

RESEARCH PAPER

Optimizing CdO and Ga₂O₃ Thin Film Composition for Enhanced NO₂ Gas Detection

Basil S. Ahmed, Saif M. Hanfoosh, Othman Abed Fahad *, Abubaker S. Mohammed

Ministry of Education, Direction of Education in AL-Anbar, Anbar, Iraq

ARTICLE INFO

Article History:

Received 28 July 2026

Accepted 30 September 2026

Published 01 January 2027

Keywords:

Cadmium oxide

Gallium oxide

Thermal chemical analysis

Thin films

XRD

ABSTRACT

Ga₂O₃-doped CdO thin films with different Ga₂O₃ concentrations (1, 3, 5, and 7 wt %) were successfully fabricated on glass and silicon substrates using the thermal chemical decomposition technique at 300 °C. The influence of Ga₂O₃ incorporation on the structural, morphological, optical, and NO₂ gas-sensing properties of CdO thin films was systematically investigated. X-ray diffraction (XRD) analysis confirmed the formation of polycrystalline cubic CdO with a preferred (111) orientation for all deposited films. Atomic force microscopy (AFM) revealed that increasing the Ga₂O₃ concentration reduced the grain size from 105.52 to 69.07 nm, while the surface roughness and root mean square (RMS) roughness decreased from 3.32 to 0.901 nm and from 3.97 to 1.05 nm, respectively. UV-Vis spectroscopy in the wavelength range of 300–1100 nm showed enhanced optical transmittance and an increase in the direct optical band gap from 2.3 to 4.0 eV with increasing Ga₂O₃ content. Gas-sensing measurements demonstrated a significant enhancement in NO₂ sensing performance after Ga₂O₃ incorporation, with the thin films deposited on silicon substrates exhibiting higher sensitivity than those prepared on glass substrates. The improved sensing characteristics are attributed to the modified microstructure and enhanced charge transport induced by Ga₂O₃ incorporation. These results demonstrate that Ga₂O₃-doped CdO thin films are promising candidates for high-performance NO₂ gas sensor applications.

How to cite this article

Ahmed B., Hanfoosh S., Fahad O., Mohammed A. Optimizing CdO and Ga₂O₃ Thin Film Composition for Enhanced NO₂ Gas Detection. J Nanostruct, 2027; 17(1):63-74. DOI: 10.22052/JNS.2027.01.007

INTRODUCTION

Thin films are made using transducers on low-cost substrates such as metal, glass, plastics, or polymer bases [1]. The most important characteristic of thin film technologies is that they contributed to a significant reduction in the thickness of semiconductor materials because of the ability of some materials to absorb high of sunlight falling within a few microns compared with

* Corresponding Author Email: othmanabad2@gmail.com

several hundred microns needed in silicon thermal technology. In addition, these technologies have enormous potential for cost reduction, primarily by making large areas of interstitial forces compact and fully automated, and thus rapid progress has been achieved with the technologies of Photovoltaic (PV) films, whether in the laboratory or in the industry [2]. Thin films are one of the



This work is licensed under the Creative Commons Attribution 4.0 International License.

To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

most suitable means to know many of their physical and chemical properties whose properties are difficult to obtain in their natural form. The term thin films are used to describe one or many layers of material atoms that do not exceed one-micron thickness [3, 4]. Transparent Conductive Oxides (TCOs) are compounds made up of oxygen-containing metal such as CdO, In₂O₃, ZnO, and SnO₂. These substances combine two properties, characterized by high electrical conductivity and optical permeability. High (transparent) extensible the permeability spectrum is between 400 - 1500 nm depending on the conditions of the material preparation. Despite the large gap in the energy of these membranes compared to the other conductors, the conduction package is filled with free electrons (shown by the high concentration of charge carriers).

For this reason, modern research has been directed to the field of TCOs because of its technological importance [5]. The cadmium oxide of semiconductors, which has negative connections (n-types), has a high correlation resulting from the presence of cadmium atoms in compensatory sites or voids due to the oxygen atoms that it operates as a donor center in the crystalline installation with a viscous cubic structure (FCC) and has a direct energy gap of 2.3 eV and has high permeability in the visible area and therefore is classified as transparent conductivity (TCOs) [6].

MATERIALS AND METHODS

It was used the chemical cadmium chloride (CdCl₂·H₂O) purity % 99.9 is a source of ions of cadmium (Cd) for the preparation of thin films pure cadmium oxide concentration (M 0.1) as well as the preparation of the thin films Cadmium oxide doped gallium oxide has attended the addition of (Ga₂O₃), a white powder added rates (7,5,3,1)% of the total mixture of the solution to the substance of cadmium chloride after dissolved with distilled water, and thus we get the cadmium chloride solution with specific ratios of vaccination component (Ga₂O₃) and then the mixture blends well stirrer using magnetic stirring while access to a homogeneous solution, clear and colorless and does not contain suspensions. The glass and silicon bases were used for deposition thin films prepared, the glass bases were cleaned by washing them with cleaning fluid and distilled water to remove any oil stains or residue and then placed under the running water to dispose

of the cleaning fluid. The bases are then placed in a basin containing distilled water and placed in an ultrasonic device for 15min. The bases are placed in a basin with pure ethanol (96%) in an ultrasonic device for 15min after drying with one direction and placed in an oven for 15 min at 60 ° C and then the bases are ready for use. The rules of silicon by immersing in the ethanol and then placed in the Ultrasonic for 15min and dried in the same way as drying the glass bases. We sprayed the solution in batches to maintain the base temperature during the spraying process where the spraying process is for 5 sec and then stop for 10 sec with a spray rate of (1ml / min). The best vertical area between the end of the spraying device and the bases on the surface of the electric heater is (30 cm). The temperature of 300 ° C was selected in the preparation of the prepared thin films. After the deposited process, the samples were left to cool down to room temperature to complete the crystalline development process. After the deposited process, we measured the thickness of the thin films using Felt metrics F20 at Malaysian University of Science - Malaysia.

RESULTS AND DISCUSSION

X-Ray diffraction

Fig. 1 shows the results of x-ray diffraction of pure cadmium oxide thin films and doped to gallium oxide and applied to glass bases. The results showed that all prepared thin films are polycrystalline and have a cubic structure. When the film is pure, it has several levels (220), (200), (111) at (2θ=55.87, 38.96, 33.34) ° preferred orientation (111) of the cadmium oxide and found that all peaks are return to cadmium oxide and this is consistent with the findings of Azhar [7]. when the doping we notice the emergence of a new peak of cadmium oxide at 2θ=66.6 and in the direction (311) with the survival of other peaks and the survival of the preferred direction (111) for cadmium oxide, we also notice a decrease in the intensity of the peaks with very little displacement towards the larger angles, When the rate of doping is increased to 3%, we observe a new peak at 2θ=24.59° and in the direction of (110).

