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Sol–gel spin coating derived cadmium oxide semiconductor thin films: Effect of Lutetium contribution

Erman Erdoğan [a,*], Güven Turgut [b,c,**], Mehmet Yilmaz [d,e]

[a] *Electronic Communication Technology Program, Vocational High School, Bilecik Seyh Edebali University, 11230 Bilecik, Turkey*
[b] *Department of Basic Sciences, Science Faculty, Erzurum Technical University, 25050 Erzurum, Turkey*
[c] *Photonic Group, High Technology Application and Research Centre (YUTAM), Erzurum Technical University, 25050 Erzurum, Turkey*
[d] *Advanced Materials Research Laboratory, Department of Nanoscience and Nanoengineering, Graduate School of Natural and Applied Sciences, Ataturk University, 25240 Erzurum, Turkey*
[e] *Department of Science Teaching, K.K. Education Faculty, Ataturk University, 25240 Erzurum, Turkey*

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ABSTRACT

Continuously developing optoelectronic technology requires alternative transparent conductive oxide (TCO) materials. Due to their high optical transmittance and conductivity, TCO materials have many application areas. Cadmium oxide (CdO) thin films, one of the most important TCO materials, are frequently used in optoelectronic technology. In this study, pure and Lu doped CdO semiconductor thin films with 1, 2, 3, 4, and 5 at% concentrations were produced using the sol-gel spin coating technique. The changes in the optical, structural and surface properties of the films were examined as a function of the doping and it was determined that the doping process caused significant changes in the properties of the films. The XRD results showed that the samples were polycrystalline cubic and the average crystallite size varied between 13.42 nm and 26.39 nm with Lu contribution. To examine the optical properties of CdO: Lu thin films, the transmittance and absorption spectra of the films were taken in the UV–VIS region. The optical absorption coefficient, refractive indexes, dielectric constants, optical-electrical conductance, and optical band-gap of films were calculated by using the obtained transmittance and absorption spectra, and the effect of doping on the optical properties of the films was investigated. Depending on the amount of Lu, some fluctuations are observed in Eg values. It was determined that Lu doping from the changes in SEM is effective in changing the properties of CdO and these films are suitable materials for sensor and display applications. SEM images revealed that the Lu contribution rate caused the surface change of thin films. With this study, the effect of Lu doping on structural, optical, and superficial properties of CdO films was investigated and it was determined that Lu doping of CdO films were suitable materials for optoelectronic applications.

1. Introduction

Technological developments offered to the service of humanity in today's modern age are based on the development of materials. The need for advanced material becomes more important than the design of the device in order to approach the imagined devices. For

* Corresponding author.
** Corresponding author at: Department of Basic Sciences, Science Faculty, Erzurum Technical University, 25050 Erzurum, Turkey.
E-mail addresses: erman.erdogan@bilecik.edu.tr (E. Erdoğan), guven.turgut@erzurum.edu.tr (G. Turgut).

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this reason, understanding the development of technology begins with knowing the development of the material [1]. Semiconductor materials have a significant share in reaching today's technology. These materials have many aspects that differ from conductive and insulating materials due to their superior optical and electrical properties [2]. Research has been going on for years to develop semiconductor technology. While some of the researches in this field are developing towards the preparation of new semiconductor materials, some of them aim to determine the electronic properties of these materials and to develop new metal-semiconductor circuit elements by taking advantage of these properties. The nanostructure of the circuit elements produced as a result of the studies in this field also constitutes an important class in terms of developing nanotechnology [3].

Metal oxides (ZnO, CdO, TiO_2, SnO_2), which form a separate group in semiconductors due to their unique properties, are important classes of materials due to their suitability in many device constructions. Cadmium Oxide (CdO) is of great interest by researchers and considered to be an important semiconductor metal oxide promising to replace semiconductor materials such as GaN (Gallium nitride) and Si (Silicon). The reason for the increasing interest in CdO, which has been studied for a long time, is the development of new production techniques and the production of more functional CdO nanostructures and this allows the production of CdO-based electronic and optoelectronic devices [4]. With the direct optical band gap between 2.2 and 2.7 eV, n-type conductivity, CdO is often used in applications such as spintronics, transparent electronics, optoelectronics, and sensors. CdO is a widely preferred material for these applications, especially photodiodes, gas sensors, solar cells, and anti-reflective coatings [5–7]. CdO is considered to be a promising material for photovoltaic applications due to its high electrical conductivity and optical transmittance in the visible region of the solar spectrum, and it is appropriate to use the particle size CdO in optoelectronic devices due to its low resistance and high-rise mobility properties [8].

CdO thin films are obtained with a wide range of deposition techniques; such as, pulsed laser deposition (PLD), spray pyrolysis, chemical bath deposition, hydrothermal synthesis, and magnetron sputtering [9–13]. Compared with these methods, the sol-gel method is a useful method for preparing metal oxide coatings because it obtains a homogeneous structure, can be kept under the control of each stage, requires simple devices, and can be applied at low temperatures. The sol-gel spin coating method is that the solutions prepared for the films to be obtained are transferred to a base, and then this base is rotated at various speeds and times and the solution is spread over this base to form a film [14]. In the spin coating method; the desired films can be easily diversified by changing the parameters such as film thickness, rotation speed, rotation time, coating number, solution volume, and annealing temperature. This method is widely preferred because it allows low cost and fast production [15].

There are many studies on the optical, structural, morphological, and electronic properties of CdO thin films deposited by the sol-gel spin coating method. Duman et al. [16] fabricated CdO thin films and examined their physical properties with the change in molar concentration of solutions. Ben Miled et al. [17] first investigated the annealing effect on the crystallographic, electrical, and optical characteristics of CdO thin films. They also investigated the molar concentration of Cd ions based on the optimum annealing temperature. Sharma et al. [18] found that the post-deposition thermal treatment of CdO thin films at various annealing temperatures uncovers important alterations in their optical and structural features. Rajput et al. [19] deposited CdO thin films on glass substrates with different Cd ion molar concentrations to investigate the oxygen gas sensing behavior of the films. Soylu [20] investigated what effects the molarity had on the physical properties of the deposited CdO thin films. Kumari and Kumar [21] successfully synthesized CdO nano thin films and found differences based on the Hall effect measurement CdO film confirms the n -type conductivity.

