldrich) was used as source material, which poured in molybdenum boat and placed in a vacuum chamber connected to a high voltage power supply. The pre-cleaned glass substrate was fixed to substrate holder displayed in schematic diagram of thermal evaporation in Fig. 1. The pressure maintained inside the chamber was 10⁻⁵/10⁻⁶ mbar and the current was allowed to increase to evaporate Sn-powder. The distance between source and substrate was kept 15 cm. Finally, the deposited film was annealed at 700° C for 20 min in presence of ambient air in the zone furnace.

The crystalline structure and morphology of SnO₂ film was examined by X-ray diffractometer (XRD, Rigaku, Ultima IV, Cu K α /40 kV/40 mA, λ = 1.5406 Å, scan range 10–80°), scanning electron microscopy (SEM, Model: JEOL-6300F), and transmission electron microscopy (TEM, Model: FEI TECNAI G2 S-TWIN instruments). Elemental analysis was

carried out using X-ray photoelectron spectroscopy (XPS, VG, Multilab 2000). The 2D and 3D atomic force microscopy (AFM) images of SnO₂ films were obtained to investigate the surface roughness. The surface wetting test was performed with Rame-Hart USA water contact angle measurement unit equipment with CCD camera. Wayne Kerr precision impedance analyzer (model: 6500 B) in the frequency range of 20 Hz-10 MHz was used for impedance measurement. Gas sensing tests were performed on in-house fabricated high temperature gas sensing measurement unit [46]. The gas response of SnO₂ film is evaluated by following relation:

$$Response (S\%) = \frac{|R_{air} - R_{gas}|}{R_{air}} \times 100 \quad (1)$$

where R_{air} and R_{gas} are the resistances of sensor in presence of air and NO₂ gas, respectively.

3. Results and discussion

3.1 Structural analysis

The XRD pattern of SnO₂ film, grown at 700° C (Fig. 2(a)), shows the number of well-defined diffraction peaks, which are indexed to the tetragonal rutile structure of SnO₂ [JCPDS file no. 41-1445]. No other peaks of impurities are detected in XRD pattern suggesting the high purity of the *as*-deposited SnO₂ product. The comparison of standard and observed 2 θ , interplanar spacing (*d*), and intensity (*I*/*I*_{max}) values with respect to their *hkl* planes of SnO₂ are given in Table 1, suggesting obtained '*d*' values are in good agreement with standard '*d*' values. The lattice parameters are obtained from following relation;

$$\frac{1}{d^2} = \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2} \quad (2)$$

The calculated lattice parameters, $a = b = 4.73$ and $c = 3.18$ Å, of tetragonal SnO₂ are in good agreement with the JCPDS file no. 41-1445. The average crystallite size, calculate along (110) plane using Scherrer relation, is found to be ≈ 30 nm. The various structural parameters, shown in Table 2, like *micro*-strain (ϵ), dislocation density (ρ), and stacking fault (*SF*) of prepared SnO₂ film have been calculated using $\epsilon = (\beta \cos\theta)/4$, $\rho = 1/D^2$, and $SF = (2\pi^2/45(3\tan\theta)^{1/2})$ relations [47]. The obtained ϵ and *SF* values for SnO₂ film are smaller, suggesting the presence of lattice imperfections and defects in *as*-prepared film [48]. The amount of defects in the crystal can be measured by ρ and smaller value of ρ obtained in the present study is supporting for the good crystallinity of SnO₂ film prepared using the thermal evaporation process.

3.2 Elemental analysis

The wide region XPS survey spectrum of SnO₂ is shown in Fig. 2 (b), from which peaks for Sn and O elements are clearly seen. The low resolution XPS spectrum can be used to measure the binding energy range. High resolution Sn-3d and O1s core level XPS spectrums are given in Fig. 2(c) & (d), respectively. The binding energy peaks (Fig. 2(c)) at 485.36 eV and 495.2 eV are due to the spin-orbit of Sn-3d_{5/2} and Sn-3d_{3/2}, matching strongly with previously reported values [49]. The peak centered at 529.2 eV (Fig. 2 (d)) indicates the existence of oxygen [50]. Thus, XPS analysis, in addition to XRD measurement, corroborates the formation of SnO₂.