This is Return to Ga₂O₃ we also note a decrease in the intensity of the other intensity of peaks of cadmium oxide with preferred trend survival (111), and then Increasing the ratio of doping to 5% we note There was no change in the crystalline structure compared with the rate of doping at

least and found that there is a slight change in the corners of the peaks of diffraction with the low intensity of all peaks and the survival of the preferred direction of cadmium oxide, and When the rate of doping is increased to 7% we notice the emergence of a new peak of (Ga₂O₃) in direction (222) at $2\theta=40.6^\circ$ with the remaining peaks of the other diffraction (CdO) and gallium oxide (Ga₂O₃) and the survival of the preferred direction (111) for cadmium oxide. The study showed a decrease in the height of the diffraction peaks of all the prepared thin films when the ratio of doping was increased and there was a very slight change in the angles of the diffraction towards the angles of the largest divergence and the doped did not change the preferred direction of cadmium oxide before and after the doping. This is consistent with the researcher Kesavan [8]. These results were compared with the standard cards (JCPDS) according to card number (6690-900-96). The decrease in the intensities of diffraction peaks

after increasing the ratio of doping it is due to the saturation of new nuclei formed material grafting to become random materials on the surfaces of the films and cause high intensity diffraction peaks at the doping rates of less than 7% due to the tendency Crystallization to the formation of centers intend (formation nuclei) new because of the entry of atoms of material grafting into the crystal structure of the reticule resulting from a decrease in the energy barrier nuclei. [9] we account rate particleboard size of all films prepared using the Scherer equation [10].

$$D = (K\lambda / w \cos \theta) \quad (1)$$

When: W= (FWHM (Full Width Half Maximum), D= is the mean size of the ordered (crystalline) domains, K= (Shape factor) = 0.94, θ = Bragg angle

It is found that the grain size of CdO is reduced when the increases doped by gallium oxide and In this way, it is likely that nanoparticles are

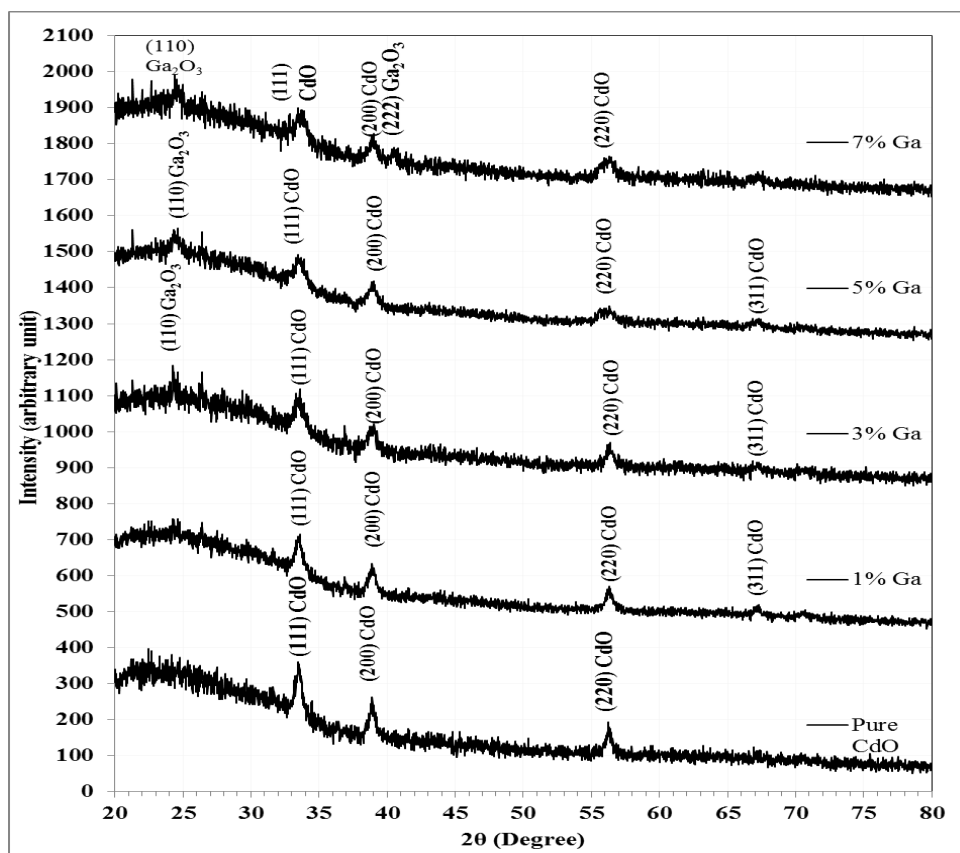


Fig. 1. X-ray diffraction of -cadmium oxide thin films doped gallium oxide with different ratios (1, 3, 5, 7) and deposited on glass substrate.

present in the preparation of the prepared films, the doping has replaced the Cd atoms, replaced with Ga atoms and merged into the crystalline structure of the film and result reduced on grain size. Table 1 show increases the width of the curve at the middle of the great end (FWHM) when increasing the doping rates. This indicates that the composition is in the direction of nano and this is consistent with the researcher Deokate and his group [11].

