Effects of Sputtering Power on Optical and Electrical Properties of Al-doped ZnO Thin Film on Flexible Substrates

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Abstract - AZO thin films were deposited using a magnetron sputtering system with an AZO target (with 3wt% Al2O3) on polyethylene terephthalate (PET) substrates with pre-strain, respectively. The effect of sputtering power on the optical and electrical properties of AZO films was investigated. For samples deposited on pre-strained PET substrates, X-ray diffraction was used to determine the c-axis orientation of AZO films deposited at 60, 80, and 100 W. Results show that resistivity decreased with increasing sputtering power, which might result from the better crystalline structure and fewer grain boundaries obtained at high power. The transmittance increased when the power was increased from 60 to 100 W. The absorption edge thus decreased for AZO film deposited at 100 W.

Keywords - AZO, Sputtering, Zinc Oxide, PET.

I. INTRODUCTION

Transparent conducting oxide (TCO) films with a very low resistivity have been extensively used in solar cells and various flat panel displays (FPD) [1–4]. Various oxide materials have been proposed as TCO films due to their good conductivity and transmittance [5-10]. Al-doped zinc oxide (AZO) is the most promising material for the TCO layer in solar cells due to its resistance to a reductive ambient and its transparency at infrared (IR) wavelengths. Many techniques have been proposed for the preparation of transparent conductive ZnO films, such as spray pyrolysis [9], metal-organic chemical vapor deposition (MOCVD) [11], reactive radio-frequency (RF) magnetron sputtering [12], pulsed laser deposition (PLD) [13], thermal oxidation [14], molecular beam epitaxy (MBE) [15], and sol-gel [16]. Among them, the sputtering technique is the most promising for obtaining uniform compositions and for mass production in industry. In the mass production of foldable displays and solar cells, a TCO film can be efficiently deposited onto a soft, flexible substrate using a rotating deposition system. The ceramic film is then deposited using the magnetron sputtering technique. However, strain might be produced between the TCO film and the curved flexible substrate, which causes structural defects and degrades the performance of the TCO layer. In order to simulate this deposition process, a mold was designed to produce a pre-strain for soft substrate during thin-film deposition. In the present study, a polyethylene terephthalate (PET) substrate was initially fixed on the mold with a certain curvature and then placed in the sputtering chamber. AZO thin film was deposited on the pre-strained PET substrate under various conditions and the optical and electrical properties were determined.

II. EXPERIMENTAL PROCEDURE

AZO thin films were deposited on a pre-strained PET substrate by an RF magnetron sputtering system. The AZO target, composed of 3 wt% Al_2O_3, with a diameter of 75 mm was used. A PET sheet with a thickness of 188 μm was used as the substrate. In order to simulate the deposition process, the mold shown in Fig. 1 was designed in this study. In this rig, the rectangular plate with a partial-arc top surface is fixed at the central region of the circular flat plate by a screw. A rectangular PET sheet was held at its two ends by clamps such that it remained fixed on the partial-arc plate. The PET substrate can be elongated to produce a fixed strain by adjusting a screw while remaining symmetrical can be slightly elongated to produce with respect to the central line of the rectangular plate. AZO thin films were deposited on the pre-strained PET substrates under various sputtering powers.

X-ray diffraction (XRD) measurements were carried out on a Rigaku diffractometer (Rigaku ATX-E, USA) in the 2θ range of 30° to 80° using a CuKα X-ray source. The 2θ scans show the angular positions of ZnO for the PET/AZO specimens with various sputtering powers. The optical properties, including the absorption and transmission spectra, of the PET/AZO specimens with various sputtering powers were recorded on a spectrophotometer (Jasco V-570, Japan).

III. RESULTS AND DISCUSSION

A fixed strain was applied on the PET substrates during the sputtering process. Then, various sputtering powers were used for the deposition of AZO thin films to investigate the effects of sputtering power on the curved PET substrates. Fig. 2 shows the X-ray diffraction patterns of AZO thin films deposited at sputtering powers of 60, 80, and 100 W, respectively. The three obvious diffraction peaks of ZnO were identified as ZnO(002), ZnO(101), and ZnO(102), respectively. No other diffraction peaks were found for the as-grown AZO thin film. As shown in Fig. 2, a strong c-axis ZnO(002) orientation was obtained, meaning that the (002) textured film formed in an effective equilibrium state, where there is sufficient surface mobility to impinge atoms under certain deposition conditions [17]. The (002) peak intensity increased with increasing sputtering power. It is well-known that ZnO thin film deposited on substrates at 100 W easily grows along with c-axis due to it having the highest sputtering power. The sputtering power is a critical parameter for obtaining good crystallinity of AZO thin films.

