

Effect of Aluminum Doping in Cadmium Oxide Thin Films which present Nanostructure in terms of Structure, Optical and Gas Sensing

Abdul-Lateef Abdul-Jabar ^{1*}

¹ Department of Physics, College of Education, Mustansiriyah University, Baghdad, Iraq
Email: ¹lateef1991@uomustansiriyah.edu.iq

*Corresponding Author

Abstract— Pure and Aluminum doped CdO nanostructured thin films (1% and 3% Al) were grown on glass substrates via chemical spray pyrolysis. We looked at the effect of Aluminum doping on structural, morphological, optical, and gas sensing properties. XRD analysis reported a polycrystalline cubic structure with preferential (111) orientation. We saw that crystallite size increased from 18.37 nm (pure) to 27.63 nm (3% Al) and that dislocation density went down from 49.38×10^{14} to 30.56×10^{14} lines/m². AFM study showed that surface roughness and average particle size went down upon Aluminum inclusion. We noted that optical transmittance went down with Aluminum concentration and that the absorption coefficient went up. Also, the bandgap narrowed from 2.78 eV to 2.66 eV. NO₂ gas-sensing at 175°C showed sensitivity decreasing from 54.1% (pure) to 14.2% (3% Al) at 225 ppm, suggesting that higher Aluminum doping reduces sensor response due to structural modifications.

Keywords— CdO, Aluminum, doping, thin films, spray pyrolysis, UV-VIS, XRD, surface morphology, NO₂ gas sensing

I. INTRODUCTION

Cadmium oxide (CdO) is a very promising transparent conducting oxide (TCO) which it's high electrical conductivity and excellent optical transparency in the visible range. These properties make CdO very attractive for a wide range of applications which include photodiodes, optoelectronic devices, transparent electrodes, and gas sensors. CdO is an n-type semiconductor with a cubic crystal structure and a direct optical band gap which varies from 2.2 - 2.7 eV. As a member of the II VI semiconductor family, it has excellent structural and electronic properties which makes it a very studied material. Cadmium oxide thin films have been produced by many deposition techniques which include chemical vapor deposition (CVD) [15], sol-gel processing [16], pulsed laser deposition (PLD) [17], thermal evaporation [18], magnetron sputtering and spray pyrolysis [21]. Out of these methods spray pyrolysis has seen great use because of its simplicity, low cost, large scale up ability and that it produces very uniform films over large substrate areas also with very good reproducibility. Also, the technique

allows for precise control over the film composition by what we put in the precursor solution and what we set the deposition parameters to. In present work we looked at pure and Aluminum doped CdO thin films which we deposited by chemical spray pyrolysis and we systemically looked at how Aluminum inclusion affected the films' structure, morphology and optical properties.

II. MATERIALS AND METHODS

1 in a ratio of 1 (v/v) deionized water to absolute ethanol. For Aluminum doping we prepared a separate 0.1 M Aluminum precursor solution which was made by dissolving Aluminum trichloride (AlCl₃) in deionized water also we added 2 vol % of concentrated hydrochloric acid which we did to improve precursor stability and also for better dissolution. We did a series of preliminary experiments in order to optimize the deposition parameters. In which we found that the best results came from a solution flow rate of 5 mL min⁻¹, a nozzle-to-substrate distance of 30 cm, a spray duration of 10 s with a 1.5 min break between each spray cycle to avoid excessive substrate cooling also we used nitrogen (N₂) as the carrier gas. The resulted CdO thin films had good adhesion to the glass substrates also they were free of visible pinholes thus we had very good film uniformity. Also, we determined the film thickness by gravimetric method and reported it to be at about 340 nm. We looked at the structural properties via X ray diffraction (XRD) and the surface morphology and topography with atomic force microscopy (AFM). Also, we looked into the optical properties of these CdO thin films with a PerkinElmer Lambda 950 UV-Vis spectrophotometer that we used to record the transmittance spectra over the range of 300-900 nm with a resolution of 1 nm. Also, we looked at the gas sensing performance of the CdO thin films by measuring the change in electrical resistance in a cylindrical sensor chamber that had dimensions of 8 cm in diameter and 17 cm in height.



Received: 27-8-2026
Revised: 24- 9 -2026
Published: 31-12-2026

III. RESULTS AND DISCUSSION

Figure 1 displays the XRD patterns for pure and Aluminum doped CdO thin films. At 2theta values of 32.95, 38.42, 58.37, and 66.31 we see diffraction peaks that we identify as from the (111) (200) (220) and (311) crystallographic planes respectively based which is in agreement with ICDD card No. 03-065-2908. Our results from the diffraction study confirm that of a cubic polycrystalline structure for the CdO thin films which also show a preference for growth in the (111) plane.

