Effect of annealing temperature on structural morphological and optical properties of spray pyrolyzed Al-doped ZnO thin films

M Humayan Kabir\textsuperscript{1}, M Mintu Ali, M Abdul Kaiyum and M S Rahman

Department of Glass & Ceramic Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh

\textsuperscript{1} Author to whom any correspondence should be addressed.

E-mail: mhk.gce11@gmail.com

Keywords: AZO thin films, Spray pyrolysis, Annealing, X-ray diffraction (XRD), Surface morphology (SEM), Optical properties

Abstract

Aluminium doped zinc oxide (AZO) thin films were prepared on glass substrate by spray pyrolysis technique and subsequently their structural, morphological and optical properties were investigated and analyzed as a function of annealing temperature. The films were deposited at 350 °C and were annealed at temperature 350, 400, 450 and 500 °C. X-ray diffraction (XRD) analysis confirms that both deposited and annealed films are polycrystalline in nature and have hexagonal wurtzite structure. The crystalline size as well as the crystalline quality of the film was found to increase with the increase of annealing temperature to a certain point. However, the dislocation density and the compressive stress induced in as-deposited AZO films reduce with annealing temperature. SEM image reveals that the deposited film has nanorope like morphology. The average diameter of the rope and the density of the morphology increases with the increase of annealing temperature. As the annealing temperature increases from 350 °C to 450 °C, the average transmittance of the films increases and the band gap value decreases from 3.25 eV to 3.17 eV. In addition, obtained results also show that Urbach energy, extinction coefficient, refractive index, optical conductivity has changes noticeably with annealing temperature.

1. Introduction

Transparent conducting oxides (TCO) materials have attracted significant research attention in the recent years due to their potential applications in optoelectronic devices such as in gas sensors, piezoelectric transducers, touch screens, liquid crystal displays, light emitting devices and in solar cells [1, 2]. So far, indium tin oxide (ITO) was a typical commercial TCO. ITO film was very popular choice for TCO materials, because of its low resistivity, good electrical and optical properties [3–5]. However, ITO film has some drawbacks including high cost, low stability in hydrogen plasma and toxicity [5]. Therefore, the supply of the rare and expensive indium in ITO is rapidly being limited [4]. However, the scarce and toxic nature of indium and instability of ITO have stimulated researchers to explore alternative TCO materials for ITO [3]. In recent years, zinc oxide (ZnO) films have become an ideal alternative TCO material due to its cost-saving and wide availability [4]. Unlike ITO, zinc oxide (ZnO) is a non-toxic and inexpensive material. ZnO is a Type II–VI semiconductor with a wide band gap (\(E_g = 3.2–3.4\) eV at 300 K), high transmittance in the visible light region, a high piezoelectric constant and a large exciton binding energy (>60 meV) [6]. It is chemically and thermally stable under hydrogen plasma processes and is commonly used for the production of solar cells, gas sensors, optical waveguides, surface acoustic devices, piezoelectric transducers and varistors [7, 8]. Nominally, pure ZnO is an n-type semiconductor, but its optical and electrical properties seem to be not very stable, especially at high temperatures [9]. For the purpose of improving electrical, optical and chemical properties, ZnO can be doped with various dopants to form new materials for TCO films [10]. The properties of ZnO thin films can be significantly modified by doping with Group III elements of the periodic table, such as aluminum (Al), indium (In), gallium (Ga), and boron (B) [6]. Another positive effect of doping of these materials is the ability to stabilize the film at
high temperature [11]. Among these possible dopants, aluminium (Al) is the best one, popularly used in growth process resulting in high–quality, low–resistivity Al-doped ZnO (AZO) thin films [9]. AZO is a key functional oxide that has attractive characteristics such as low cost, non–toxicity, strong ultraviolet emission, good optical transmission in the visible and near-infrared (IR) regions, high electrical conductivity, mechanical stability etc [8, 9, 12]. Now a days, Al-doped ZnO (ZnO:Al) thin films have become an alternative potential candidate for ITO films recently because of not only their comparable optical and electrical properties to ITO films, but also their higher thermal and chemical stability under the exposure to hydrogen plasma and low fabrication cost than ITO [5, 11, 13]. Due to the large value of optical transmittance and high carrier concentrations AZO film has numerous applications involving transparent electrodes in solar cells, flat panel displays, liquid crystal displays (LCDs), organic light emitting diodes (OLEDs), and dye-sensitized solar cells (DSSCs) and transparent thin film transistors [1, 11]. In general, the material properties can be enhanced by annealing processes. During post-annealing process of thin films, recrystallization occurs, which causes improvement in crystallinity of the films and increases grain size depending up on the working temperature. Therefore, annealing of the films at optimized conditions could modulate residual stress and improve the film quality with reduced surface roughness and defects present in the films [6, 10, 14]. Several techniques have been used for the preparation of AZO thin films. The most explored deposition techniques include spray pyrolysis, chemical vapor deposition, sputtering, reactive evaporation, pulsed laser ablation, spin coating, dip coating, hydrothermal method etc [7]. Out of these, spray pyrolysis is of particular interest due to its inexpensive cost, simplicity, no high vacuum requirement, safety, less waste production and capability of coating large areas [2]. In this research work, 2 wt% Al-doped ZnO thin films has been fabricated by spray pyrolysis technique. Further, the films were annealed at different temperature (350, 400, 450 and 500 °C) to investigate the effect of annealing on structural, morphological and optical properties of AZO thin films.