Atomic Force Microscopic

Fig. 2 shows three-dimensional images of the Atomic Force Microscope (AFM) showing the surface topography of CdO pure and doped Ga₂O₃ thin films was deposited on glass substrate, with different ratios (1, 3, 5, 7) % prepared by chemical spray pyrolysis method (300°C) The graph

of the distribution of granular aggregates formed on the surface of the films (CdO, CdO: Ga₂O₃) Which has been deposited. It was found that the average diameter of the distribution of granular aggregates on the surface of the CdO (105.42 nm) was determined by analytical images that the roughness average was equal to (3.32 nm) for the cadmium oxide film and RMS for cadmium oxide (3.97nm), which represents the square of surface elevations and decreases divided by the total number of their numbers and increasing this value increases the average roughness of the film and vice versa [12]. Table 2 shows the parameters of the atomic force microscope of average diameter, roughness and root mean square. The table shows that the average diameter of the (CdO, CdO:Ga₂O₃, decreases when the gallium doping increasing about (69.07 nm), At the highest rate doping of

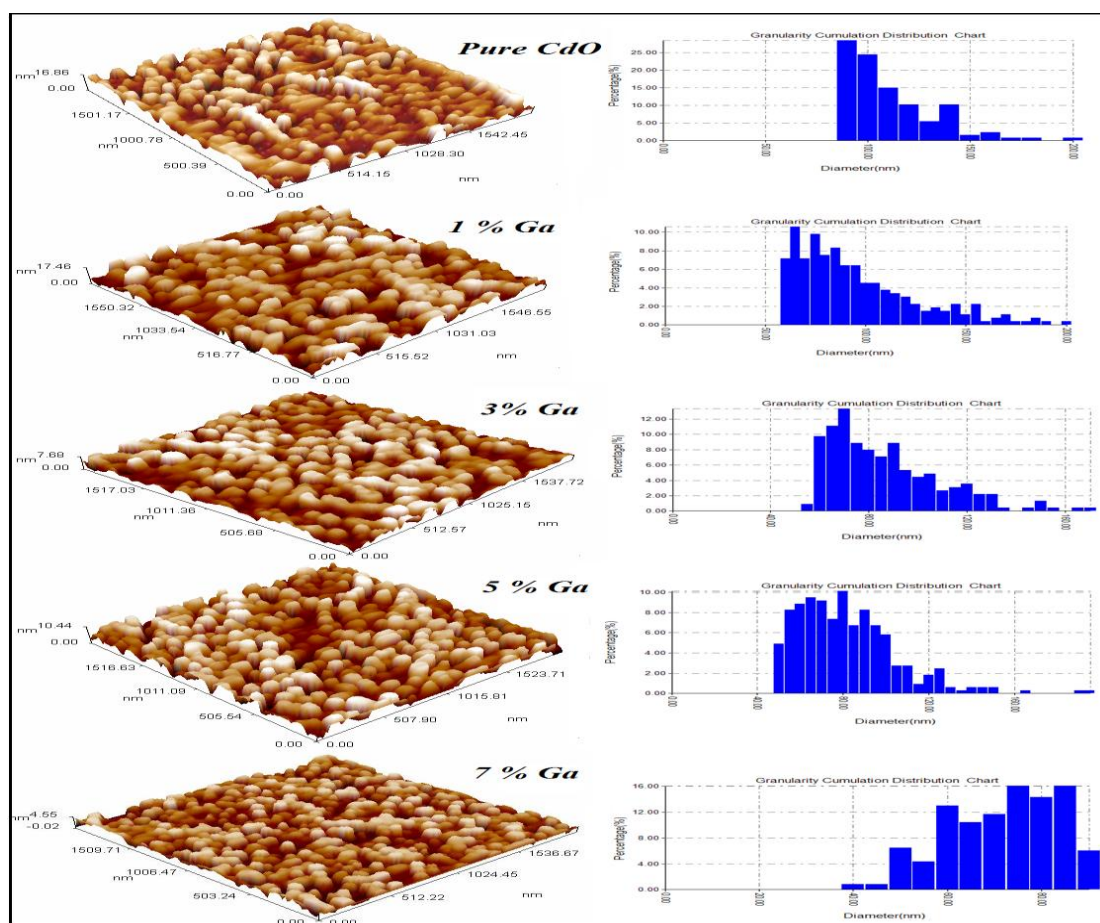


Fig. 2. 3D AFM images and a graph of the distribution of granular aggregates grown on the surface of pure CdO and doped (CdO: Ga₂O₃) thin films with different ratios (1, 3, 5, 7) %.

7% due to the development of crystalline grains of grain perpendicular to the surface and this is consistent with researcher Yahia [13]. This is evidenced by the increase in crystalline growth due to the increase in the concentration of gallium oxide in the solution and the decrease in the ratio of cadmium oxide where the images show that the atoms of the film have been distributed on all parts of the surface so this membrane is topographically regular. Also, the root mean square of the (CdO:Ga₂O₃) thin films was decreases when the gallium doping incentives compared to the cadmium oxide pure film to reach (1.05 nm). This is consistent with Ramiz [14]. The table shows that there is a decrease in the average roughness surface of (CdO:Ga₂O₃) film compared with CdO pure to reach (0.901 nm) at the highest rate of concentration indicating that the deposited atoms on the surface of the membrane have crystallized Nanoparticles [15].

Optical properties

We studied the optical properties of the thin films prepared by measuring the absorbance spectroscopy as a function of the wavelength of the photons falling in the confined area between (300-1100) nm. The optical power gap (E_g), Transmittance (T), absorbance (A) and absorption coefficient A). The Transmittance (T) of films (CdO, CdO:Ga₂O₃) was calculated using the following relationship [16].

$$T = I_t / I_o \quad (2)$$

I_t : Radiation intensity passing, I_o : Radiation intensity on the surface.

The relation between the Transmittance (T) and the wavelength (λ) was plotted as in Fig. 3. It was observed that the Transmittance of the pure cadmium oxide (35.45%) and transmittance increases when the gallium doping increasing

Table 1. Atomic Force Microscopy (AFM) for pure CdO and doped (CdO:Ga₂O₃) with different ratios.

Ga ₂ O ₃ %	Ave. diameter (nm)	Roughness average (nm)	Root mean square (nm)
0	105.42	3.32	3.97
1	92.66	3.23	3.86
3	83.82	1.52	1.81
5	79.11	2.13	2.53
7	69.07	0.901	1.05