3.3 Morphological analysis

The SEM images of *as*-synthesized SnO₂ film (Fig. 3(a)) present uniformly distributed and interconnected globules which are composed of large number of NPs. Few voids are seen between them. Such kind of morphology can be beneficial for gas sensing application as it may support for the adsorption of gas molecules on the surface of film [51]. The elemental composition present in the *as*-synthesized SnO₂ film examined by EDAX spectrum (shown in Fig.3 (b)), which confirms the presence of Sn and O elements without any other noticeable impurity. The elements present and their respective weight percentages of SnO₂ film are given in the inset of Table in Fig. 3(b). The 2D and 3D AFM micrographs of the SnO₂ film are shown in Fig. 3(c) & (d), respectively. The 2D AFM image of the film surface demonstrates the interconnected globules-type surface. Rough surface consisting of globules with a RMS roughness of 53.1 nm is evidenced from 3D AFM image. Interconnected NPs, with an average diameter of 27 nm, are confirmed from the TEM image (Fig. 4(a)) analysis. The SAED pattern (Fig. 4(c)) is supporting for the polycrystalline nature and rutile phase of *as*-synthesized SnO₂ as there are well-defined circular rings, instead of regular spots and cloudy fuzzy white background whose radii are closely matching to that of lattice spacing of XRD planes. The surface wettability test (water contact angle measurement) performed on SnO₂ film surface, which correlates with the interfacial tensions i.e. water/air, water/solid, and solid/air. The ratio among these tensions determines the contact angle ' θ ' between the water droplet and the surface of SnO₂ film. Less than 20° water contact angle specifies entirely wetting behavior i.e. surface is hydrophilic, and on the other hand if water contact angle is more than 150° signifies the surface is hydrophobic. From Fig. 4(c) it is clear that, the SnO₂ film surface is hydrophilic, as the water contact angle is

81° (less than 90°) which can be useful for building intimate contact of SnO₂ surface when applied in gas sensing application.

3.5 Gas sensing properties

3.5.1 Selectivity study

Selectivity, the ability of a sensor to respond to a certain gas in presence of other test gases, is considered as essential parameter of chemiresistive type of sensors. Therefore, for the selectivity study, initially the sensing performance of SnO₂ sensor film towards fixed 100 ppm concentration of various oxidizing (NO₂ and Cl₂) and reducing (H₂S, NH₃, and CH₃OH) gases are tested and the subsequent results are presented in Fig. 5(a). The sensor film exhibits a high response of 403% to NO₂ gas as compared to other target gases (Cl₂ = 88%, H₂S = 92%, NH₃ = 7%, and CH₃OH = 9%) @200° C, confirming the better selectivity of SnO₂ film to NO₂ gas than other gases. On exposure to oxidizing gases SnO₂ film resistance is increased and for reducing gases it is decreased, suggesting an *n*-type conduction-behavior of SnO₂. Furthermore, the selectivity coefficient (*K*) is calculated using the relation,

$$K = \frac{S_A}{S_B} \quad (4)$$

where *S_A* is the response of film to target gas (here NO₂) and *S_B* is the response of film to other gas. The calculated *K* values are displayed in Table 3. Obtained higher *K* value for a particular gas is nothing but a superior capability of sensor to distinguish the target gas from the mixture of gases [52]. In order to optimize the operating temperature of SnO₂ sensor film, the gas sensing measurements were performed at different temperatures from 100 to 300° C (Fig.5 (b)), where the SnO₂ film shows the higher response to NO₂ gas @200° C than that of other operating temperatures. Therefore, for the rest of gas sensing measurement studies 200° C operating temperature of SnO₂ film sensor is kept constant.

3.5.2 Gas sensing mechanism

The sensing mechanism of SnO₂ film, in presence of air and NO₂ gas, is shown in Fig.6 (a). When NO₂ gas molecules adsorb on the surface of SnO₂ film sensor then they interact directly with the accessible Sn sites and extract electrons from the conduction band of SnO₂ by forming NO₂⁻. The interaction between the NO₂ gas molecules and SnO₂ takes place in the following ways [54],

The decrease in the concentration of electrons within the conduction band of SnO_2 results into the increase of the sensor resistance (R_g). As a result, change in electrical resistance helps to find response of SnO_2 sensor (using equation 1). During the recovery time, these adsorbed NO_2^- species desorbs as NO gas molecules by leaving chemisorbed oxygen species behind (Eq. (5)) on the surface of SnO_2 film through the subsequent reaction:

Afterward, the chemisorbed oxygen species on the SnO_2 surface release O_2 gas according to Eq. (6 & 7). Thus, the resistance retains its original value (R_a). From Fig. 6(b) it is observed that, in presence of NO_2 gas, the resistance of SnO_2 film sensor is increases rapidly with respect to time and a flat terrain region is achieved in a few seconds, signifying the fast response to NO_2 gas. For the recovery of the sensor, on opening outlet of the chamber fresh air is allowed to pass in as a result NO_2 molecules desorbs and the sensor once again regains at its initial value of resistance. Thermally activated electron transfers reaction and hence SnO_2 shows fast recovery [55].