2. Materials and methods

2 wt% Al-doped ZnO thin films were deposited on glass substrate by spray pyrolysis (SP) technique at 350 °C. The glass substrate was cleaned by dissolving it into liquid detergent solution about 24 h, then washed it by distilled water and dried. The glass substrate was cleaned carefully because any dirt or impurity may incorporate to the growth of films and can reduce the quality of the films. 0.1 M concentrated solution was prepared by dissolving zinc acetate dihydrate (Zn(CH₃COO)₂·2H₂O) and aluminum nitrate nonahydrate (Al(NO₃)₃·9H₂O) into distilled water. The details SP process was described in our previous work [15]. The possible chemical reaction between the source materials on heated glass substrate may be taken place as follows [16].

\[(\text{CH}_3\text{COO})_2\text{Zn} \cdot 2\text{H}_2\text{O} + \text{Al(NO}_3)_3 \cdot 9\text{H}_2\text{O} + \text{H}_2\text{O} \rightarrow \text{ZnO} + \text{Al}_2\text{O}_3 + \text{CO}_2 + \text{CH}_4 + \text{Steam}\]

The deposited AZO films were then annealed in a muffle furnace at various temperatures (350, 400, 450 and 500 °C) for 30 min under air ambient atmosphere. The heating rate was maintained 3 °C min⁻¹. The time-temperature annealing cycle is graphed in figure 1.

The crystal structure of the deposited and annealed AZO thin films was analyzed by Bruker D8 Advanced x-ray Diffractometer with CuKα (λ = 1.5406 Å) radiation within the Bragg angle 20–60°. The surface morphology of the films was revealed by EVO-18 research scanning electron microscopy (SEM). Optical properties such as transmittance and absorbance values of the films were recorded using Halo SB-10 UV–vis single beam spectrophotometer within the wavelength from 300 to 900 nm.
3. Results and discussions

3.1. Structural analysis (XRD)

X-ray diffraction (XRD) technique has been used to identify the crystalline structure of AZO thin films. Figure 2 shows the XRD pattern of as-deposited and annealed at 350, 400, 450 and 500 °C AZO thin films. It is observed that the XRD pattern has five well defined peaks. The peaks are around at 31.93, 34.54, 36.38, 47.56 and 56.75° angular position and their corresponding miller planes are (100), (002), (101), (102) and (110) which matches the JCPDS data (Card No. 36-1451). It is clear that all films are polycrystalline hexagonal wurtzite in nature and grows along (101) plane.