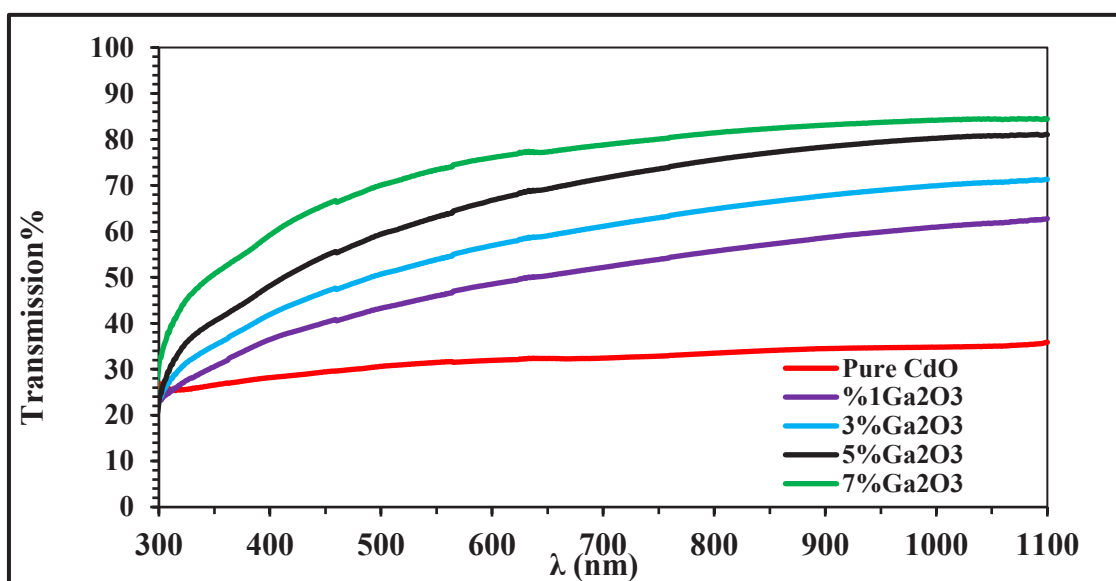


Fig. 3. the permeability spectrum of (CdO, CdO: Ga₂O₃) thin films.

to 84.4% at the highest doping rate (7%), this is consistent with the researcher [7, 11]. The difference in transmittance values may be due to the thickness factor, The transmittance is inversely proportional to the thickness of the films, since the higher thickness allows greater chance for different optical absorption processes in the film and thus attenuation of a larger part of the beam falling on the film, as well as the presence of surface defects and the high roughness of the surface cause increased dispersion of falling radiation [17]. The optical absorption coefficient (α) of the pure CdO and the CdO: Ga₂O₃ thin films were measured with different concentrations [16].

It was found to be more valuable than (10^4 cm^{-1}) and thus the films have a direct energy gap. The correlation between the absorption coefficients was drawn of $\text{cm}^{-1}(\alpha)$ as a function of the wavelength as shown in Fig. 4 Within the restricted spectral range (300 - 1100) nm is observed from the figure the absorption coefficient decreases when the gallium doping increasing, the optical absorption edge is oriented towards the wavelengths while the wavelength gain is observed within the range of (300-1100) nm. This is due to the increase of spectral transmittance within this spectral range and the absorption coefficient is reduced at the high wavelengths of almost all the films, That

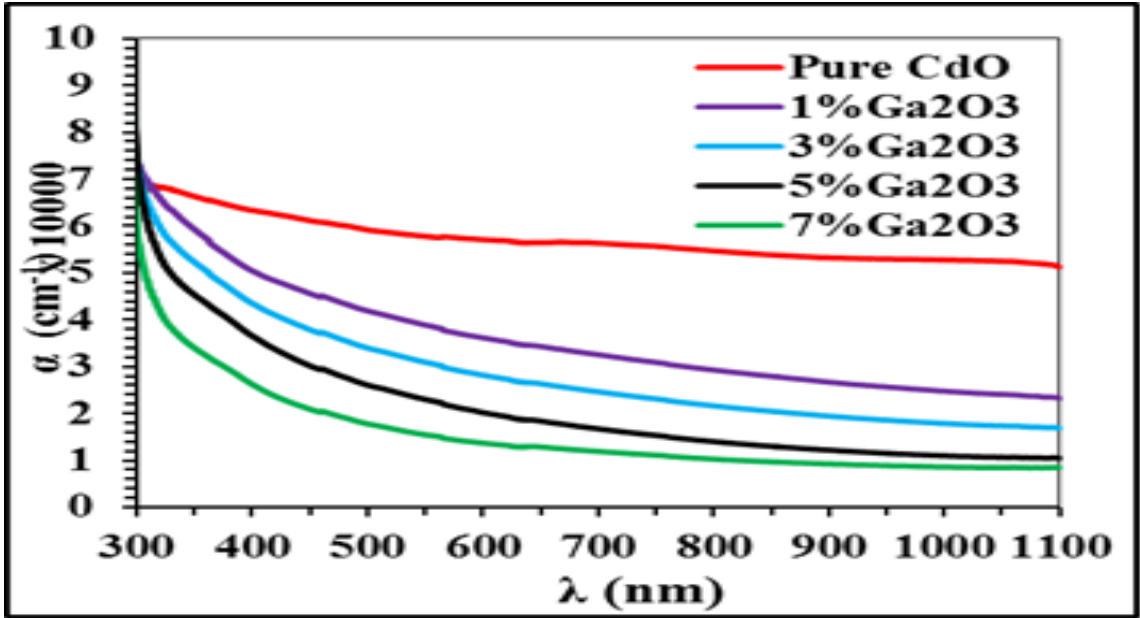


Fig. 4. Optical absorption coefficient of (CdO, CdO: Ga₂O₃) thin films.

Table 2. shows the values of the optical energy gap and the Transmittance and optical absorption coefficient of the (CdO, CdO:Ga₂O₃) thin films at 500 nm wavelength with different doping ratios.

Ga ₂ O ₃ %	T%	$\alpha \text{ (cm}^{-1}\text{)}$	Eg (eV)
0	30.58	59233	2.30
1	43.22	41938	3.10
3	50.65	34015	3.60
5	59.34	26093	3.70
7	70.01	17825	4.00

mean the probability of electronic transitions is low within this spectral region But its value is Increased at the edge of absorption and depends on the composition of the film and its components and this is consistent with researcher Kumaravel [18, 19].

The optical energy gap was determined by drawing the photonic relationship between the photon energy ($h\nu$) and $(\alpha h\nu)^2$. Fig. 5 shows the optical energy gap values of pure CdO and CdO:Ga₂O₃ with a with different ratios 1, 3, 5, 7 %, It was found that the values of the energy gap that increases with the increase in gallium oxide concentration.

This is consistent with the previous study [11, 20] where the value of E_g equals (2.3 eV) for pure cadmium oxide thin films and the value of (E_g) equals 4 eV for CdO: Ga₂O₃ thin films at the highest ratio concentration (7%). This is due to increased material crystallization and reduction of defects, thus reducing the local levels near the edge of the valance and conduction band, which led to an increase in the energy gap, and thus we conclude

that the optical energy gap can be controlled by controlling the added impurities.