When studies conducted in recent years are examined, CdO films are doped with many elements and their physical properties are investigated. Having a wide range of optical bands, CdO becomes a suitable material for optoelectronic devices if it is doped with elements called rare earth (RE) elements. CdO doped with rare earth metals (La and Gd) with sol-gel spin coating technique are impressive materials due to their ability to change some physical properties [22,23]. In CdO structure, Cd and O have 2 + and 2- oxidation states and its optical permeability and electrical conductivity can be increased when doped with elements with oxidation states greater than 2 + or less than 2–. The element Lu is a good candidate as it has a valence state of 3 + and can be easily replaced by Cd^{2+} as its ionic radius is less than Cd^{2+}. Particularly, films containing Lu ions are a good candidate for optoelectronic devices because of the playing carrier donors and energy transfer [24]. Lu^{3+} has an ionic radius of 0.086 nm which is slightly less than the host Cd^{2+} radius of 0.095 nm.

According to extensive literature research, there has been no study on Lu-doped CdO films. Thus, a lot of studies about Lu-doped CdO should be conducted to understand its effect on the features of CdO. In this novel work, Lu-doped CdO films have been prepared with a sol- gel spin coating technique, for the first time in the literature, and the effect of Lu doping on the crystalline, morphological, and optical properties of CdO has been examined.

2. Experimental

Pure cadmium oxide precursor and Lu-loaded sol-solutions were set by using 0.3 M $Cd(CH_3COO)_2 \bullet 2H_2O$ and 0.3 M $LuCl_3$, 2-methoxy ethanol, and monoethanolamide (MDA) to be the precursor and doping salts, solvent, and stabilizer. For the preparing of un-doped, 1 at%, 2 at%, 3 at%, 4 at%, and 5 at% Lu-doped CdO samples, the necessary amounts of these solutions were mixed. The microscope glass as substrate was cleaned with various alcohols and pure water. The pure and Lu-doped solutions have been dropped on glasses and then they have been spin-coated at the speed of 3000 rpm for 25 s through a Laurell Spin Coating Unit. After the coating, the layers were sintered at 200 °C for 10 min. The coating and sintering procedures were repeated ten times. And finally, the films were annealed in the air at 500 °C for 1 h.

The surface morphologies of the pure and Lu doped CdO films were studied using the FEI Quanta FEG 250 scanning electron microscope (SEM). X-ray diffraction (XRD) spectra of the films were taken using the GNR EXPLORER XRD device at $2\theta = 20–90°$ in 0.02° steps. XRD measurements were performed with a monochromatic CoKα (λ = 1,78897 Å) beam. Optical properties were evaluated by

UV–VIS/NIR spectrophotometer (Shimadzu UV-3600 Plus) in the wavelength range of 300–1300 nm. All characterization measurement has been taken at Erzurum Technical University High Technology Research and Application Center (ETU-YUTAM).

3. Results and discussions

3.1. XRD investigations

A crystal is described as a solid composed of atoms of a pattern that repeats periodically in three-dimensional space. Accordingly, the crystal structure of solids is formed by the combination of atoms, atom groups, and molecules that make up the material in a specific geometric order. Viewing the atomic structure of a material is possible using a variety of high-resolution electron microscopes. However, diffraction techniques can be used to determine unknown structures or to determine structural parameters. The most widely used diffraction technique to study the crystal structures of solids is the x-ray diffraction technique.

For Lu doped and pure CdO thin films, x-ray diffraction patterns were measured using a CoKα beam with a wavelength of λ = 0.1789 nm. In Fig. 1, the x-ray diffraction pattern of pure, 1%, 2%, 3%, %4, and %5 Lu added CdO thin films are given. When XRD patterns were examined, five main peaks were determined for each film and (111), (200), (220), (311), and (222) were observed. This shows that the films have a poly-crystal structure.

The intensity and width of the peaks are examined in order to understand whether the crystallization of films is good or bad from the X-ray diffraction patterns. High-density sharp peaks in the XRD spectrum of a sample indicate low FWHM values indicating high crystallinity, while the opposite indicates low crystallization. However, the fact that the intensity of the peaks on the XRD patterns increases with the Lu contribution, except for the CLu-4 film, means that the lattice structure is improved.

The 2θ value of the CdO semiconductor before and after Lu doping was found to be cubic as a result of scanning between 20 and 90 degrees. Apart from these peaks, it can be interpreted that the absence of peaks of Lu^{+3} ions does not affect the CdO crystal structure of Lu^{+3} ions. It can be seen from here that there has been no change in the cubic structure depending on the Lu doping and its ratio. This situation shows that no oxidized structures that may occur with Lu in the structure. However, as seen in Fig. 1, the peaks generally increased. This situation can be interpreted as Lu atoms in the structure cause the crystal structure to improve [25]. Besides, as seen in Table 1, a shift occurred in peak positions with Lu contribution. This shift is thought to be due to Lu and CdO interaction, that is; the replacement of Cd atoms and Lu atoms in the structure. We think that the different ionic radii of Cd atoms and Lu atoms cause changes in the CdO: Lu structure of the two displaced atoms. These changes in a structural sense may cause deviations in 2θ values [26].