To analyze and compare the effect of annealing temperature on AZO films, the full width at half maximum (FWHM, $\beta$) have been calculated along (101) plane from the x-ray diffraction spectrogram and are tabulated in table 1. The intensity value of the (101) peak was measured and it was found 70, 173, 184, 223 and 155 for deposited and annealed at 350, 400, 450 and 500 °C AZO thin films respectively. The intensity of (101) peak increases and the FWHM value decreases with the increase of annealing temperature up to 450 °C. Hence the peak intensity of the AZO film annealed at 500 °C was found to decrease. The increase in peak intensities indicates an improvement in the crystallinity of films i.e. the crystalline quality of the AZO film improved when annealed at a higher temperature [4–7, 10, 11, 17]. From this statement it can be said that the film which has been annealed at 450 °C have the enhanced crystalline quality. Moreover, the crystallite size corresponding to (101) plane of the films has been calculated by Scherrer formula [1]. The crystallite size of the films increases from 14.32 to 19.66 nm when the annealing point reaches to 450 °C. This indicates that the grain size became larger and the crystallinity becomes better with increasing annealing temperature [4, 5, 7].


Table 1. X-ray diffraction (XRD) parameters of as-deposited and annealed Al-doped ZnO thin films for (101) plane.

| Sample          | FWHM ($\beta$) | Grain size, D (nm) | Dislocation density $\delta \times 10^{-3}$ (lines nm$^{-1}$) | Strain, $\varepsilon$ (%) | Stress (GPa) |
|-----------------|-----------------|--------------------|---------------------------------------------------------------|---------------------------|--------------|
| As-deposited    | 1.1676          | 14.32              | 4.87                                                          | 0.24                      | −55.87       |
| Annealed at 350 °C | 1.0838      | 15.44              | 4.20                                                          | 0.23                      | −53.54       |
| Annealed at 400 °C | 1.0766      | 15.54              | 4.14                                                          | 0.22                      | −51.22       |
| Annealed at 450 °C | 0.8514      | 19.66              | 2.59                                                          | 0.17                      | −39.58       |
| Annealed at 500 °C | 0.9844      | 17.00              | 3.46                                                          | 0.20                      | −46.56       |

Dislocations are linear defects in the crystal structure. Dislocation density ($\delta$) is defined as the dislocation line length in the unit volume and is a measure of the number of defects in the crystal [18]. The dislocation density of the deposited and annealed films can be calculated by the following equation [2]

\[
\delta = \frac{1}{D^2}
\]  

(1)

Here, $D$ is the grain size. The FWHM ($\beta$) values have been used to determine the strain ($\varepsilon$) of the films by the following relation [19]

\[
\varepsilon = \frac{\beta \cos \theta}{4}
\]  

(2)

The stress induced in the AZO films can be obtained by using the biaxial strain model [1]

\[
\sigma_{film} = -232.8 \times \varepsilon \text{ (GPa)}
\]  

(3)

The calculated values of dislocation density, strain, stress are tabulated in table 1. From table 1 it is found that the calculated stress values both for as-deposited and annealed films are negative. The negative sign of the stress value indicates that all the films are in compressive stress. It is noticeable that the as-deposited films have larger stress value and this stress value decreases as the annealing temperature reaches to 450 °C i.e. annealing temperature relaxes the film stress.

The dislocation density and strain values of the film have been found to decrease with the increase of annealing temperature up to 450 °C and then increases. This tendency indicates that annealing reduces the lattice defects of the films and increases the crystalline quality by modifying the periodic arrangements of atoms in the crystal lattice [1, 2, 18, 19]. The dislocation density and strain value show a reverse relation when the films are annealed above 450 °C i.e. at 500 °C temperatures. Because higher annealing temperature deteriorate the crystalline quality of the films. Besides, Tseng [12] reports that this may be caused by the oxidation of the dopant aluminum in AZO thin films during the high annealing temperature.

3.2. Surface morphology (SEM)

The surface morphology of the AZO films was observed by SEM. Figures 3 and 4 shows the surface morphology of AZO films at low (150X) and high magnifications (200X).

Figure 3 shows that the morphology of the films consists of ring like structure distributed all over the surface. The diameter and density of the ring becomes higher when the films are annealed at 400 °C compared to the as-deposited films. However, when the films are annealed after 450 °C, the micro-ring disappears. However, when the films annealed at 500 °C, it gets oxidized and which induced roughness into the film surface. Besides there also have a lot of voids and pinholes into the films surface. Due to the presence of roughness, cracks and voids into the films, the properties of the films may be altered.