3.5.3 Dynamic response of SnO_2 sensor

Fig. 7(a) shows the variation of response value of SnO_2 film towards 1 and 100 ppm NO_2 @200° C, suggesting the SnO_2 film exhibits 23% response to 1 ppm and 403 % to 100 ppm of NO_2 . Fig. 7(b) shows the dynamic response curve of SnO_2 sensor film as a function of time to 1-100 ppm concentration levels of NO_2 gas @200° C, where the response values are increased with increasing NO_2 concentration. The response values, calculated using eqⁿ(1), of SnO_2 film at 1, 5, 10, 20, 40, 60, 80, and 100 ppm levels of NO_2 gas are 23, 31, 112, 176, 234, 336, 352, and 403 %, respectively. With increase in NO_2 gas concentration the response of sensor is increased which can be explained on the basis of surface area and the number of available active sites of the sensor film. At higher NO_2 gas concentration (herein 100 ppm), gas molecules cover excess surface area and there can be several reactions due to availability of more active sites on SnO_2 sensor surface. On the other hand, at low concentration (herein 1 ppm) gas molecules cover limited surface area due to which few surface reactions are possible on SnO_2 sensor surface and thereby, sensor demonstrates lower response [53].

3.5.4 Response and recovery time values

Response and recovery times are considered as key parameters for the practical sensor application. The time required for sensor to attain 90% of the maximum increase in resistance on

exposure of target gas is referred as response time and the recovery time is the time to recover 90% of the maximum resistance when sensor exposed to fresh air. The response and recovery times for SnO₂ sensor to diverse concentrations of NO₂ are calculated from the response curve (Fig. 7(b)) and are presented in Table 5. The response time values are decreased from 10 s to 4 s and recovery time value are increased from 123 s to 210 s with increase of NO₂ gas concentration from 1 to 100 ppm. The decrease in response time is attributed to the availability of vacant sites on SnO₂ sensor films for adsorption of gas. The behavior of increasing recovery time with increasing NO₂ concentration is due to gas reaction species which residual after gas interaction resulting in decrease in desorption rate [56]. The comparison report with different sensing parameters of SnO₂ sensor film, synthesized by thermal evaporation route, is tabulated in Table 4.

3.5.5 Reproducibility and stability studies

Fig. 7(c) shows that the repetitive electrical response for SnO₂ film sensor upon exposure of 100 ppm NO₂ gas. An identical response value upon repeating 100 ppm NO₂ gas concentration is confirming the superb repeatability of the SnO₂ sensor film. Fig. 7(d) shows the stability study of SnO₂ sensor film to fixed 100 ppm of NO₂ gas @200° C for a period of 60 days. Primarily, SnO₂ sensor film demonstrates the maximum response of 403% and after 30 days which drops to 251% with stability of 62%. After 30 days, the response value of SnO₂ is nearly identical. This decrease in the response of SnO₂ sensor is due to aging effect [57]. Gas sensing results reveal that the SnO₂ sensor films, prepared by thermal deposition method, are reasonably sensitive to NO₂ gas as linear variation in response between 1-100 ppm of NO₂ with very fast response and recovery times, an excellent reproducibility in response value, and long term stability, are evidenced. These properties make it as a potential candidate for the detection of NO₂ gas at its initial stage.