By using the equation of 2θ values of plane peaks in the X-ray diffraction pattern of pure and doped CdO films, the distance between the planes of the structure (d_{hkl}) was calculated by following formula [27] and obtained values were given in Table 1:

$$n\lambda = 2d_{hkl}sin\theta \tag{1}$$

To get detailed information about the crystal structure, the crystal dimensions D of all planes were determined using the modified Scherrer plot based on the following formula [28]:

$$\ln\beta = ln\frac{0.9\lambda}{D} + ln\frac{1}{\cos\theta} \tag{2}$$

where, "D" is the estimated crystal size, "λ" is the wavelength (1.78897 Å) of the incoming X-ray, β is the Full width half maximum

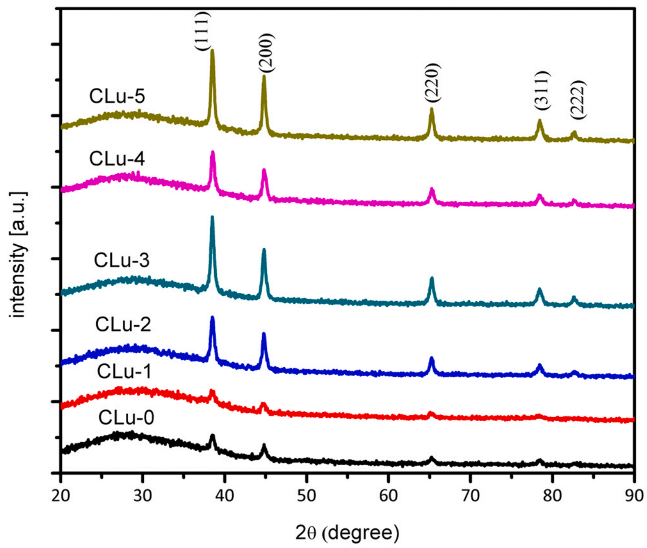

Fig. 1. XRD diffraction pattern of pure and Lu doped CdO thin films.

Table 1
Comparison of some structural parameters of CdO: Lu thin films (d_{hkl}: interplanar distance, FWHM: full width half maximum, $D_{SR\text{-}ort}$: crystal size from modified Scherer plot, $D_{W\text{-}H\text{-}ort}$: crystal size from W-H plot, $\varepsilon_{W\text{-}H}$: microstrain from W-H plot.

	(hkl)	d_{hkl} (Å)	2θ (°)	FWHM (°)	$D_{SR\text{-}ort}$ (nm)	$D_{W\text{-}H\text{-}ort}$ (nm)	$\varepsilon_{W\text{-}H}$ (x10^{-3})
CLu-0	(111)	2.7103	38.54	0.5718	19.19	18.23	-0.270
	(200)	2.3472	44.80	0.4506			
	(220)	1.6591	65.25	0.5661			
	(311)	1.4137	78.50	0.5892			
	(222)	1.3533	82.74	0.6412			
CLu-1	(111)	2.7110	38.53	0.5892	13.42	12.90	-1.620
	(200)	2.3522	44.70	0.6239			
	(220)	1.6609	65.17	0.6585			
	(311)	1.4149	78.42	0.9011			
	(222)	1.3546	82.65	0.3253			
CLu-2	(111)	2.7131	38.50	0.4969	23.74	27.42	1.010
	(200)	2.3492	44.76	0.4332			
	(220)	1.6593	65.24	0.4390			
	311)	1.4145	78.45	0.5799			
	(222)	1.3532	82.75	0.7740			
CLu-3	(111)	2.7131	38.50	0.4159	26.39	39.85	1.880
	(200)	2.3472	44.80	0.4245			
	(220)	1.6581	65.29	0.4852			
	(311)	1.4152	78.40	0.6932			
	(222)	1.3552	82.60	0.6912			
CLu-4	(111)	2.7097	38.55	0.4246	21.18	22.77	0.342
	(200)	2.3472	44.80	0.4852			
	(220)	1.6581	65.29	0.5758			
	(311)	1.4146	78.44	0.6701			
	(222)	1.3540	82.69	0.4967			
CLu-5	(111)	2.7137	38.49	0.3899	24.24	23.67	-0.274
	(200)	2.3477	44.79	0.3875			
	(220)	1.6591	65.25	0.4274			
	(311)	1.4145	78.45	0.5430			
	(222)	1.3548	82.63	0.3759			

(FWHM) value in radians and the θ is the Bragg angle of the diffraction peaks. If we draw the results of ln β according to ln (1/cos θ), a straight line with an approximate slope and an intersection of ln 0.9λ/D should be obtained. Therefore, a single value of D in the nanometer can be calculated.

According to the calculated average crystal size values of the samples determined from the intercept of the plot given in Fig. 2, it was concluded that the crystal size varied with increasing Lu amount. When the obtained crystallite size values are examined, as can be seen in both Table 1 and Fig. 1, the peak intensities of CLu-2, CLu-3, and CLu-5 films are sharp and narrow, the values of full width half maximum are low and the crystallite size values are high. These observations show that the films obtained at these doping rates have a better crystal structure. Similar observation for Y doped CdO film can be found in that study done by S. Ahmed et al. [29].

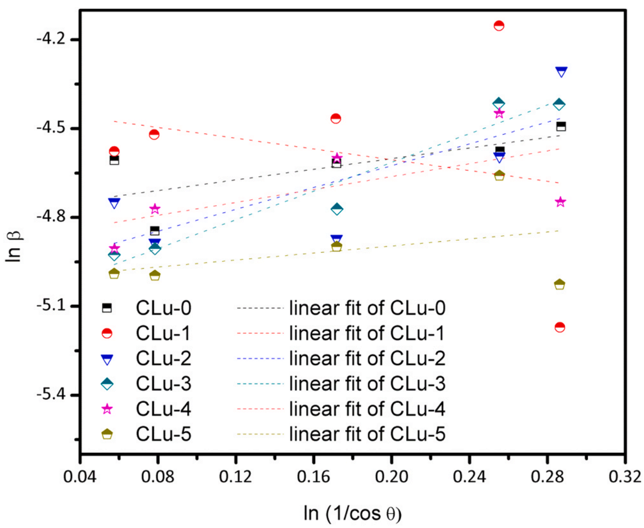

Fig. 2. Modified Scherrer plots of pure and Lu doped CdO thin films.

