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Ceramics International 39 (2013) S269–S272

CERAMICS INTERNATIONAL

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Zinc oxide films deposited by radio frequency plasma magnetron sputtering technique

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Available online 16 October 2012

Abstract

Zinc oxide (ZnO) is a wide band gap transparent conductive oxide (TCO) material with a lot of potential applications including transparent thin-film sensors, transistors (TFTs), solar cells, and window insulation systems. In this work, ZnO films were deposited on glass substrates by the radio frequency (RF) plasma magnetron sputtering deposition technique. The effects of the RF power on the properties of the ZnO films were elucidated. The influences of the RF power on the surface morphology, structural, and optical properties of the ZnO films were investigated by Mahr surface profilometer, Atomic Force Microscopy (AFM), X-ray diffractometer (XRD), and ultraviolet–visible (UV–VIS) spectrophotometer. To allow for accurate comparison of the power effects, ZnO films with similar thickness deposited at different RF powers were examined. The RF power effects on the properties of the ZnO films are revealed and discussed in this paper.

Keywords: B. Grain size; C. Optical properties; D. ZnO; RF magnetron sputtering

1. Introduction

Zinc oxide (ZnO) is an unintentional n-type hexagonal wurtzite structure and II–IV semiconductor material. ZnO has a direct band gap of ~3.37 eV, high transmittance in visible region, high conductivity, and free exciton binding energy (60 meV) at room temperature [1]. ZnO has also several substantial advantages such as being abundant, inexpensive, non-toxic, and exhibiting active ultraviolet (UV) response [1]. As a result of these superior characteristics, ZnO has been suggested for many important large area electronic applications including transparent thin-film sensors, transistors (TFTs), solar cells, and window insulation systems [2,3].

Many studies have been reported to produce ZnO films with a variety of processing techniques, including the magnetron sputtering deposition technique [4], the sol–gel process [5,6], and the pulsed laser deposition (PLD) technique [7]. The magnetron sputtering deposition technique has potential to achieve great enhancement on deposited films such as good reproducibility, high deposition rate, enhanced adhesion, superior control of film thickness, maintain film uniformity, large area substrates coating, and film stoichiometry is preserved [8]. In literature, there are investigations on ZnO using direct current (DC) [9] and radio frequency (RF) [10] plasma magnetron sputtering techniques. Most of the studies are centered on investigation and optimization of the properties of ZnO by tuning the sputtering parameters [4,9,10].

To the best of our understanding, the influence of RF power on both structural and optical characteristics of ZnO films using RF magnetron sputtering processing parameter is rarely investigated in the literature [11], especially for low power (<90 W) effects. High RF powers have induced serious surface damage and producing poor crystalline quality ZnO films [11]. There is a need of further investigation on low RF power effect.

In this work, the ZnO films have been deposited on glass substrates by applying the RF magnetron sputtering deposition technique. The surface morphology, structural, and optical properties of the ZnO films with same thicknesses were investigated and RF power effects for the ZnO films with similar thickness are divulged.

2. Experimental

The experimental setup and process parameters are summarized in Table 1. Film thickness measurement was

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http://dx.doi.org/10.1016/j.ceramint.2012.10.075

Table 1
Experimental details of the RF sputtering depositions.

Substrate	Glass slide
Substrate geometry	$\approx 12\ mm \times 6\ mm \times 1\ mm$
Target type and size	ZnO, circular 50.8 mm diameter
Target purity	99.995%
Target–substrate distance	7 cm
Base pressure	$\leq 10^{-6}$ torr
Ar flow rate	20 sccm
Ar gas purity	99.999%
Deposition pressure	7 mtorr
Substrate temperature	27 °C
RF power	25–150 W
Deposition duration	40–96 min

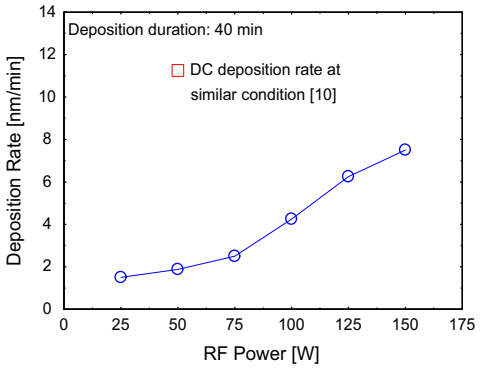

Fig. 1. Deposition rate as a function of RF power.