Fig. 6 shows the relationship between the optical energy gap and the grain size of the pure cadmium oxide and doped with the gallium oxide thin films, where the optical energy gap is found to increase when the grain size decrease of the prepared thin films.

sensitivity measurements

This section includes an analytical presentation of allergy characteristics including measures of sensitivity change with doped rates as well as temperature, response time and recovery time for pure cadmium oxide doped with gallium oxide thin films in percentages (1,7)%, prepared by chemical spray pyrolysis technique and deposited on silicon substrate (CdO, CdO:Ga₂O₃/ Si).). Fig. 7 shows the change in resistance as a function of time at temperatures of (100, 200 and 300) °C for pure CdO and CdO: Ga₂O₃ thin films with adopting rate of (1.7%) using to nitrogen dioxide gas (NO₂) with concentration ratio of 3%.

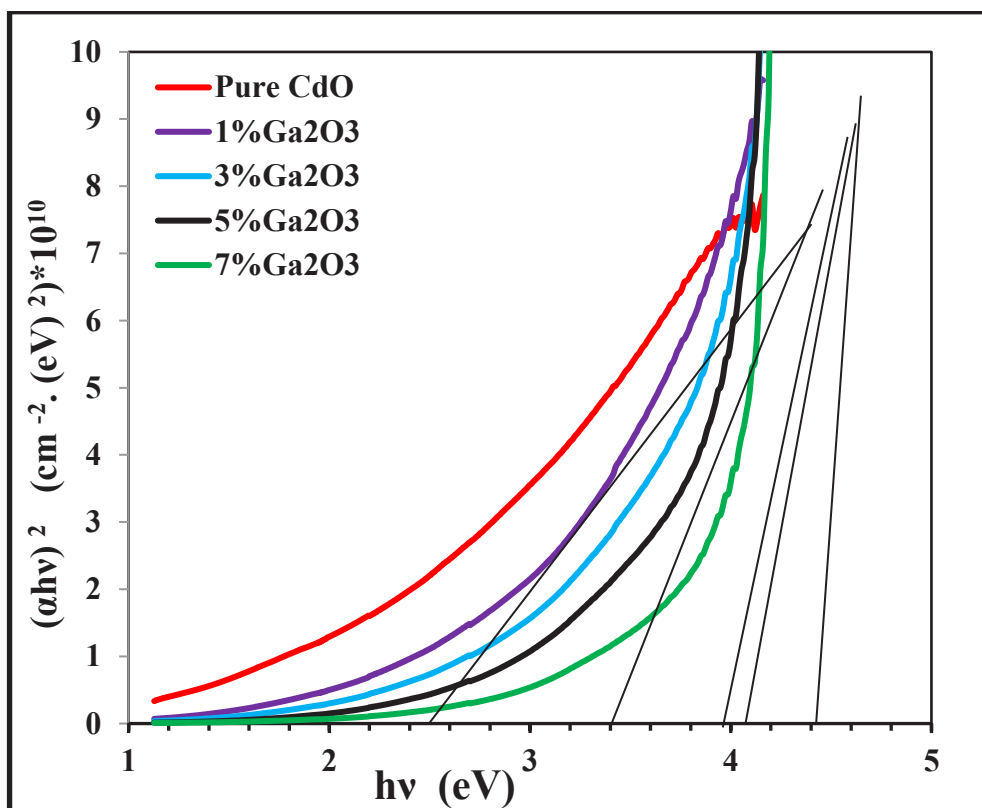
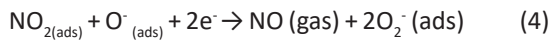


Fig. 5. Optical energy gap values for CdO and CdO:Ga₂O₃ thin films with different doping rates.

The resistance of the CdO and CdO: Ga₂O₃ thin films increased when the film was exposed to gas and after the resistance returned to the first level before the NO₂ reaction. This was the result of NO₂ reaction with the surface of CdO [21]. As well as the result of the integration of gallium atoms in the CdO film, which give the levels of scalable and thus snaps electrons from the conduction band and the interaction of NO₂ gas with the sensor gets oxidized and thus increase the resistance of the film because NO₂ gas snake's electrons from oxygen O₂⁻ As follows [22]:



Sensitivity values were calculated according to the following equation [23]:

$$S = |(R_g - R_a) / R_a| \times 100\% \quad (5)$$

R_g: The electrical resistance of sensing film with the gas.

R_a: The electrical resistance of the film to the sensor in the air.

Fig. 8 shows the sensitivity change as a function

of the doping rates for pure CdO and CdO:Ga₂O₃ thin films at a rate of (1.7)% at (100,200,300) ° C, It was found that the sensitivity of the pure films at the temperature of 100°C is (12.5%) and that this value increases with increasing the temperature up to (22.2%) at the temperature of 200°C and when the temperature increase to 300°C, The sensitivity of the surface of the metal oxide is increased due to the interaction between the oxygen and the surface. In the case of vaccination with the lowest ratio of 1%, it is found that the sensitivity is greater than in the pure membranes. At the temperature of C100, the sensitivity value is 13.3% , When the temperature increases, the sensitivity increases to 27.3% at C200 and increases when the temperature rises to reach the highest sensitivity value of membranes prepared on silicone bases (40%) at C300 ° C and the reason for increased susceptibility to vaccination with this behavior can be explained by the fact that vaccination in general gives a larger surface area of the grafted membranes and more porous ,As well as different interaction between gas and the vaccination particles , So all these processes increase the interaction of gas with the oxide, which increases the value of sensitivity and this is consistent with what the researcher found Shaath [24], and when