In reality, not all materials crystallize perfectly. There are necessarily deformed situations. The strain is a defect that occurs as a result of the crystal's imperfection or strain on the lattice. Grain size and defects affect the half width of peak. Using the Williamson-Hall (WH) method, crystal size and lattice tension can be calculated for each sample [30]. The WH technique is a very useful and experimental technique that distinguishes these two effects from each other. Strain and particle size are not linearly independent of each other. The peak width of the Bragg reflections on this face is given by the following equations as the sum of the peak widths from both effects. Considering that the contribution of particle size and stress to line expansion is independent of each other, the observed line width is the sum of the two terms [31]:

$$\beta_D{}^2 = \beta_{measered}{}^2 - \beta_{instrumental}{}^2 \tag{3}$$

$$D = \frac{K\lambda}{\beta_D \cos\theta} \rightarrow \cos\theta = \frac{K\lambda}{D}\left(\frac{1}{\beta_D}\right) \tag{4}$$

where β_D is the FWHM of the peak broadening, K is the shape factor, D is the crystallite size and λ is the wavelength of the CoK_α radiation. Taking above equations into consideration [32]:

$$\beta_{hkl} = \beta_s - \beta_D \tag{5}$$

$$\beta_{hkl} = \left(\frac{k\lambda}{Dcos\theta}\right) + (4\varepsilon tan\theta) \tag{6}$$

$$\beta_{hkl}cos\theta = \left(\frac{k\lambda}{D}\right) + (4\varepsilon sin\theta) \tag{7}$$

When the 4sinθ versus βcosθ graph is drawn using the allowed planes of the crystal, the microstrain "ε" is calculated from the slope and the crystal size is calculated from the y-axis cut point [33], as shown in Fig. 3. Their variations and the values of D, ε are calculated using the modified Scherrer method and W–H analysis for pure and Lu doped CdO films and given in Table 1. Furthermore, the values of (hkl), 2θ, and β_{hkl} used for the modified Scherrer method and W–H method are also summarized in Table 1.

As seen in Fig. 3, the plotted graph clearly indicates that CLu-0, CLu-1, and CLu-5 samples exhibit negative gradient which represents the negative strain as well as CLu-2, CLu-3, and CLu-4 samples exhibit positive gradient which represents the positive strain. Calculated average crystal sizes of the all films appear in harmony with each other. Considering the XRD measurements, it can be said that the film quality varies with the addition of Lu as the strain value appears at different values in the CdO structure.

3.2. Optical investigations

As the use and technology of optoelectronic circuits improve, the study of optical properties of semiconductor materials is becoming increasingly important. The working principle of optoelectronic circuits is based on the interaction of the electrons of the semiconductor and the photons sent on the material to form free charge carriers in the semiconductor. Therefore, studying the interaction of electrons with photons gains importance in terms of the practical application of semiconductors and the determination of their physical properties. Semiconductors absorb and emit photons by undergoing transitions between different allowed energy levels, in accordance with the general theory of photon–atom interactions. The absorption of a photon can create an electron–hole pair and

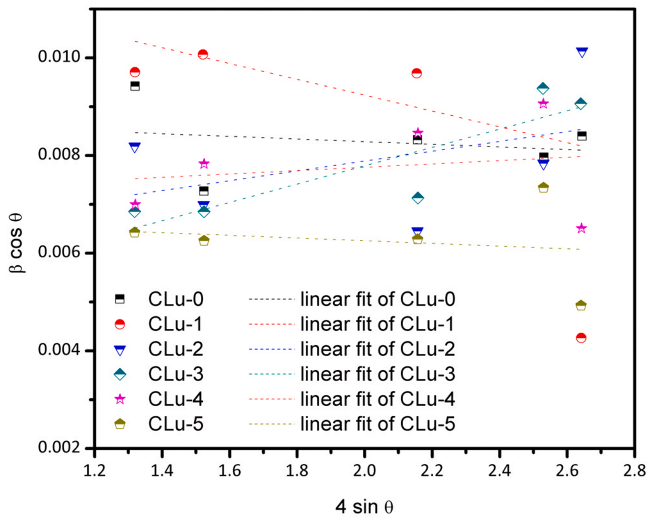

Fig. 3. Williamson-Hall (WH) plots of pure and Lu doped CdO thin films.

the recombination of an electron and a hole can result in the emission of a photon are the two fundamental processes that operate of almost all semiconductor optoelectronic devices [34]. When a photon is sent on a semiconductor; as a result of the interaction of electrons of atoms with photons, many optical phenomena such as absorption, transmittance, and reflection take place. A photon is sent on a semiconductor material; if the semiconductor has an energy equal to or greater than the forbidden energy range (E_g), then an electron in the valence band is excited and passes to the conduction band, and this phenomenon is called absorption. Absorption measurements, which is one of the methods we can learn about some optical properties of thin films, were taken between 300 and 1300 nm wavelengths for Lu doped CdO thin films and the results are shown in Fig. 4.

As seen in Fig. 4, the absorption graph of all other films showed a sharp increase from 600 nm to 300 nm except for pure and 1% Lu doped CdO films. Outside this absorption limit, the samples at wavelengths greater than 600 nm behaved as almost transmissive and as a strong absorber at wavelengths smaller than 600 nm. Absorption graphics of pure and 1% Lu doped CdO films started to increase by 500 nm. When the absorption edges of all films in the wavelength range of 300–600 nm were examined, it was found that the absorption edge of CdO films shifted towards longer wavelengths due to the increase in Lu contribution. A similar observation was studied for Ga-loaded CdO nanocrystalline thin films [35]. This shift may result from the s, p-d spin exchange interaction between the free s- or p-type band electrons of the Cd and O atoms [36].

If the photons sent onto the material do not have the energy to excite an electron to a higher energy level, they are substituted for absorption and the material behaves as transparent. As can be seen from the transmittance spectra of CdO thin films produced with different Lu additives in Fig. 5, all samples exhibited high transmittance in the visible region, which is a typical feature of CdO thin films, and a relatively low transmittance in the ultraviolet region [37]. In the transparent region, the average % transmittance was found to be 92.71, 93.64, 76.47, 69.00, 81.82 and 58.04 for CdO films with 0%, 1%, 2%, 3%, 4%, and 5% Lu dopants, respectively.