determined with Mahr surface profilometer. The surface morphology of film was examined by atomic force microscopy (AFM). The structural property was measured by X-ray diffractometer (XRD) (Bruker AXS D8 Advance). The optical property of the film was measured by ultraviolet–visible (UV–VIS) (Ocean Optics S2000) spectrophotometer for wavelengths spanning from 350 to 850 nm.

3. Results and discussion

The deposition rate as a function of the RF power is plotted in Fig. 1.

Increasing of the RF power leads to an increase of the deposition rate, as reported in reference [12]. The enhancement of bombardment by argon (Ar) ions leads to the increase of the number of the sputtered ZnO molecules at the target surface as the RF power is increased [12]. At higher RF power, the adatoms obtain higher energy that contributes to the film growth [13]. It is worth mentioning that the achieved deposition rate for RF sputtering here is lower than DC sputtering [14] at comparable growth condition, which may be due to lower discharge voltage on the target, lower energy of the sputter gas atoms arriving at the target, and ionization in the plasma is affected by the RF excitation directly [15].

In order to investigate the effects of the RF power on the properties of the ZnO films, the film thickness was maintained at 80 nm by adjusting the deposition duration for each RF power deposition run, which is a novel investigation.

Fig. 2 shows the two dimensional (2D) AFM images of the ZnO films, deposited with RF powers ranging from 25 to 100 W. For ZnO film with RF power of 25 W, the grains are smaller compared to the grains in ZnO film with RF power of 100 W. In order to qualitatively analyze the AFM images, the lateral and root mean square (RMS) area roughness data of the ZnO films were extracted. Lateral size was estimated by measuring the average diameter of the granular structures in the scanned image area.

In Fig. 3, the lateral size increases with RF power, from 77 to 140 nm. This is due to the adatoms have higher kinetic energy and mobility to diffuse from one position to another, thus densely packed grains are formed [16]. The RMS area roughness is approximately 5–6 nm.

XRD spectra for the ZnO thin films are shown in Fig. 4.

XRD measurements show a strong and narrow (002) peak at about 34.25° for all investigated samples. Only (002) peak is detected, indicating that the film is with the preferred c-axis orientation, lowest surface free energy on the (002) surface, and crystalline [17]. The peak is identified from the JCPDS Card no. 36-1451 of ZnO. The crystallite sizes are in the range of 10–14 nm, estimated using Scherrer's formula [18]. It is worth mentioning that the crystallite size here is the size of a single crystal inside the grains, so that the value is expected to be few times smaller than the lateral size measured for the agglomerated grains. The trend of the crystallite size is unclear, which is also experienced by Han et al. [19].

Optical study revealed that the transmittance in visible range achieves above 80%. The transmittance in Fig. 5 increases with RF power. The increase of transmittance is attributed to the increase of structural homogeneity [20]. The transmittance can be used to extract the optical band gap of the ZnO films by using the Tauc model [21]. The extracted direct band gap (E_g) values decrease from 3.19 to 3.12 eV when RF power increases from 25 to 100 W. For n-type semiconductor, when electron concentration is high enough with increasing RF power deposition, the Fermi energy penetrates into the conduction band, which will lead to the decrease of band gap [22].

4. Conclusions

ZnO films with similar thickness deposited at various RF powers are examined. Experimental results reveal that deposition rate of RF magnetron sputtering is lower than DC magnetron sputtering. AFM results show the granular structure enhanced with high RF power. XRD results show that ZnO films have preferred c-axis orientation at (002) peak. Optical properties demonstrate high transmittance