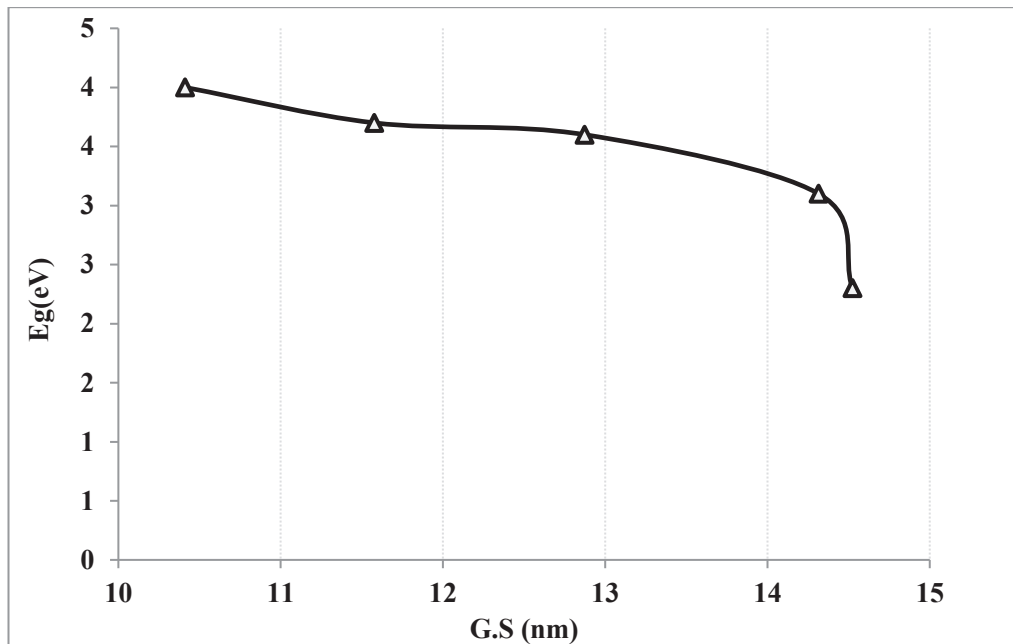


Fig. 6. The energy gap as a function of grain size of (CdO, CdO:Ga₂O₃) thin films.

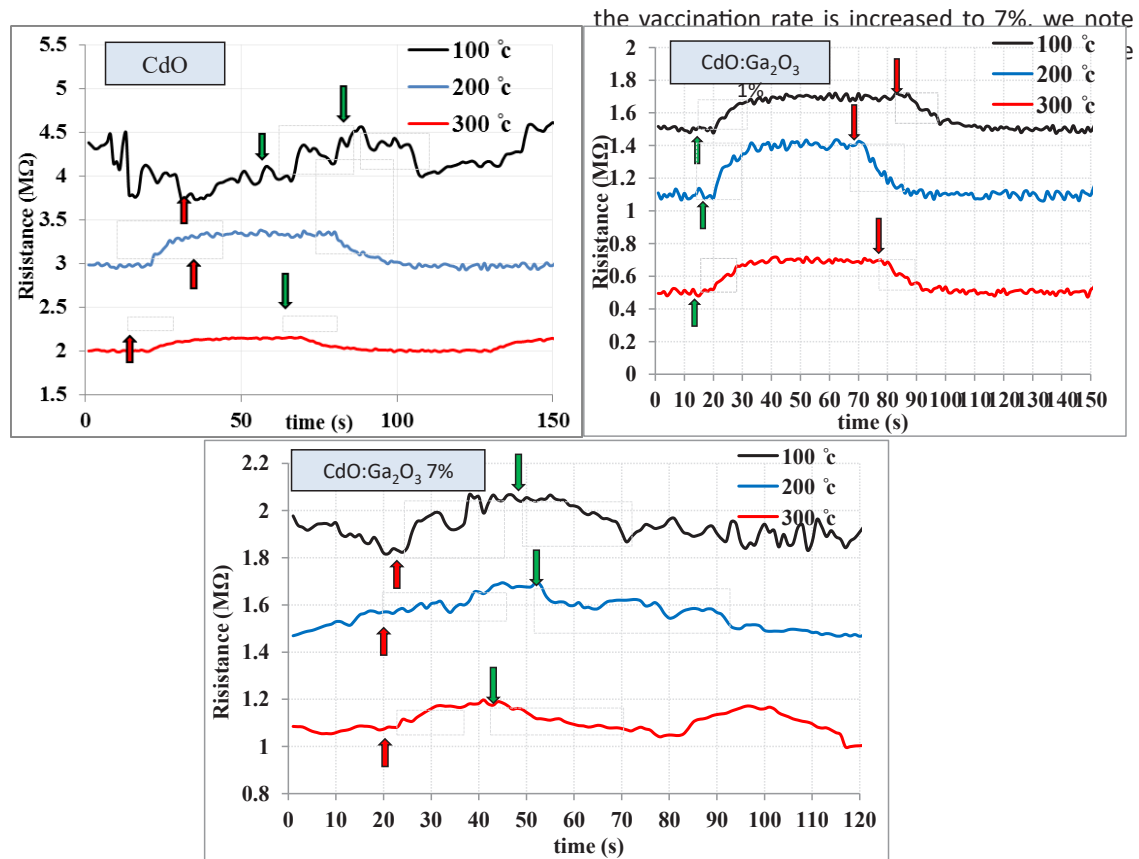


Fig. 7. Change in the resistance with time for pure CdO film and doped CdO: Ga₂O₃ at concentration (1.7) % and deposited on silicon substrate at (100, 200, 300) °C.

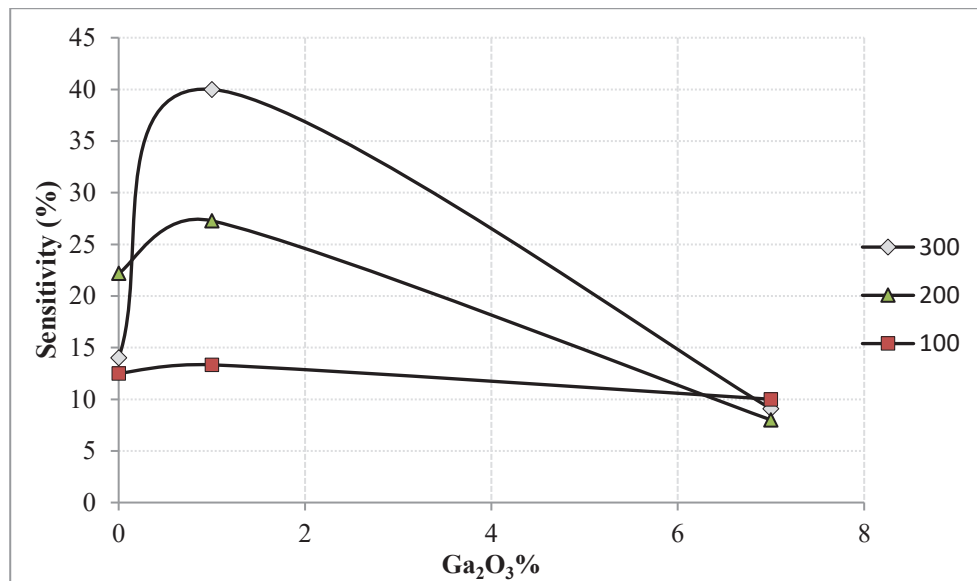


Fig. 8. Sensitivity changes as a function of the percentage of pure CdO and gallium oxide adsorbed at (1.7%) at temperatures (100, 200, 300) using NO₂.

in the membranes with 1% pure membranes and also decrease in temperature. The reason may be due to the inclusion of this sample on a large amount of impurities so we note the lack of stability, The reason may be that the surface will

not be able to oxidize the gas too intensely and NO₂ may be burned before reaching the surface of the membrane and thus the sensitivity decreases with increasing temperature [25].