The transmittance of the pure and 1% Lu doped CdO thin films in the visible region corresponds to approximately 93% and 94%, which indicates that the films are transparent in the visible region. With the increase of Lu additive, there was a decrease and an increase in the average transmittance values of thin films and it finally decreased up to 58% in the 5% Lu doped CdO thin film. Ganesh et al. found that the average transmittance of the sol-gel derived 3% Ce-doped CdO thin films is almost 80% in the transparent region [38].

Using the basic absorption spectrum data obtained from UV–Vis Spectroscopy measurements, it was determined that thin films have direct band structures. Then, using the Tauc method, the optical band gap values were calculated as follows [39,40]:

$$(\alpha h\nu)^2 = A(h\nu - E_g) \tag{8}$$

Here, "α" is the absorption coefficient, A is a constant value and the hv is energy of photon. The direct band gap of the films is obtained with the fit applied on the energy axis of the linear part of the $(\alpha h\nu)^2$ graphic against $(h\nu)$ [41]. Calculated Eg values are in the range of 2.24–2.69 eV as given in Fig. 6.

Depending on the amount of Lu, some fluctuations are observed in Eg values. That is, by increasing the amount of Lu contribution from 0% to 1%, the Eg value increased from 2.58 eV to 2.69 eV, and then this value decreased to 2.41 eV and 2.34 eV for 2% and 3% Lu contribution, respectively. It increased again in 4% Lu additive amount and finally, the Eg value of 5% Lu contribution decreased to 2.24 eV. The possible reason for the increase in Eg value during the transition from pure CdO to 1% Lu doped CdO can be explained by the Burstein-Moss effect (BM effect) [42]. This change in the optical band gap values of the films can be the result of the change in the crystal structure of the CdO films as a result of Lu doping at different rates. The change in the crystallite size of the films mentioned in the structural analysis part directly affects the optical properties of the material [43].

Another interaction between semiconductor material and photon is reflection. The intensity of the light falling on the material is proportional to the intensity of the light reflected on the material. In this case, the surface of the semiconductor material is flat and the

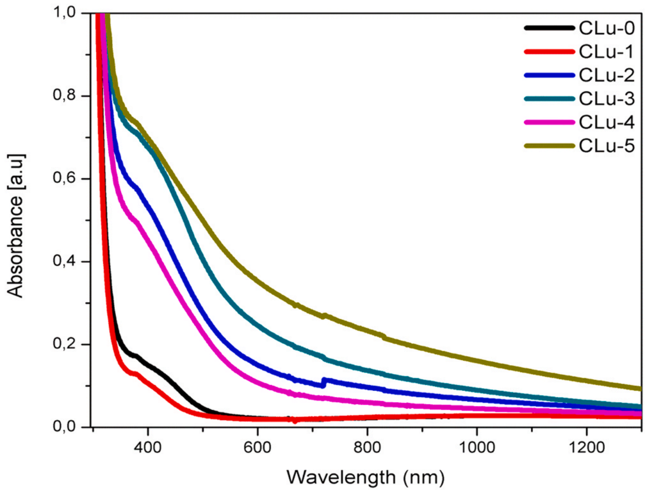

Fig. 4. Optical absorbance spectra of the CdO films with various Lu content.

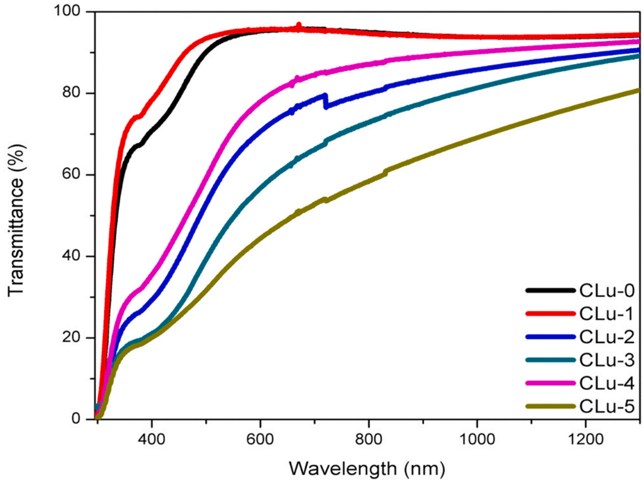

Fig. 5. Optical transmittance spectra of the CdO films with various Lu content.