The average crystallite size (D) was determined from the XRD data with the help of Scherrer equation [22]:

$$D = \frac{0.94\lambda}{\beta \cos \theta} \quad (1)$$

Where β is the X ray wavelength and θ is Bragg angle. We report in Table 1 the results which show a trend of gradual increase in crystallite size (D) from 18.37 nm for pure CdO film to 27.63 nm for the film doped with 3% Al which we put forth as evidence that Aluminum incorporation promotes crystallite growth and improves the crystalline quality of the deposited films [23]:

$$\delta = \frac{1}{D^2} \quad (2)$$

The reported dislocation density (δ) went from 49.38×10^{14} lines/m² in pure CdO thin film to 30.56×10^{14} lines/m² in the film doped with 3% Al. This reduction we see as an improvement in the films' crystalline quality which we attribute to better crystallite growth and the also seen decrease in crystallographic defects upon Aluminum inclusion [25].

Strain (ϵ) was determined by the following equation [26]:

$$\epsilon = \frac{\beta \cos \theta}{4} \quad (3)$$

The microstrain (ϵ) value of pure CdO thin film reported at 29.63×10^{-4} which reduced to 20.30×10^{-4} for the film doped with 3% Al which in turn indicates a decrease in lattice distortion and internal stress as we increase Aluminum content. This trend puts forth that Aluminum inclusion into the structure improves the CdO thin films' crystallinity by in large eliminating structural defects [27].

The we report on structural parameters which include the (D), (δ), (ϵ) and lattice constant they are presented in Table 1. In Figure 2 we present the (FWHM) and (D) as well as (δ) and (ϵ) which vary with doping.

TABLE I. STRUCTURAL PARAMETERS OF THE DEPOSITED FILMS

Specimen	2 θ ($^\circ$)	(hkl) Plane	FWHM ($^\circ$)	E _g (eV)	D (nm)	$\delta \times 10^{16}$ (lines/m ²)	ϵ ($\times 10^{-4}$)
Pure CdO	111	32.95	0.67	2.78	18.37	49.38	29.63
CdO: 1% Al	111	38.42	0.61	2.72	24.83	35.19	23.31
CdO: 3% Al	111	66.31	0.57	2.66	27.63	30.56	20.30

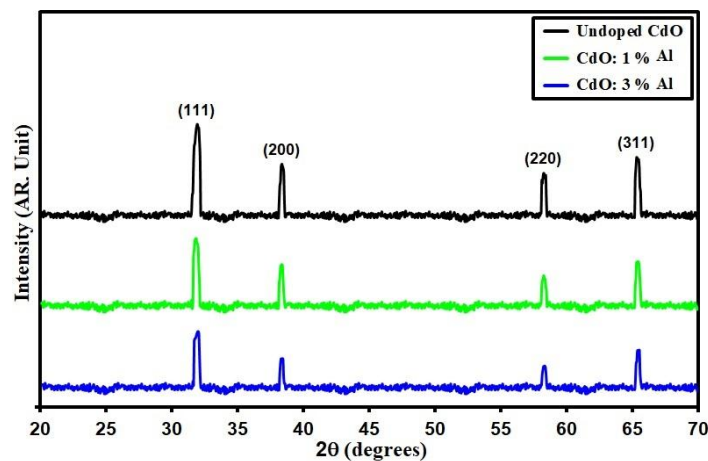


Fig. 1. XRD patterns of the deposited films.

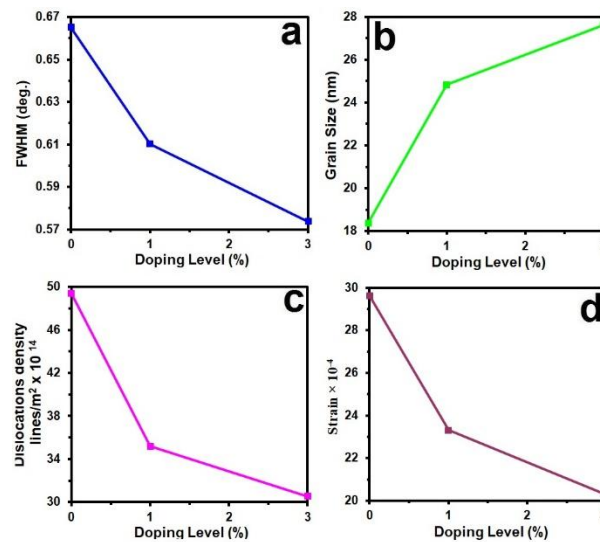
Fig. 2. D, (c) ϵ , and (d) δ of the deposited films.