3.6 Impedance Spectroscopy of SnO₂ film

The impedance measurement on SnO₂ sensor film was carried out before and after exposure of NO₂ gas in the frequency range of 20 Hz to 10 MHz and the subsequent results are presented in Fig. (8). Plot of imaginary component (Z'') against the real component (Z') is a perfectly semicircle. The impedance spectrum of SnO₂ film analyzed by means of the equivalent circuit is shown in inset of Fig. 8(a) where R_o is in series with two RC networks (R_o-frequency independent resistance, C_b-bulk capacitance, R_b-bulk resistance, C_g-grain boundary capacitance,

and R_g -grain boundary resistance) [57]. The values of impedance parameters obtained from impedance spectra are tabulated in Table 5. There is very good agreement between the experimental data and simulated data (shown by solid red lines in Fig. 8(a)) is observed. On exposure to 100 ppm NO_2 gas, both C_b and C_g values are decreased while R_b and R_g are increased. The change in the values of resistance and capacitance due to the interaction of NO_2 gas is due to; SnO_2 grains contain considerable fraction of O^{2-} adsorbates at grain boundaries which catch electrons from the grains of SnO_2 and results in decreasing carrier density and conductivity. On the interaction of SnO_2 film with oxidizing NO_2 gas, adsorbed oxygen on the grain boundary of the SnO_2 film can be replaced by gaseous species, as a result due to electron withdrawing nature of NO_2 the resistance of SnO_2 film is increased. Such an increase in resistance on NO_2 exposure is mainly contributed by the grain boundaries of the SnO_2 film.

Finally, we have compared the obtained gas sensing results with some of the reports (NO_2 entirely) on semiconducting SnO_2 and SnO_2 modified with suitable catalysts and the resulting comparison is tabulated in table 3. The SnO_2 films synthesized in present study exhibits good gas sensing properties (based on the comparison in table 3), in terms of lower operating temperature, fast response/recovery times, and lower detection limit, than previous reports.

4. Conclusions

Nanostructured SnO_2 films are synthesized onto a glass substrate *via* inexpensive thermal evaporation method and their gas sensing properties were carried out towards host of gases such as NO_2 , Cl_2 , H_2S , CH_3OH , and NH_3 . The SnO_2 films found quite sensitive to NO_2 gas @200° C with a maximum response of 403% (100 ppm NO_2). Moreover, the SnO_2 film sensor detects as low as 1 ppm of NO_2 with 23% response value. Impedance spectroscopy analysis is used to study the interaction between SnO_2 film and NO_2 gas as well as to calculate the impedance parameters such as bulk and grain boundary resistance and capacitance. Based on the gas sensing results, it is concluded that the nanostructured SnO_2 sensor film demonstrates high response, excellent selectivity, lower detection limit, good reproducibility and stability to NO_2 gas @200° C.

Acknowledgements

Prof. V. B. Patil would like thank to DAE-BRNS, for financial support through the scheme no. 34/14/21/2015-BRNS and RUSA for financial support through the scheme no. RUSA/R& I / 2016-17/267. FJS would like to thank National Science Foundation of China (21574086), Nanshan District Key Lab for Biopolymers and Safety Evaluation (No. KC2014ZDZJ0001A), Shenzhen Sci & Tech research grant (ZDSYS201507141105130), and Shenzhen City Science and Technology Plan Project (JCYJ20140509172719311) for financial support

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Figure captions:

Fig. 1. Schematic of thermal evaporation process-mediated SnO₂ film formation.

Fig. 2. (a) XRD, (b) XPS survey spectra, (c) core level Sn, and (d) core level O-1s spectrums of SnO₂ film.

Fig. 3. (a) SEM, (b) EDAX, (c) 2D, and (d) 3D AFM images of SnO₂ film.

Fig. 4. (a) TEM, (b) SAED, and (c) contact angle measurement images of SnO₂ film.

Fig. 5. (a) Sensitivity study of SnO₂ film towards 100 ppm of various gases, and (b) plot of variation of response of SnO₂ sensor with respect to different temperatures.

Fig. 6 (a) Schematic of gas sensing mechanism of SnO₂ film with NO₂ gas, (b) Plot of change in electrical resistance of SnO₂ film upon the interaction of NO₂.

Fig. 7. (a) Plots of response as a function of time from 1 to 100 ppm of NO₂, (b) dynamic plot of variation of response of SnO₂ film sensor to various concentrations of NO₂, (c) response repeatability, and (d) stability study of SnO₂ sensor film @200° C.

Fig. 8. (a) Impedance spectra of SnO₂ film before and after exposure to NO₂ @200° C, (inset shows an equivalent circuit used to interpret the impedance spectroscopy data).

Table captions:

Table 1: Standard and observed 2θ , d , and $(I/I_{\max})$ values with corresponding hkl plane of SnO₂ film.

Table 2: Structural parameters of SnO₂ film.

Table 3: Selectivity coefficient (K) values of SnO₂ sensor film with NO₂ as a target gas.