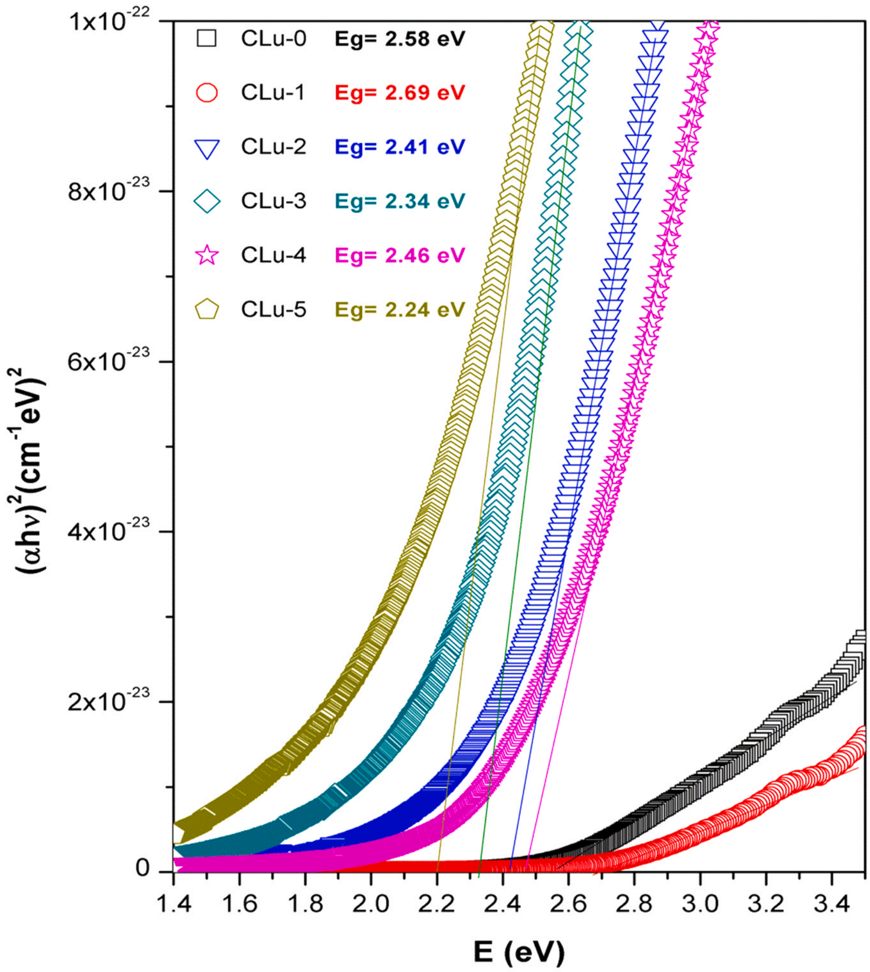

Fig. 6. Variation of optical band gap of CdO films with Lu content.

intensity of the light falling on the sample (photon energy) is lower than the forbidden band gap energy of the semiconductor material, and some of the photons are reflected. The reflectance for the samples has been determined by using the transmission (T) and absorbance (A) data. Using these spectra, the dependence of the refractive index to the wavelength was obtained for the samples using the below formula [44] and is shown in Fig. 7:

$$n = \frac{1+R}{1-R} + \sqrt{\frac{4R}{(1-R)^2} - k^2} \tag{9}$$

This equation is the real part of the refractive index, $k = \alpha\lambda/4\pi$ is the imaginary part of the refractive index and is expressed as the extinction coefficient. The refractive index of the material is a function of the wavelength. Materials with a high refractive index are more reflective because the reflection values are directly dependent on the refractive index values. As the atomic number increases, the number of electrons will increase and the polarization will increase, so photons are more affected and more refracted. For CdO: Lu thin films, it is seen that the refractive indices increase from long wavelengths to shorter wavelengths. The value of n lies between 1.31 and 2.57 in the visible and IR spectrum for all the films and is consistent with the reports on Tb-doped CdO films were studied by Ganesh et al. [45]. When the energy of the photons on the material increases, they will interact more strongly with the electrons and thus they will be broken more. As a result of this, it is an expected result that the refractive index of the material increases towards shorter wavelengths. A similar type of trend is observed in that the nitrogen is showing a considerable influence on the refractive index of CdO semiconducting thin films [46].

One of the optical parameters of any material is its complex dielectric constant. The dielectric coefficient for a semiconductor is a measure of the ability to store charges on that semiconductor. In semiconductors, the fundamental electron excitation spectrum of thin film is related with the frequency dependent complex electronic dielectric constant. Also, the frequency distribution of the complex dielectric constant fully characterizes the propagation, reflection and loss of light in multilayer structures. Dielectric constant consists of real (ε_1) and imaginary (ε_2) parts and is calculated from the following equations depending on the refractive index and extinction coefficient [47]:

$$\varepsilon_1 = n^2 - k^2 \tag{10}$$

$$\varepsilon_2 = 2nk \tag{11}$$

The variation of the dielectric constant of thin films with wavelengths of the real (ε_1) and imaginary (ε_2) parts is given in Figs. 8 and 9. As a result of these graphs, it is seen that the real part of the dielectric constant of the films is very close to the refractive index graph. It has been observed that the real and imaginary dielectric coefficient values of pure and Lu doped CdO thin films decrease with increasing wavelength. According to the above result, the increase in the doping concentration rate may lead to a rearrangement of the localized state, which causes a decrease in the dielectric constants of the films due to the increase in constant actual isolation.

The real part of the complex dielectric constant is higher than the imaginary part of the dielectric constant. A similar observation was found for sol-gel coated Sb-doped CdO films studied by Serbetci et al. [48].

It is important to know the optical conductance of the pure and Lu doped CdO thin films for their applications in optoelectronic devices. Optical conductance (σ_{op}) is one of the important quantities that define the optical properties of materials. σ_{opt} is used to detect allowable interband optical transitions of a material and its formula is given as follows [49]:

$$\sigma_{op} = \frac{\alpha nc}{4\pi} \tag{12}$$

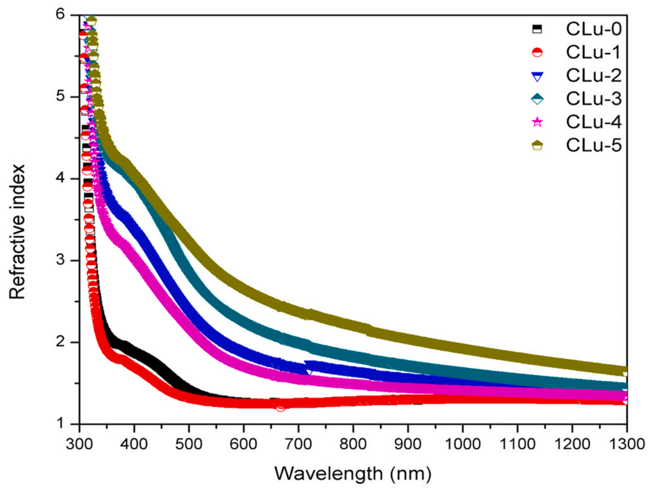

Fig. 7. The variation of refractive index with wavelength for pure and Lu-doped CdO.