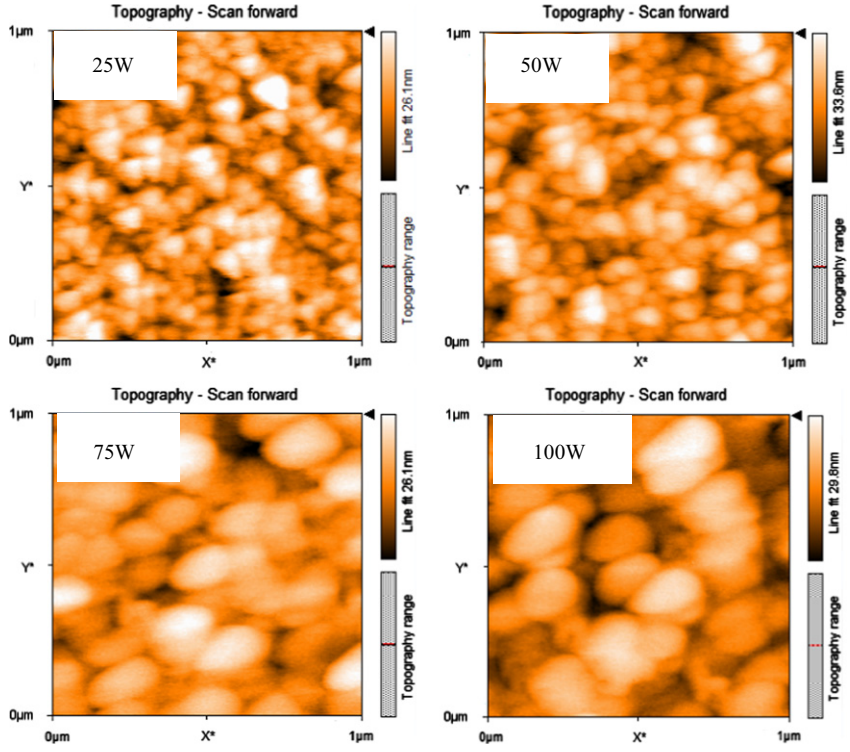

Fig. 2. AFM images of the ZnO films deposited at varied RF power for same film thickness investigation.

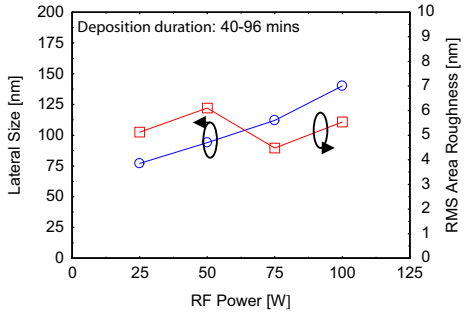

Fig. 3. Lateral size and RMS area roughness versus RF power for ZnO films.

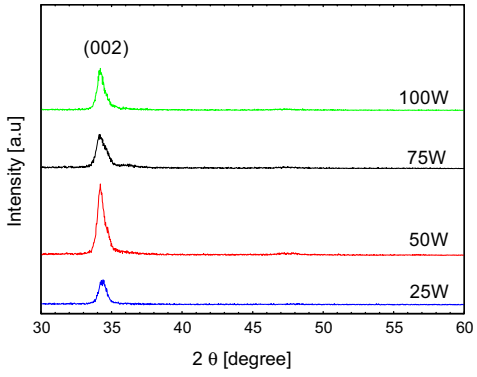

Fig. 4. XRD spectra of the ZnO films.

above 80% and decreasing optical band gap with increasing RF powers, due to the penetration of Fermi energy into the conduction band.

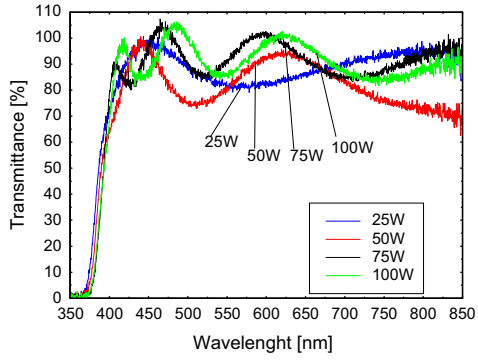

Fig. 5. Transmittance spectra of the ZnO films.

Acknowledgments

We would like to express our gratitude to Multimedia University and TM R&D, for financing and facilitating this research project.

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