Figure 4 clearly indicates that the as-deposited film has rope like structure. The ropes have random orientation all over the surface. The average diameter of the rope was found approximately 388 nm for the as-deposited films. The average diameter of the rope increases from 388 nm to 616.5 nm when the films are annealed at 450 °C temperature i.e. the diameter of the rope increases with the increases of annealing temperature. However major change was noticed at 500 °C annealing temperature. It is obvious that, the shape of the ropes almost changes when the films are annealed at 500 °C. This tendency may due to oxidation of the films at higher temperature as the films have been annealed at air ambient. However, agglomeration has also been observed for 500 °C annealed film. Besides, the density of the microstructure of the films increases with the increase of annealing temperature. Sabeeh et al [17] reported that the density of AZO films increases with annealing temperature. However due to annealing at higher temperature, the grain boundaries got sufficient energy and merge with each other forming a bigger grain. The internal stresses of the films, which was generated during deposition process also removed during annealing at elevated temperatures. From the XRD analysis it was also observed that with the increase of annealing temperature the crystallite size increases i.e. SEM result has...
good agreement with XRD analysis. Thus, the crystal growth of the AZO films can be controlled by post heating temperature [11].

3.3. Optical properties
The knowledge of optical properties of materials has a great significance in the designing and analysis of optoelectronic devices. Moreover, optical measurements are extensively used for characterization of the quality of the materials [7, 20]. Figure 5 shows the optical transmittance spectra of the deposited and annealed thin films within the wavelength range 370 to 900 nm. Figure 5 clearly indicates that the annealing temperature affects the optical transmittance of AZO thin films. The average transmittance value within the visible region was found 70.30% for the as-deposited film. However, the average transmittance value within the visible region reaches to 73.59, 78.47, 82.46 and 81.16% when the films are annealed at 350, 400, 450 and 500 °C respectively. So, the transmittance values of the films have been found to increase with annealing temperature up to 450 °C and then decreases afterwards. Many authors report that the increase in transmittance of the films obtained by annealing is related to an increase in crystallinity of the films and the improvement of crystallinity leads to decrease in optical scattering and defects [5, 6, 13, 17]. Besides, the decrement behavior of transmittance obtained at annealing temperature 500 °C may be due to the oxide formation into the films. However the film annealed at

Figure 3. SEM image of as-deposited and annealed Al-doped ZnO thin films.
500 °C is not smooth enough and still contains void as shown in figures 3 and 4. As a result the optical scattering is high (F-centers) and is responsible for the decrease in transmittance.

The transmittance value of the films decreases near the ultraviolet region and the fundamental absorption edges are found at 382 nm for deposited film and at 393 nm for 500 °C annealed thin films. So, the absorption edge shifts from the lower to higher wavelength with annealing, which indicates the increase of optical transmittance. Many researcher reports that the film had an average transparency ≥75% in the visible region which may be associated with the film’s good structural homogeneity and crystallinity and this is good for optical device application [2, 14, 21].

Optical transmittance data were used to calculate the optical band gap ($E_g$) energy of the AZO films by using the Tauc’s model [20]

$$\alpha(h\nu) = A(h\nu - E_g)^m$$  \hspace{1cm} (4)

Here, $\alpha$ is the absorption coefficient, $\nu$ is the photon frequency, $A$ is a constant, $h\nu$ is the photon energy, and $m$ is a constant that determines the type of optical transition. The absorption coefficient, $\alpha$ was obtained through Lambert’s Law [15]. The optical band gap value was obtained from the plot $(\alpha h\nu)^2$ versus $(h\nu)$ as shown in figure 6 and the calculated values are tabulated in table 2.
The linear dependence of \((\alpha h\nu)^2\) with \((h\nu)\) indicates that both as-deposited and annealed ZnO thin films are direct transition type semiconductors \([1, 20]\). The value of optical band gap of as-deposited AZO film was found 3.25 eV. From table 2, it is noticeable that the optical band gap changes with annealing temperature. With the increases of annealing temperature upto 450 °C, the band gap value decreases to 3.17 eV. Furthermore, the band gap value increases with the increases of annealing temperature i.e. optical band gap shows a reverse relationship with annealing temperature. Many author reports that annealing process improves the crystallinity and increases average grain size of the films that results in decreasing defects concentration as well as reduce the strain in the films; therefore, the optical band gap energy decreases \([17, 22]\). The band gap of the AZO film annealed at 500 °C was found to increases, this tendency may occur due to the oxide formation into the films at this elevated temperature.