Table 4: Comparison of different sensing parameters of SnO₂ sensor film.

Table 5: Impedance parameters of SnO₂ sensor film.

Table 6: Comparison of obtained gas sensing results with those of the reports (NO₂ entirely) on semiconducting SnO₂ and modified SnO₂ with suitable catalysts.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Table 1

2 θ (°)		d (Å)		$I/I_{\max}$ (%)		hkl
Standard	Observed	Standard	Observed	Standard	Observed	
26.61	26.60	3.3474	3.3488	92	100	(110)
33.89	33.85	2.6430	2.6463	88	73.08	(101)
37.94	37.98	2.3693	2.3675	27	22.24	(200)
38.96	39.00	2.3097	2.3079	5	7.98	(111)
42.63	24.77	2.1192	3.5919	1	4.01	(210)
51.78	51.87	1.7643	1.7615	100	46.58	(211)
54.65	54.7	1.6780	1.6768	26	12.25	(220)
57.81	57.82	1.5936	1.5935	12	6	(002)
61.87	61.99	1.4986	1.4960	23	9.98	(310)
64.71	64.68	1.4394	1.4401	26	9.95	(112)
65.93	65.99	1.4157	1.4147	31	11.38	(301)
71.27	71.27	1.3222	1.3223	14	5.01	(202)
78.71	78.72	1.2148	1.2147	23	6.84	(321)

Table 2

Crystallite size (nm)	Micro-strain	dislocation density (cm ⁻²)	Stacking fault
30	0.114	0.001	0.5207

Table 3

Gas	H ₂ S	Cl ₂	CH ₃ OH	NH ₃
'K' value	4.38	4.57	44.77	57.57

Table 4

Sample	Operating Temp.	Conc. of NO ₂ gas (ppm)	Response (%)	Response time (s)	Recovery time (s)
SnO ₂	200°C	1	23	10	123
		5	31	9.0	135
		10	112	8.7	144
		20	176	8.0	153
		40	234	7.6	160
		60	336	6.4	172
		80	352	5.0	180
		100	403	4.0	210

Table 5

Parameters →	R_o (k Ω)	C_b (nF)	R_b (M Ω)	C_g (nF)	R_g (M Ω)
Unexposed (In air)	7	155.8	0.16	75	166547
Exposed to 100ppm NO ₂	7	75.7	0.38	1.01	334436

Table 6

Material	Synthesis route	Catalyst/modifier	Sensing Temp. (°c)	Response value [conc.]	Response / Recovey time	Ref.
SnO ₂ thin film	Sol-gel	SnO ₂	250	40 [5 ppm]	80 s/1h	[35]
SnO ₂ nano-composite	Reverse micro emulsion	ZnO	250	34 [500 ppm]	-	[36]
SnO ₂ pellete hetrojunction	Powder mixing (ball milling)	WO ₃	300	6.5 [5 ppm]	-	[37]
SnO ₂ nanoparticles	RF sputtering	MWCNTs	300	5.35 [1.2ppm]	50 s/100 s	[38]
SnO ₂ thin film	Rheotaxial growth (Ar Gas)	WO ₃	300	40 [10 ppm]	10 min/15 min	[39]
SnO ₂ thick film	Screen printing	WO ₃ -Au	-	1 [10 ppm]	2 min/3 min	[40]
SnO ₂ thin film	Screen printing	WO ₃	200	400 [200 ppm]	-	[41]
SnO ₂ thin film	Slide of transfer printing	WO ₃	400	8 [100 ppm]	20 s/80 s	[42]
SnO ₂ nanomaterials	Chemical route	Pd	300	0.1 [200 ppm]	0.2 s /1 s	[43]
SnO ₂ thin film	sputtering	Pt	360	1 [3 ppm]	-	[44]
SnO ₂ thin film	Sputtering (Ar Gas)	Mo	270	20 [10 ppm]	-	[45]
SnO₂ nanoparticles	Thermal evaporation (air)	-	200	0.23 [1 ppm]	10 s /123 s	Present work

Graphical abstract

Nanostructured Tin Oxide Films: Physical Synthesis, Characterization, and Gas Sensing Properties

S. M. Ingole, S. T. Navale, Y. H. Navale, D. K. Bandgar, F. J. Stadler, R. S. Mane, N. S.

*Ramgir, S. K. Gupta, D. K. Aswal, V.B. Patil**