Figure 5 displays the AFM surface morphology of pure and Aluminum doped CdO thin films. We see that the films which have been deposited have smooth, compact, and homogeneous surfaces which also report good substrate coverage. The grain sizes which we estimated from the AFM images also play along with what we got from XRD analysis. We see that the average grain size goes down from 69.03 nm for the pure film to 41.21 nm for the film which has 3% Al, which indicates that Aluminum in fact causes grain growth to be suppressed and instead we see the formation of finer grains. Also we note that the surface morphology changes as we increase Aluminum content. Pure and 1% Al doped films we see to have irregular grain shape with a high density of surface defects, but the 3% Al doped film is made up of very uniformly distributed spherical grains and a more homogeneous surface. Also we see that the surface roughness goes down with Aluminum doping, we go from an average roughness (Ra) and root mean square roughness (RMS) of 8.79 to 3.26 nm and from 7.78 to 3.23 nm respectively which we take to mean that Aluminum incorporation does in fact improve the surface quality and compactness of the CdO thin films [28].

Table 3. The morphological properties of the films.

Samples	Tp (nm)	Ra (nm)	R. M. S. (nm)
Pure CdO	69.03	8.79	7.78
CdO: 1% Al	55.20	4.32	4.32
CdO: 3% Al	41.21	3.23	3.23

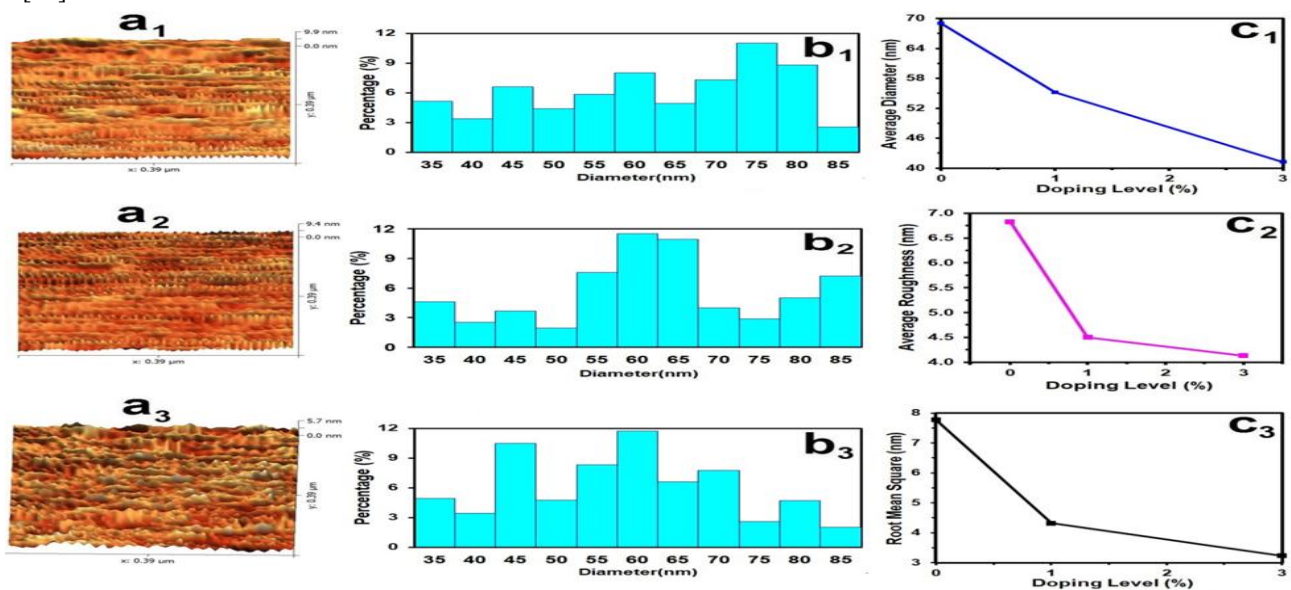


Fig. 3. AFM images of the films we deposited.

Figure 4 displays transmittance spectra of pure and Aluminum doped CdO films (300-900 nm). In the pure films we see greater transparency which is a result of enhanced light scattering and absorption from the effect of the dopant induced structural changes [29].

The optical absorption coefficient (α) was determined by the following relation [30]:

$$\alpha = 2.3026 \left(\frac{A}{t} \right) \quad (4)$$

In which we see A is the absorbance and t film thickness, in Figure 5 we note that the absorption coefficient (α) for CdO films has a large growth when Aluminum is added and is at about 10^4 cm^{-1} at the edge of absorption. This is because of changes in the electronic band structure and the increased free-carrier concentration resulting from aluminum incorporation into the material [31, 31].