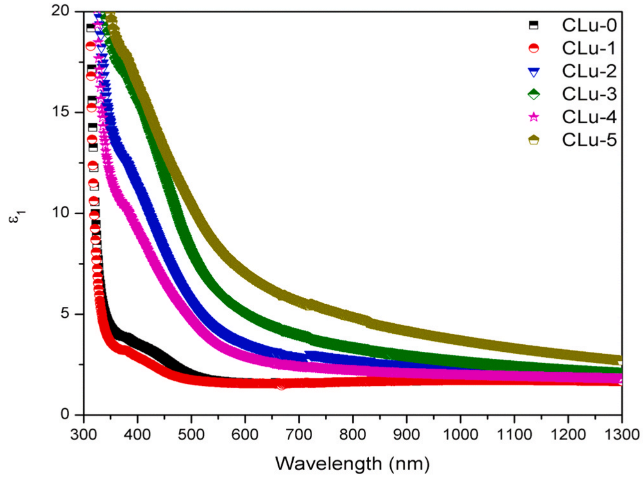

Fig. 8. The variation of real dielectric constant with wavelength for pure and Lu-doped CdO.

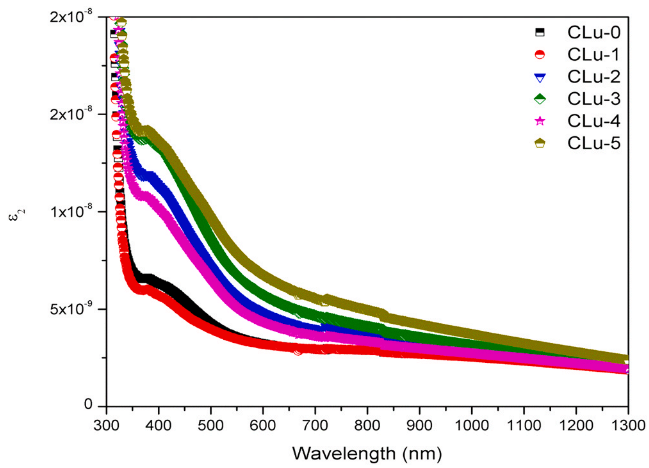

Fig. 9. The variation of imaginary dielectric constant with wavelength for pure and Lu-doped CdO.

where c is the velocity of light. The σ_{opt} plot as a function of photon energy for pure and Lu doped CdO thin films are shown in Fig. 10.

For optoelectronic applications, electrical conductance (σ_{elec}) has a significant impact on performance of materials. The σ_{elec} values of the pure and Lu doped CdO thin films were obtained from the following equation [50]:

$$\sigma_{elec} = \frac{2\lambda\sigma_{op}}{\alpha} \tag{13}$$

As can be seen in Figs. 10 and 11, the optical and electrical conductance values for pure and Lu doped CdO thin films varied with the Lu contribution as a function of energy. Also, it is observed that optical and electrical conductance values increase with the increasing energy value for all films. This may be due to the excitation of electrons by photon energy, and the optical and electrical conductance increases with doping. A similar observation in optical conductance was found in In: CdO film with increase doping concentration studied by Ganesh et al. [51]. Also, the electrical conductance values are about 10^{14} times bigger than that of the optical conductance values. Ganesh et al. studied sol-gel deposited Er-loaded CdO thin films and they found that the optical conductivity is in the order of 10^{13} bigger than compared to that of the electrical conductance values [52]. Both the electrical and optical conductivities are comparable to other metal oxide thin films [53].

3.3. SEM investigations

SEM, which reflects the changes of many properties such as; optical, electrical etc. and can be used for a preliminary evaluation to determine whether the material is suitable for the desired application in a way, offers researchers much better images with the device technology developed in recent years. In order to have information about whether there is a change in the surface morphology of the

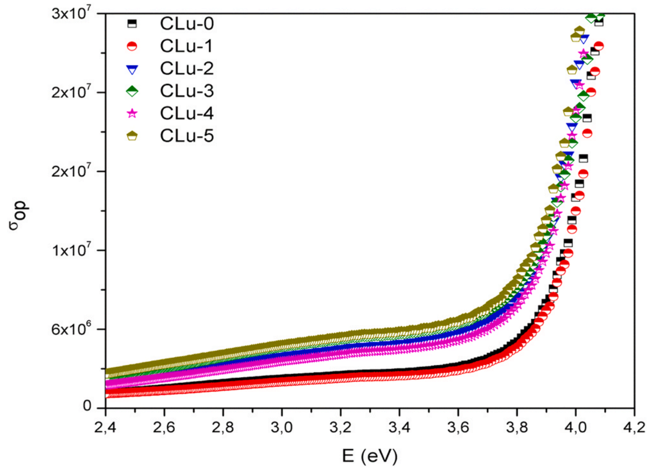

Fig. 10. The optical conductance versus photon energy of the pure and Lu-doped CdO.

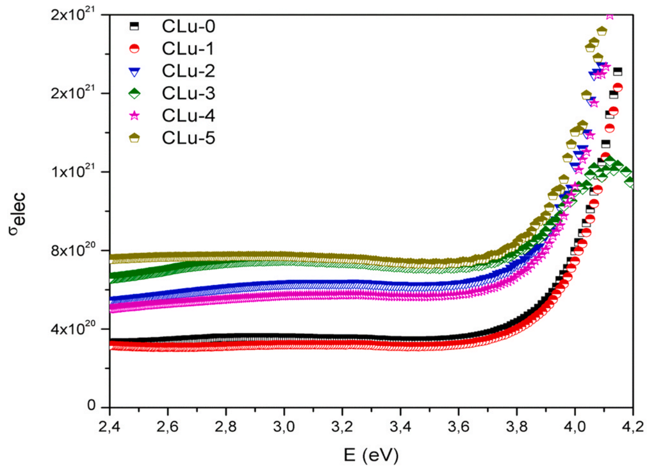

Fig. 11. The electrical conductance versus photon energy of the pure and Lu-doped CdO.

pure and Lu doped CdO semiconductors before and after the doping, the surface images of the samples were taken 100.000 times magnified and shown collectively in Fig. 12. In Fig. 12, it is seen that the surface morphologies of the samples change as the Lu contribution increases.

In Fig. 12, SEM images are taken from CdO: Lu thin films are given. When the surface properties are examined from these pictures, it is seen that the CdO structure is homogeneously covered on the substrate, there are no agglomeration formations and there are no gaps on the surface, so that the grains have better adhered to each other. The SEM observation is similar to the earlier study for Eu- loading CdO semiconducting thin films [54]. The particles were formed as a mixture of columnar and granular microstructures.