We also calculated response time and latency

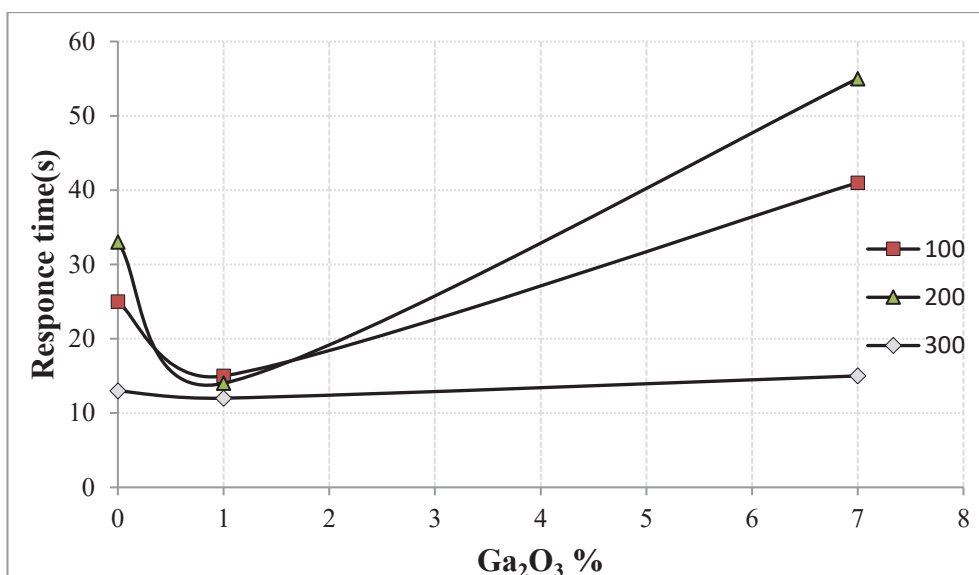


Fig. 9. Response time with vaccination ratios for pure CdO membranes and gallium oxide (1.7%) was changed from (100,200,300) °C to NO₂.

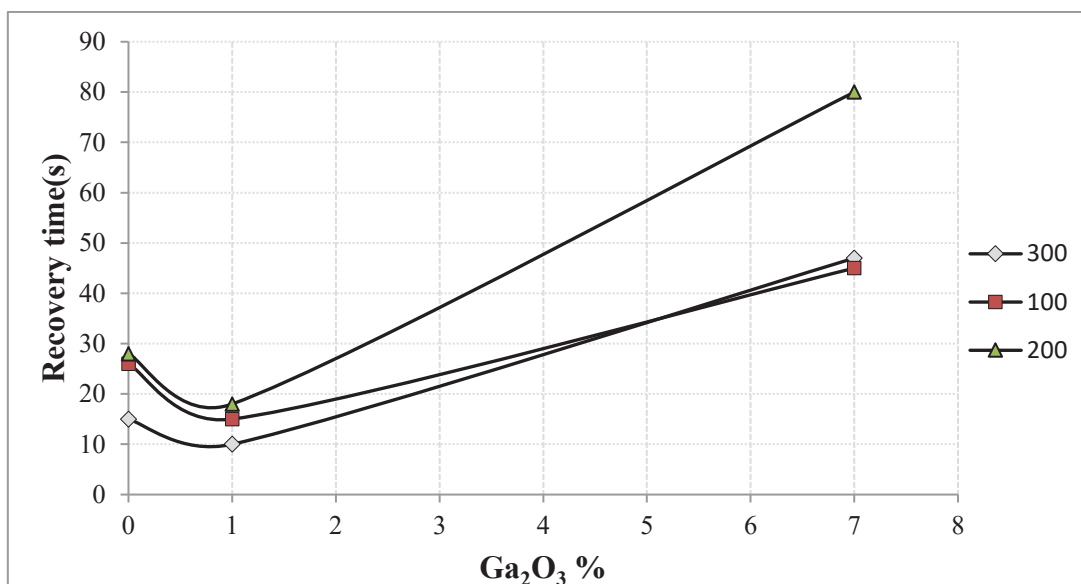


Fig. 10. The recovery time was changed with the percentage of pure CdO membranes and gallium oxide (1.7%) than the temperature of (100,200,300) °C to NO₂.

according to the following equations [26]:

$$\text{Response time} = (t_{\text{gas(on)}} - t_{\text{gas(off)}}) \times 0.9 \quad (6)$$

$$\text{Recovery time} = (t_{\text{gas(off)}} - t_{\text{gas(recovery)}}) \times 0.9 \quad (7)$$

Figs. 9 and 10 shows the relationship between response time and recovery time as a function of the vaccination rates at temperatures of (100, 200, 300) °C For pure CdO membranes and gallium oxide CdO: Ga₂O₃ with percentages of inoculation% (1,7) and the precipitation on the silicon bases the direction of NO₂ gas by 3%. Its shown that The response time and recovery time were reduced by 1% with vaccination and increased by 7% for all membranes, The best sensitivity was obtained at 40% at the response time (s12) and the retrieval time (45s) at 300 °C, and that this rapid response of the sensor may be due to the small particle size, which leads to the large granular boundaries where the interaction occurs between gas and oxygen absorption and thus occur rapid oxidation of gas [27].

CONCLUSION

The X-ray diffraction results showed that the pure cadmium oxide atoms were vaccination with gallium oxide that Prepared, all of which have a polycrystalline and cube-type structure, and the vaccination has led to the emergence of new peaks of calcium oxide, as well as reduced granular size. The results of AFM images showed that granular particle size decreased when calcium oxide was used for all vaccination rates as well as surface roughness. The study of optical properties showed that the thin Cdo: Ga₂O₃ membranes have a straight gradient energy gap whose values vary between 2.3-4 eV depending on the vaccine. The optical energy gap can be controlled by vaccination. This is used to obtain better quality membranes for applications the operation. The permeability of membranes also increased when the vaccination rate increased. We found CdO membranes that vaccination with gallium oxide that deposition on silicon bases it has a greater sensitivity than the inorganic membranes That is, vaccination has improved the protective properties of CdO membranes Gallium oxide was not altered by the type of conductivity and remained n-type.