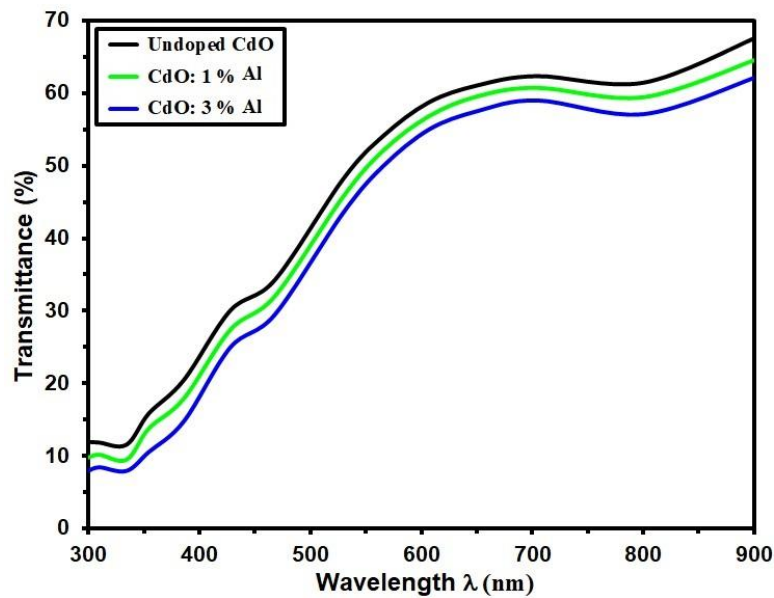


Fig. 4. Transmittance of the as deposited films.

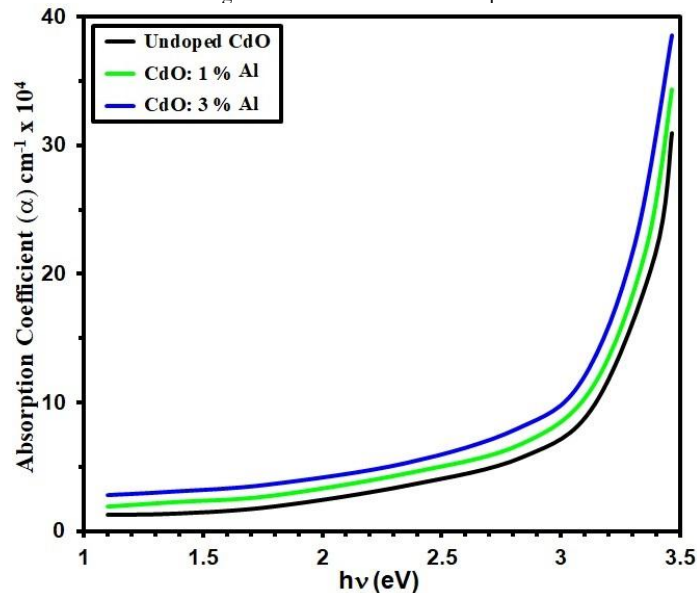


Fig. 5. change in α with $h\nu$ (eV).

The optical band gap energy (E_g) was determined by means of the Tauc equation [32]

$$\alpha h\nu = k(h\nu - E_g)^n \quad (5)$$

In which k is a proportionality constant and n is a term that defines the type of optical transition. For CdO we have $n=1/2$ which reports a direct allowed transition [33]. In Fig. 6, the

optical bandgap decreases from 2.78 eV (pure) to 2.66 eV (aluminum-doped). This bandgap reduction is due to Aluminum incorporation which in turn introduces localized defect states and impurity levels that in turn promote bandgap reduction also which we see as enhanced carrier scattering [34].

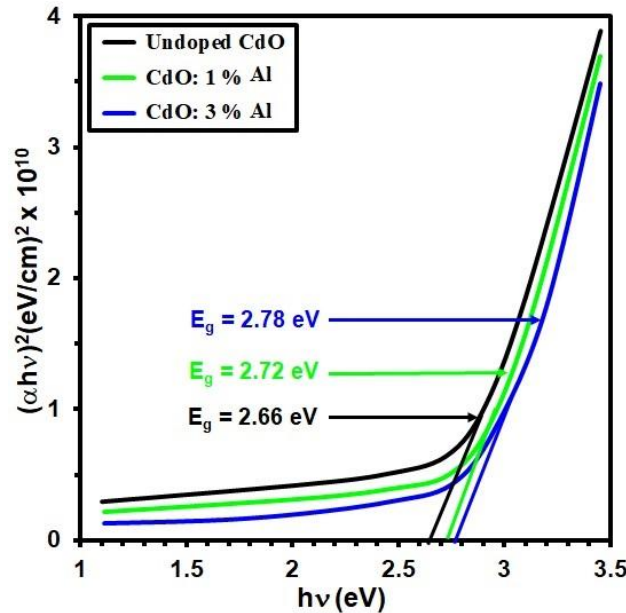


Fig. 6. The band gap values of the deposited films.

The value of the extinction coefficient (k) was determined by the following relation [12]:

$$k = \frac{\alpha\lambda}{4\pi} \quad (6)$$

Figure 7 displays the variation of the extinction coefficient with respect to wavelength in pure and Aluminum doped CdO thin films. We see that the extinction coefficient goes down as the Aluminum doping concentration is increased which in turn indicates a reduction in optical losses in the doped films [15].

The refractive index (n) was measured by means of the following expression [16]:

$$n = \left(\frac{1+R}{1-R}\right) + \sqrt{\frac{4R}{(1-R)^2} - k^2} \quad (7)$$

In Figure 8 we see that refractive index of CdO films goes down with increase in Aluminum doping which is a result of changes in electronic structure and optical polarizability due to Aluminum's introduction [35].