The Urbach tail is an essential parameter used to estimate the level of crystallinity and structural defect or degree of disorder present in the film materials \([13, 14, 23]\). Generally, the optical transmittance and optical band gap structure affected by the width of localized states available in the films which are known as Urbach tail. This exponential tail appears in the low crystalline, poor crystalline, the disordered and amorphous materials because these materials have localized states which extended in the band gap \([23, 24]\). The urbach energy \((E_U)\)
are given as
\[
\alpha_0 = \text{constant}
\]

Figure 7 shows the ln(α) versus (hυ) curve of as-deposited and AZO films annealed at different temperature. The urbach energy was estimated by taking the reciprocal value of the straight line cuts the x-axes and the values are tabulated in table 2.

From the data table 2, it is observed that the urbach energy or the width of the band tail decreases with the increases of annealing temperature up to 450 °C. This tendency proves that the degree of structural disorder decreases with the increase of annealing temperature up to a certain point i.e. 450 °C. From the calculated value it is obvious that the film shows minimum structural disorder when the films are annealed at 450 °C. Afterwards with the increase of annealing temperature the urbach energy increases. However, oxide may be formed into the films surface at 500 °C annealing temperature. Thus, the distortion of crystal structure of the film annealed at 500 °C occurred due to oxide formation which may cause sudden increase of urbach energy.

The extinction coefficient (k) can be calculated from the following relation
\[
k = \frac{4\pi k}{\lambda}
\]

Table 2. Optical band gap and Urbach energy of as-deposited and annealed Al-doped ZnO thin films.

| Sample           | Band gap, E_g (eV) | Urbach energy, E_u (eV) |
|------------------|--------------------|-------------------------|
| As-deposited     | 3.25               | 0.3578                  |
| Annealed at 350 °C | 3.23                | 0.3556                  |
| Annealed at 400 °C | 3.18                | 0.3544                  |
| Annealed at 450 °C | 3.17                | 0.3501                  |
| Annealed at 500 °C | 3.19                | 0.3523                  |

where α_0 is a constant. Figure 7 shows the ln(α) versus (hυ) curve of as-deposited and AZO films annealed at different temperature. The urbach energy was estimated by taking the reciprocal value of the straight line cuts the x-axes and the values are tabulated in table 2.

The extinction coefficient (k) can be calculated from the following relation [15]
\[
\alpha = \frac{4\pi k}{\lambda}
\]

Here α is the absorption coefficient. Figure 8 shows the wavelength dependent extinction coefficient spectrograph of as-deposited and AZO thin films annealed at different temperature.

It is observed from figure 8 that the extinction coefficient decreases with the increases of annealing temperature up to 450 °C and then increases onwards. This decrement behavior of extinction coefficient with the increase of annealing temperature proves that the fraction of light lose due to the scattering process decreases with the increase of annealing temperature up to a certain point [25, 26].

The refractive index (n) is a fundamental property for any optical material. It is closely related to the electronic polarization of ions and the local field inside these optical materials. So, the determination of refractive indices is considerably very important, especially for the materials that can be used for the fabrication
of any optical devices, e.g. switches, filters and modulation, etc. The refractive index can be calculated by using the reflectance value as follows [27]

\[ n_r = \frac{1 + R}{1 - R} + \frac{4R}{(1 - R)^2} - k^2 \]  

Figure 8. Extinction coefficient of as-deposited and annealed Al-doped ZnO thin films.

Figure 9. Wavelength dependent refractive index of as-deposited and annealed Al-doped ZnO thin films.

Here, \( R \) is the reflectance and \( k \) is the extinction coefficient. The wavelength dependent refractive indexes of deposited and annealed Al-doped ZnO thin films are illustrated in figure 9. It is noticed that the refractive index decreases sharply with the increase of the wavelength of light. This tendency indicates that all the films have normal dispersion behavior. Besides the refractive index was found to decrease from 1.96 to 1.53 with the increase of annealing temperature till 450 °C, which may be due to the decrease of surface roughness of the films [25].