ACKNOWLEDGEMENTS

The thin film laboratory at the College of

Science, University of Anbar.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

REFERENCES

1. Palmisano L, Di Marco G. Thin-Film Photovoltaics 2011. International Journal of Photoenergy. 2012;2012:1-2.
2. Golshahi S, Rozati SM, Martins R, Fortunato E. P-type ZnO thin film deposited by spray pyrolysis technique: The effect of solution concentration. Thin Solid Films. 2009;518(4):1149-1152.
3. Methuen, Sir Algernon Methuen Marshall, (23 Feb. 1856–20 Sept. 1924), head of Methuen and Co., Ltd, publishers. Who Was Who: Oxford University Press; 2007.
4. Pauller P, Sybil P, Parker (ed.). Me Graw — Hill Dictionary of Scientific and Technical Terms. 3rd ed., Mc Graw Hill Book Co., New York, St. Louis, San Francisco. 1984. 1846 p. \$ 282.80. ISBN 0-07-045269-5. Cryst Res Technol. 1986;21(4):476-476.
5. Fahad OA, Abdulkareem FA, Mohammed AS, Kareem OA. Produce of Selenium Nanoparticles by Pulsed Laser Ablation for Anticancer Treatments. International Journal of Nanoscience. 2021;20(06).
6. Mazhir SN, Mohammd SJ, Rifaht ZM. Structural and solar cell properties of Cr doped ZnO: CdO/Si thin films prepared by laser induced plasma. Journal of Optics. 2024;55(3):2660-2667.
7. I. Hassan A, S. khashan K, A. Hadi A. Optical and Structural Properties of Cdo Thin Film. Engineering and Technology Journal. 2013;31(5 B):613-620.
8. Hameed SA. Effect of Thickness on Structural and Optical Properties of CdO Thin Films Prepared by Chemical Spray Pyrolysis Method. NeuroQuantology. 2020;18(4):20-26.
9. Li G, Zhu X, Tang X, Song W, Yang Z, Dai J, et al. Doping and annealing effects on ZnO:Cd thin films by sol-gel method. J Alloys Compd. 2011;509(14):4816-4823.
10. Mohammed RF, Bdaiwi W. Novel Fiber-Reinforced Composites for Lightweight Ballistic Protection: A Structural and Performance Study. Revue des Composites et des Matériaux Avancés. 2025;35(1):51-62.
11. Deokate RJ, Salunkhe SV, Agawane GL, Pawar BS, Pawar SM, Rajpure KY, et al. Structural, optical and electrical properties of chemically sprayed nanosized gallium doped CdO thin films. J Alloys Compd. 2010;496(1-2):357-363.
12. Mohammed AS, Fahad OA. Sensitivity enhancement for NO₂ gas sensor based on Alq₃:TiO₂. AIP Conference Proceedings: AIP Publishing; 2021. p. 040008.
13. Hanfoosh SM, Mohammed AS, Fahad OA. Superior room-temperature sensing of toxic NH₃ gas by La₂O₃-doped CdO thin film sensors. Journal of Materials Science. 2025;60(37):16768-16778.
14. Ali O. Study Of Structural, Morphological And Optical Properties Of Pure Cdo And Cdo:Ag Doped Thin Films On Glass Substrates With High Relatively Ag Concentrations (2.5%, 5% 10% And 15%) Prepared By Sol-Gel Method. IOSR Journal of Applied Physics. 2017;9(01):01-08.
15. Sankarasubramanian K, Soundarrajan P, Sethuraman K, Ramamurthi K. Chemical spray pyrolysis deposition of

- transparent and conducting Fe doped CdO thin films for ethanol sensor. *Mater Sci Semicond Process*. 2015;40:879-884.
16. Greenaway DL, Harbeke G. *EXCITONS. Optical Properties and Band Structure of Semiconductors*: Elsevier; 1968. p. 113-128. <http://dx.doi.org/10.1016/b978-0-08-012648-7.50012-2>
 17. Fahad OA, Mohammed AS, Salih EY, Mohammed MKA. Perpendicular sheet-like alignment of a self-driven MoS₂/Si heterostructure for Vis-NIR wavelength detection. *Nanoscale*. 2025;17(30):17795-17802.
 18. Kumaravel R, Ramamurthi K, Krishnakumar V. Effect of indium doping in CdO thin films prepared by spray pyrolysis technique. *J Phys Chem Solids*. 2010;71(11):1545-1549.
 19. Sze SM, Ng KK. *Physics of Semiconductor Devices*: Wiley; 2006 2006/04/10.
 20. Velusamy P, Babu RR, Ramamurthi K, Elangovan E, Viegas J, Dahlem MS, et al. Characterization of spray pyrolytically deposited high mobility praseodymium doped CdO thin films. *Ceram Int*. 2016;42(11):12675-12685.
 21. Yaseen MT. An Investigation of the Mechanical Properties of PMMA-based Composites Reinforced with PZT Ternary Nanoparticles. *NeuroQuantology*. 2020;18(2):56-61.
 22. Low Temperature Sensing Of NO₂ Gas Using SnO₂-ZnO Nanocomposite Sensor. *Advanced Materials Letters*. 2013;4(3):196-201.
 23. Patil LA, Bari AR, Shinde MD, Deo VV, Amalnerkar DP. Synthesis of ZnO Nanocrystalline Powder From Ultrasonic Atomization Technique, Characterization, and its Application in Gas Sensing. *IEEE Sens J*. 2011;11(4):939-946.
 24. Shammon Batros S. Investigation of pyrolysis method for preparing CdO:In₂O₃ thin films gas sensor for NO₂ gas. *Engineering and Technology Journal*. 2015;33(6B):1134-1144.
 25. Garde AS. Electrical and Humidity Sensing Properties of WO₃ Thick Film Resistor Prepared by Screen Printing Technique. *Sensor Lett*. 2017;15(11):915-923.
 26. Yang Z, Liu Q-H. Controllable synthesis and optical characterizations of ZnO nanostructures by citric acid-assisted annealing process. *Physica E: Low-dimensional Systems and Nanostructures*. 2008;40(3):531-535.
 27. Liang Q, Li D, Gao S, Jiang D, Zhao J, Qin J, et al. Room-temperature NH₃ sensors with high sensitivity and short response/recovery times. *Chin Sci Bull*. 2014;59(4):447-451.