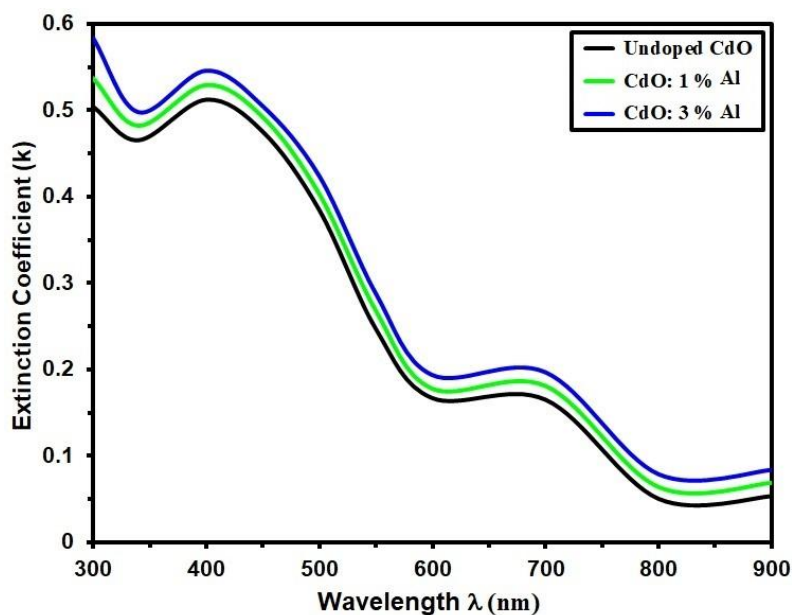


Figure 7. k of the deposited films.

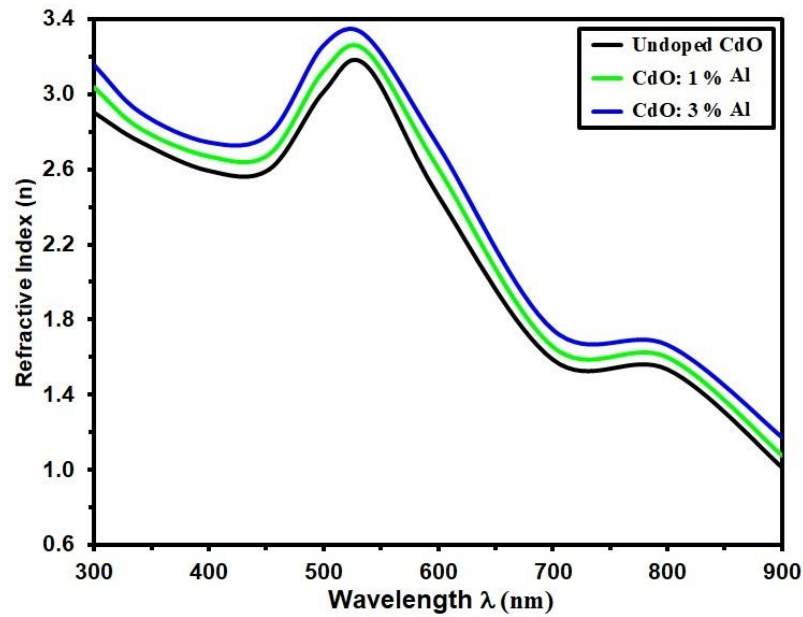


Fig. 8. n of the deposited films.

Aluminum thin films were at 175 °C during operation. In Figure 9 we see that the resistance of the films which resulted from exposure to 225 ppm of NO₂ gas. Pure CdO films had the lowest resistance [18]. Also we see that the CdO films doped with 3% Aluminum had a great deal more resistance which is a result of what we attribute to changes in the electronic structure brought about by the Aluminum dopant [36].

The gas sensor's sensitivity is ascertained, based on the relationship expressed in Equation (8), as described in reference [19].

$$Sen. = \frac{\Delta R}{R_g} = \left| \frac{R_g - R_a}{R_g} \right| \times 100 \% \quad (8)$$

Where R_a is the resistance in the presence of NO₂ gas and R_g is the baseline resistance in air. As shown in Figure 10, sensitivity measurements were conducted for pure CdO, CdO doped with 1% Aluminum, and CdO doped with 3% Aluminum under varying NO₂ concentrations. A clear trend is observed: Increasing the Aluminum content results in a large drop in sensitivity. For example, sensitivity values decrease from 54.1% to 7.8 % at 75 ppm, from 43.6% to 10.3% at 150 ppm and from 54.1% to 14.2% at 225 ppm as Aluminum doping increases from 0% to 3%. This reduction in sensitivity can be attributed to the modification of the charge-carrier concentration and electrical conductivity induced by Al doping [37].