The information of optical conductivity (\( \sigma_{\text{opt}} \)) is very essential for the exploration of electronic condition and optical response of a material of materials. The optical conductivity can be calculated by the following relation [15, 23]
Here $n$ is the refractive index and $c$ is the speed of light. Figure 10 shows the effect of annealing temperature on optical response of AZO thin films. It is noticeable that the optical conductivity of AZO film decreases with the increase of annealing temperature. Besides, both deposited and annealed films show higher optical conductivity at lower wavelength region which subsequently decreases sharply with the increases of the wavelength of light.

### 4. Conclusions

Aluminium doped zinc oxide (AZO) thin films were fabricated on glass substrate by spray pyrolysis technique successfully. The deposited films were then annealed at temperature 350, 400, 450 and 500 °C respectively to characterize and compare their structural, morphological and optical properties. Structural analysis confirms that both deposited and annealed films are polycrystalline in nature and comparatively the peak intensity (corresponding to (101) plane) increases with the increases of annealing temperature up to 450 °C. The crystallite size of the films increases from 14.32 nm to 19.66 nm with the increases of annealing temperature. It was found that the as-deposited films have poor crystalline quality. Afterwards with the increase of annealing temperature the crystalline quality of the films increases up to 450 °C annealing temperature and then decreases onwards. The XRD study also shows that annealing temperature reduces the stresses of the AZO films that arise in the deposited films. SEM image reveals that the deposited films have rope like morphology and the morphology changes with annealing temperature. The average diameter of the rope increases from 388 nm to 495 nm with the increase of annealing temperature up to 450 °C. As compared to the as-deposited film, the average optical transmittance value within the visible region increases from 70.30% to 82.46%, as the annealing temperature reaches to 450 °C. With the increase of annealing temperature, the value of optical band gap increases and the Urbach energy decreases with respect to the deposited films. The optical conductivity was found of the order of $10^{13}$ S$^{-1}$ and the refractive index varies from 1.96 to 1.53 with annealing temperature. Experimental result shows that annealing temperature greatly affects the investigated properties of AZO films and subsequently the obtained properties show a reverse tendency when the films are annealed above 450 °C temperature. It can be concluding that the Al-doped ZnO thin films annealed at 450 °C exhibited better crystalline quality with enhanced morphology as well as optical properties. The obtained results indicate that the AZO film annealed at 450 °C temperature can be used for transparent window layer of solar cell.

### Acknowledgments

One of the authors M. Humayan Kabir is grateful to the department of Electrical and Electronic Engineering, Rajshahi University of Engineering & Technology for facilitating UV–vis spectrophotometer for optical properties testing.
ORCID iDs
M Humayan Kabir @ https://orcid.org/0000-0001-7312-6665