4. Conclusion

In this study, doping was applied to optimize the physical, structural and surface properties of CdO films and to increase the efficiency of the devices they are used in, and Lu element was preferred for this. For the production of CdO: Lu thin films, the sol- gel spin coating technique was used and the structural, surface and optical properties of all films. As a result of the analysis of x-ray diffraction patterns of CdO: Lu thin films, it was determined that all films belong to CdO in cubic structure and they have a polycrystalline structure. For samples in which the crystallite sizes of films obtained from the modified Scherrer Method were smaller than the crystallite sizes obtained from W–H Analysis, the strain of these samples has a negative value. It was observed from the optical spectroscopy measurements, the average % transmittance was found to be 92.71, 93.64, 76.47, 69.00, 81.82 and 58.04 for CdO films with 0%, 1%, 2%, 3%, 4%, and 5% Lu dopants, respectively in the transparent region. The absorption graph of all other films showed a sharp increase from 600 nm to 300 nm except for pure and 1% Lu doped CdO films. By calculating the absorption coefficient from the basic absorption spectra, optical band gap energies of the films were found between 2.24 and 2.69 eV. The refractive index decreases with increasing wavelength, that is, it exhibits a normal dispersion feature. From the surface photographs of the CdO: Lu thin films

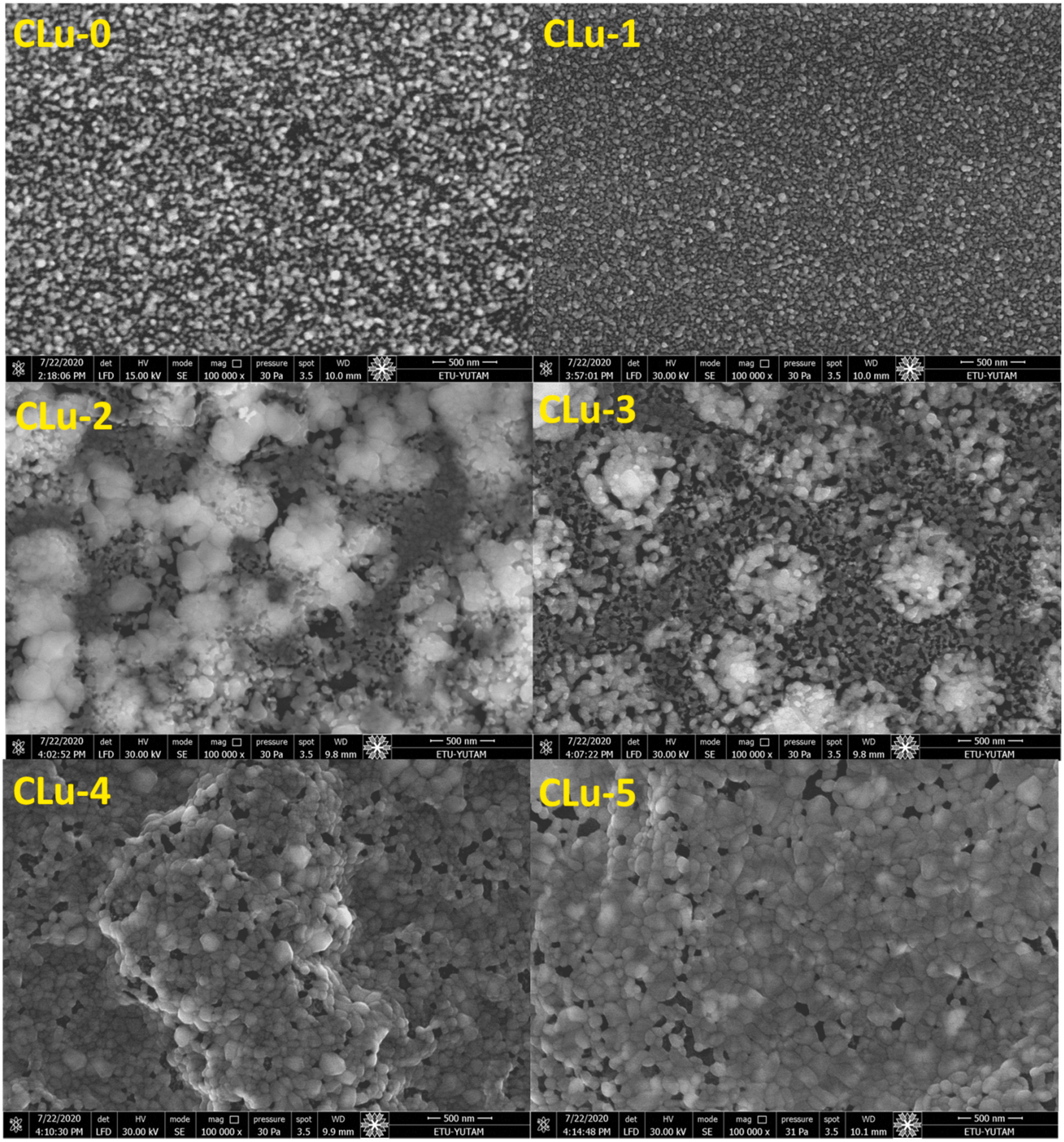

Fig. 12. SEM images of pure and Lu doped CdO thin films.

examined by SEM, it was seen that the CdO films have an almost homogeneous structure. It was observed that the real and imaginary dielectric coefficient values of pure and Lu doped CdO thin films decrease with increasing wavelength. It was observed that optical and electrical conductance values increase with the increasing energy value for all films. The changes in the physical properties of all films might be attributed to the smaller radius of the dopant ion, compared to the ionic radius of the Cd^{2+} in the Lu^{3+}-doped CdO nanomaterials. Thus the sol gel method and spin coating is a good technique for producing nano-structured materials. Lu doped CdO is a good candidate for optoelectronic devices based on the tunable band gap and optical characteristics.

Declaration of Competing Interest

The author declares that there is no conflict of interests regarding the publication of this paper.

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