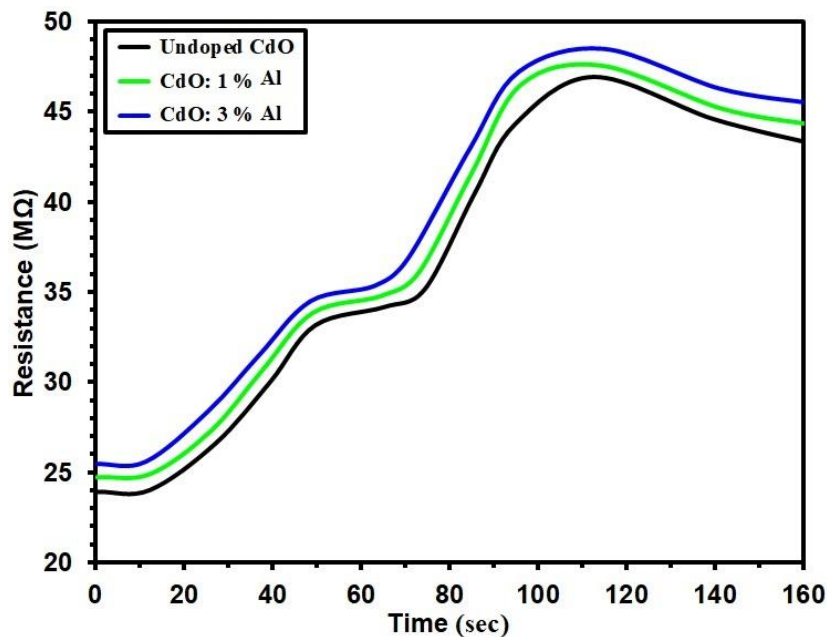


Fig. 9: Resistance via time of Pure & CdO: Al with different dopants.

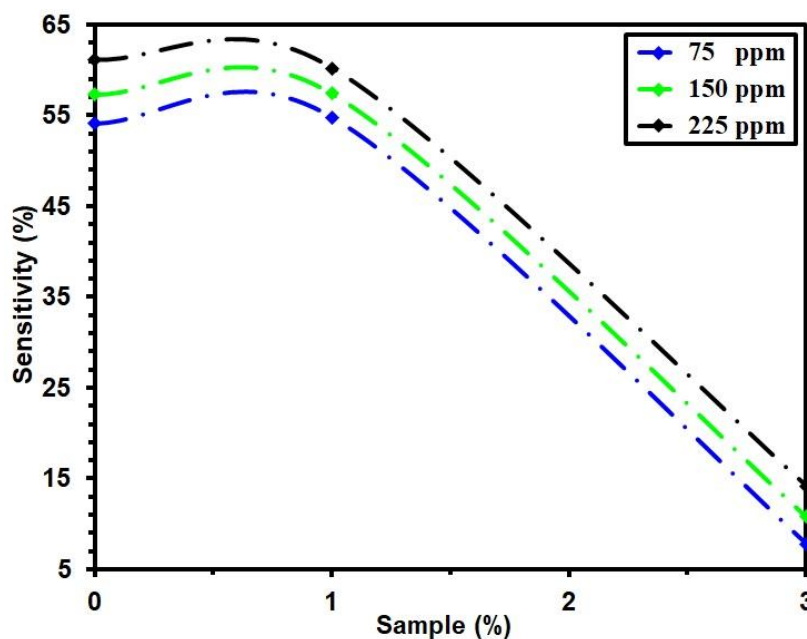


Fig. 10: Sensitivity of Pure & CdO: Al with different dopants.

IV. CONCLUSION

Pure and Aluminum doped CdO nanostructured thin films were produced by chemical spray pyrolysis. XRD reported a polycrystalline cubic structure which had a preferential (111) orientation. Also Aluminum doping which we report here increased crystallite size from 18.37 nm to 27.63 nm. while dislocation density decreased from 49.38×10^{14} to 30.56×10^{14} lines/m. AFM revealed reduced surface roughness and particle size upon Aluminum incorporation. Optically, transmittance decreased with Aluminum concentration, while absorption coefficient increased. The bandgap narrowed from 2.78 eV to 2.66 eV due to Aluminum-induced localized defect states. Both refractive index and extinction coefficient decreased with higher Aluminum content. At 175°C in the NO₂ gas sensing we saw a drop in sensitivity from 54.1% to 14.2% at 225 ppm with increase in Aluminum doping which in turn suggests that as Aluminum concentration goes up sensor response goes down due to structural changes.

ACKNOWLEDGMENT

The author is thankful to Mustansiriyah University for its support of this research.