References

[1] Kaur G, Mitra A and Yadav K L 2015 Pulsed laser deposited Al-doped ZnO thin films for optical applications Prog. Nat. Sci. Mater. Int. 25 12–21
[2] Muchuweni E, Sathiraj T S and Nyakatyo H 2017 Synthesis and characterization of zinc oxide thin films for optoelectronic applications Heliyon 3 e00285
[3] Wang A, Chen T, Lu S, Wu Z, Li Y, Chen H and Wang Y 2015 Effects of doping and annealing on properties of ZnO films grown by atomic layer deposition Nanoscale Res. Lett. 10 75
[4] Cho H J et al 2010 The effect of annealing on Al-doped ZnO films deposited by RF magnetron sputtering method for transparent electrodes Thin Solid Films 518 2941–4
[5] Mei-Zhen G, Feng Z, Jing L and Hui-Na S 2009 Effect of annealing conditions on properties of sol–gel derived Al-doped ZnO thin films Chinese Phys. Lett. 26 088105
[6] Lai C M, Lin K M and Rosnaidah S 2012 Effect of annealing temperature on the quality of Al-doped ZnO thin films prepared by sol–gel method J. Sol-Gel Sci. Technol. 61 249–57
[7] Kuo S Y, Chen W C, Lai F I, Cheng C P, Kuo H C, Wang S C and Hsieh W F 2006 Effects of doping concentration and annealing temperature on properties of highly-oriented Al-doped ZnO films J. Cryst. Growth 287 78–84
[8] Kim H, Pique A, Horwitz J S, Murata H, Kafafi Z H, Gilmore C M and Chrisey D B 2000 Effect of aluminum doping on zinc oxide thin films grown by pulsed laser deposition for organic light-emitting devices Thin Solid Films 377 798–802
[9] Lu J G et al 2006 Structural, optical, and electrical properties of (Zn, Al) O films over a wide range of compositions J. Appl. Phys. 100 73714
[10] Jun M C, Park S U, Lee K J, Moon B M and Koh J H 2012 The microstructure of Al-doped ZnO thin films by a sol-gel dip-coating method J. Ceram. Process. Res. 13 721–724
[11] Jun M C and Koh J H 2013 Effects of annealing temperature on properties of Al-doped ZnO thin films prepared by sol-gel dip-coating method J. Electr. Eng. Technol. 8 163–7
[12] Tseng S F 2018 Investigation of post-annealing aluminum-doped zinc oxide (AZO) thin films by a graphene-based heater Appl. Surf. Sci. 448 163–7
[13] Chen Y, Yu W and Liu Y 2004 Effects of annealing on structural, optical and electrical properties of Al-doped ZnO thin films Sci. in China Ser. G: Phys. Mech. Astronomy. 47 588–96
[14] Rasool S et al 2019 Effect of annealing on the physical properties of thermally evaporated In2S3 thin films Curr. Appl. Phys. 19 108–13
[15] Kabir M H, Rahman M S and Khan M K R 2018 Influence of Al doping on microstructure, morphology, optical and photoluminescence properties of pyrolytic ZnO thin films prepared in an ambient atmosphere Chinese J. Phys. 56 2275–84
[16] Rahman M M et al 2012 Effect of Al doping on structural, electrical, optical and photoluminescence properties of nano-structural ZnO thin films J. Mater. Sci. Technol. 28 329–32
[17] Sabeeh S and Jassam R H 2018 The effect of annealing temperature and Al dopant on characterization of ZnO thin films prepared by sol-gel method Results Phys. 10 212–6
[18] Erdogan E and Kundakçı M 2019 Investigation of GaN/InGaN thin film growth on ITO substrate by thermionic vacuum arc (TVA) SN Appl. Sci. 1 9
[19] Rahman M A and Khan M K R 2014 Effect of annealing temperature on structural, electrical and optical properties of spray pyrolytic nanocrystalline CdO thin films Mater. Sci. Semicond. Process. 24 26–33
[20] Rao T P, Kumar M S, Angaraykannu S A and Ashok M 2009 Effect of stress on optical band gap of ZnO thin films with substrate temperature by spray pyrolysis J. Alloys Compd. 485 413–7
[21] Shinde S S, Shinde P S, Oh Y W, Hanarith D, Bhosale C H and Raipure K Y 2012 Structural, optoelectronic, luminescence and thermal properties of Ga-doped zinc oxide thin films Appl. Surf. Sci. 258 9969–76
[22] Fang G J, Li D and Yao B L 2002 Influence of post-deposition annealing on the properties of transparent conductive nanocrystalline ZAO thin films prepared by RF magnetron sputtering with highly conductive ceramic target Thin Solid Films 418 156–62
[23] Alam M R, Rahman M M, Karim A T and Khan M K R 2018 Effect of Ag incorporation on structural and opt–electric properties of pyrolyzed CdO thin films Int. Nano. J. 8 287–95
[24] Hassanien A S and Akl A A 2016 Effect of Se addition on optical and electrical properties of chalcogenide CdSSe thin films Superlattices Microstruct. 89 153–69
[25] Tigatu N, Condurache-Bota S, Drasovean R, Cringanu J and Gavrila R 2017 Vacuum annealing effect on the structural and optical properties of antimony trioxide thin films Rom. J. Phys. 62 604
[26] Sharma I, Tripathi S K and Barman P B 2007 An optical study of a–Ge20Se80 — xIn2O3 — yIn2O3 thin films in sub-band gap region J. Phys. D: Appl. Phys. 40 4460–5
[27] El-Nahass M M, Ali M H and El-Denglawey A 2012 Structural and optical properties of nano-spin coated sol–gel porous TiO2 films Trans. Nonferrous Met. Soc. China 22 3003–11