REFERENCES

- [1] O. Gomezdaza, A. Arias-Carbajal Readigos, J. Campos, M. T. S. Nair, and P. K. Nair, "Substrate spacing and thin-film yield in chemical bath deposition of semiconductor thin films," *Semicond. Sci. Technol.*, vol. 15, pp. 1022–1029, 2000.
- [2] F. S. Ahmed, N. Y. Ahmed, R. S. Ali, N. F. Habubi, K. H. Abass, and S. S. Chiad, "Effects of substrate type on some optical and dispersion properties of sprayed CdO thin films," *NeuroQuantology*, vol. 18, no. 3, pp. 56–65, 2020.
- [3] D. C. Renolds, D. C. Look, and B. Jogai, "Optically pumped ultraviolet lasing from CdO," *Solid State Commun.*, vol. 99, pp. 873–875, 1996.
- [4] N. O. Ongwen, A. O. Oduor, and E. O. Ayieta, "Effect of deposition temperature on the optical properties of iron doped cadmium stannate thin films deposited by spray pyrolysis," *IJSTRE*, vol. 4, p. 3, 2019.
- [5] B. Sahin, Y. Gulen, F. Bayansal, H. A. Cetinkara, and H. S. Guder, "Structural and optical properties of Ba-doped CdO films prepared by SILAR method," *Superlattices Microstruct.*, vol. 65, pp. 6–63, 2014.
- [6] Y. Gulen, B. Sahin, F. Bayansal, et al., "Solution-phase synthesis of un-doped and Pb doped CdO films," *Superlattices Microstruct.*, vol. 68, pp. 48–55, 2014.
- [7] F. P. Koffyberg, "Diffusion of donors in semiconducting CdO," *Solid State Commun.*, vol. 9, pp. 2187–2189, 1971.
- [8] M. S. Othman, Kh. A. Mishjil, H. G. Rashid, S. S. Chiad, N. F. Habubi, and I. A. Al-Baidhany, "Comparison of the structure, electronic, and optical behaviors of tin-doped CdO alloys and thin films," *J. Mater. Sci.: Mater. Electron.*, vol. 31, pp. 9037–9043, 2020.
- [9] R. Kumaravel, K. Ramamurthi, and V. Krishnakumarm, "Effect of indium doping in CdO thin films prepared by spray pyrolysis technique," *J. Phys. Chem. Solids*, vol. 71, no. 11, pp. 1545–1549, 2010.
- [10] Y. Gulen, B. Sahin, F. Bayansal, et al., "Solution-phase synthesis of un-doped and Pb doped CdO films," *Superlattices Microstruct.*, vol. 68, pp. 48–55, 2014.
- [11] R. L. Mishra, A. K. Sharma, and S. G. Prakash, "Gas sensitivity and characterization of cadmium oxide semiconducting thin film deposited by spray pyrolysis technique," *Dig. J. Nanomater. Biostruct.*, vol. 4, pp. 511–518, 2009.
- [12] R. S. Ali, K. S. Sharba, M. H. Al-Timimi, K. H. Abass, N. F. Habubi, I. A. Al-Baidhany, and S. S. Chiad, "Enhancement of CdO film via Li additive: Structural and optical properties," *Test Eng. Manage.*, vol. 83, pp. 11148–11153, 2020.
- [13] O. Niitsoo, S. K. Sarkar, C. Pejoux, S. Rühle, D. Cahen, and G. Hodes, "Chemical bath deposited," *J. Photochem. Photobiol., A*, vol. 181, no. 306, 2006.
- [14] M. K. Khan, M. A. Rahman, M. Shahjahan, M. M. Rahman, M. A. Hakim, D. K. Saha, and J. U. Khan, "Effect of Al-doping on optical and electrical properties of spray pyrolytic nano-crystalline CdO thin films," *Curr. Appl. Phys.*, vol. 10, pp. 790–796, 2010.
- [15] K. Z. Yahya and M. Adel, "Influence of substrate temperature on structure and optical properties of CdO thin films prepared by pulsed laser deposition," *Eng. Tech. J.*, vol. 30, no. 3, pp. 416–425, 2012.
- [16] S. Aksoy, Y. Caglar, S. Ilcan, and M. Caglar, "Effect of heat treatment on physical properties of CdO films deposited by sol-gel method," *Int. J. Hydrogen Energy*, vol. 34, pp. 5191–5195, 2009.
- [17] A. A. Dakhel and F. Z. Henari, "Optical characterization of thermally evaporated thin CdO films," *Cryst. Res. Technol.*, vol. 38, no. 11, pp. 979–985, 2003.
- [18] R. K. Gupta, K. Ghosh, R. Patel, and P. K. Kahol, "Highly conducting and transparent Ti-doped CdO films by pulsed laser deposition," *Appl. Surf. Sci.*, vol. 255, no. 12, pp. 6252–6255, 2009.
- [19] B. Saha, R. Thapa, and K. K. Chattopadhyay, "Wide range tuning of electrical conductivity of RF sputtered CdO thin films through oxygen

- partial pressure variation," *Sol. Energy Mater. Sol. Cells*, vol. 92, pp. 1077–1080, 2008.
- [20] Q. Zhou, Z. Ji, B. B. Hu, C. Chen, L. Zhao, and C. Wang, "Low resistivity transparent conducting CdO thin films deposited by DC reactive magnetron sputtering at room temperature," *Mater. Lett.*, vol. 61, pp. 531–534, 2007.
- [21] C. H. Bhosale, A. V. Kambale, A. V. Kokate, and K. Y. Rajpure, "Structural, optical and electrical properties of chemically sprayed CdO thin films," *Mater. Sci. Eng., B*, vol. 122, no. 1, pp. 67–71, 2005.
- [22] A. W. Metz, J. R. Ireland, J. G. Zheng, R. P. S. M. Lobo, Y. Yang, J. Li, C. L. Stern, V. P. Dravid, N. Bontemps, C. R. Kannewurf, K. R. Poeppelmeier, and T. J. Marks, *J. Am. Chem. Soc.*, vol. 126, pp. 8477–8492, 2004.
- [23] S. Jin, Y. Yang, J. E. Medvedeva, J. R. Ireland, A. W. Metz, J. Ni, C. R. Kannewurf, A. J. Freeman, and T. J. Marks, *J. Am. Chem. Soc.*, vol. 126, pp. 13787–13793, 2004.
- [24] L. R. de León-Gutiérrez, J. J. Cayente Romero, J. M. Peza-Tapia, E. Barrera Calva, J. C. Martínez-Flores, and M. Ortega López, "Some physical properties of Sn-doped CdO thin films prepared by chemical bath deposition," *Mater. Lett.*, vol. 60, pp. 3866–3870, 2006.
- [25] N. M. Ahmed, H. H. Afify, and F. M. Ibrahim, "Aluminum incorporation impacts on some physical properties of pure CdO film synthesized by spray pyrolysis," *Int. J. Nanoelectron. Mater.*, vol. 11, no. 2, pp. 195–210, 2018. F. Yakuphanoglu, "Preparation of nanostructure Ni doped CdO thin films by sol gel spin coating method," *J. Sol-Gel Sci. Technol.*, vol. 59, pp. 569–573, 2011.
- [26] V. Radhika and V. Annamalai, "Antibacterial application of pure and doped CdO nanocrystalline thin films," *J. Environ. Nanotechnol.*, vol. 8, no. 2, pp. 1–10, 2019.
- [27] K. I. Hussein, S. O. Allehabi, E. E. Assem, E. S. Yousef, and E. R. Shaaban, "Studying of cadmium oxide/Aluminium films for optoelectronics: structural, optical and electrical characteristics," *Inorg. Chem. Commun.*, vol. 160, art. no. 112191, 2024.
- [28] G. Olcay, A. Ferhunde, and A. Idris, "The optical, electrical and surface properties for annealed CdO films deposited by ultrasonic spray pyrolysis," *SAU J. Sci.*, vol. 17, no. 3, pp. 295–300, 2013.
- [29] M. Rajini, M. Karunakaran, and K. Kasirajan, "An investigation of SILAR grown CdO thin films," *Mater. Sci.-Pol.*, vol. 37, no. 1, pp. 25–32, 2019.
- [30] I. S. Yahia, G. F. Salem, M. S. Abd El-sadek, and F. Yakuphanoglu, "Optical properties of Al-CdO nano-clusters thin films by sol-gel spin coating method," *Superlattices Microstruct.*, vol. 64, pp. 178–184, 2013.
- [31] G. Kaaviya, P. Monisha, S. S. Gomathi, and K. Pushpanathan, "Effect of Mn doping on the structural, optical and antibacterial properties of CdO nanoparticles," vol. 6, no. 3, 2019.
- [32] R. S. de Biasi and M. L. N. Grillo, "Measurement of small concentrations of manganese in cadmium oxide (CdO) using electron magnetic resonance," *Ceram. Int.*, vol. 39, no. 2, pp. 2171–2173, 2013.
- [33] H. Güney and D. İskenderoğlu, "The effect of Zn doping on CdO thin films grown by SILAR method at room temperature," *Physica B*, vol. 552, pp. 119–123, 2019.
- [34] S. S. Chiad, N. F. Habubi, W. H. Abass, and M. H. Abdul-Allah, "Effect of thickness on the optical and dispersion parameters of Cd_{0.4}Se_{0.6} thin films," *J. Optoelectron. Adv. Mater.*, vol. 18, no. 9-10, pp. 822–826, 2016.
- [35] Z. Zhao, D. L. Morel, and C. S. Ferekides, "Electrical and optical properties of tin-doped CdO films deposited by atmospheric metalorganic chemical vapor deposition," *Thin Solid Films*, vol. 413, pp. 203–211, 2002.
- [36] K. Gurumurugan, D. Mangalraj, and S. K. Narayanandas, "Correlations between the optical and electrical properties of CdO thin films deposited by spray pyrolysis," *Thin Solid Films*, vol. 251, pp. 7–9, 1994.