Fig. 3 shows the surface morphologies of AZO thin films deposited on pre-strained PET substrates at sputtering powers of 60, 80, and 100 W, respectively. The grain size of AZO film sputtered at 60 W is quite small; the small grains aggregated into larger grains. Therefore, the grains had various shapes. When the sputtering power was increased to 80 and 100 W, the AZO grains became larger and the surface morphology became more uniform. As a result, a non-uniform surface morphology was obtained for AZO film deposited at a low sputtering power, such as 60 W. The deposition results improved when the sputtering power was increased to 80 and 100 W. Larger energy was obtained by the atoms and therefore increased the opportunity for AZO film deposited on pre-strained PET substrate.

In order to evaluate the optical properties of AZO thin films, the transmittance was measured. The results for visible and IR wavelengths are shown in Fig. 4. For the visible wavelength region, the transmittance is around 60% (at 600 nm) for AZO film sputtered at 60 W. The transmittance increased with increasing sputtering power. Of note, the transmittance increased by 15% when the sputtering power was increased to 80 W. The transmittance was over 80% (at 600 nm) for AZO thin film prepared at 100 W. The increase in transmittance might be due to the improved crystallinity of AZO thin films as a result of increased sputtering power. In contrast, the transmittance in the IR wavelength region decreased with the increasing sputtering power. The decrease in transmittance might have been caused by increase in crystallinity due to increased sputtering power.

The absorption coefficient was affected by the deposition power. The absorption coefficient (α) can be calculated using [18]:

$$\alpha = ln(1/T)/d \quad (1)$$

where T denotes transmittance and d denotes film thickness. The optical band gap, Eg , dependence on the absorption coefficient, α , can be written as [19]:

$$(\alpha h\nu)^2 = A(h\nu - Eg) \quad (2)$$

where A is a constant. The energy gap (Eg) can be determined by extrapolating the linear portion of the curve to intersect the axis. Fig. 5 shows the variation of with the value of AZO films. The energy gap increased with increasing sputtering power, reaching a maximum value of 3.23 eV. As described above, the grain and crystallinity improved with increasing sputtering power. The increased energy gap might be caused by the increase of carrier concentration. This result is confirmed by the decreasing sheet resistance shown in Fig. 6. The sheet resistance of AZO film deposited at 60 W was 330 kΩ/□ and decreased to 5.9 kΩ/□. When the carrier concentration increased in AZO thin film, the possibility of carriers transferring from the valence band to the conduction band also increased. More carriers with electron transferred to the conduction band would accumulate at the bottom of the conduction band, and therefore increased the area of bottom conduction band with carriers occupied. More carriers transferred to the conduction band have to cross larger distance to reach the vacancy in the bottom conduction band and therefore increased the energy gap. As more carriers with electron were generated, the conductivity was therefore increased, the resistivity and sheet resistance were oppositely reduced, as shown in Fig. 6.

Based on the discussion above, the crystallinity, absorption coefficient, and energy gap are affected by sputtering power on a pre-strain PET. The figure of merit (FOM) was obtained from the transmittance at a specific wavelength and resistivity [20]. The performance of a TCO film can be specified by the FOM over a wide range of wavelengths. Fig. 7 shows the FOM values of AZO thin films. The FOM value increases with increasing sputtering power for all visible wavelengths. For a sputtering power of 100 W, the FOM value of AZO film sputtered on a substrate with pre-strained PET substrate is best. This result proves that the optical and electrical properties of AZO thin film are affected by sputtering power.

IV. CONCLUSION

A mold was used for applying fixed strain on substrates onto which AZO thin films were deposited. The TCO-related characteristics of AZO thin films were investigated to determine the effects of sputtering powers on film performance. The results show that the crystallinity of AZO films on a pre-strained substrate improved with increasing sputtering power. The grain size also increased since atoms gained more energy to overcome the strain on the substrate. The transmittance increased and the absorption decreased with increasing sputtering power. Moreover, the energy gap increased due to the increased carrier concentration, which was reflected in the sheet resistance. The FOM value presents the optimal sputtering parameters for preparing AZO thin film on the pre-strained PET substrate.

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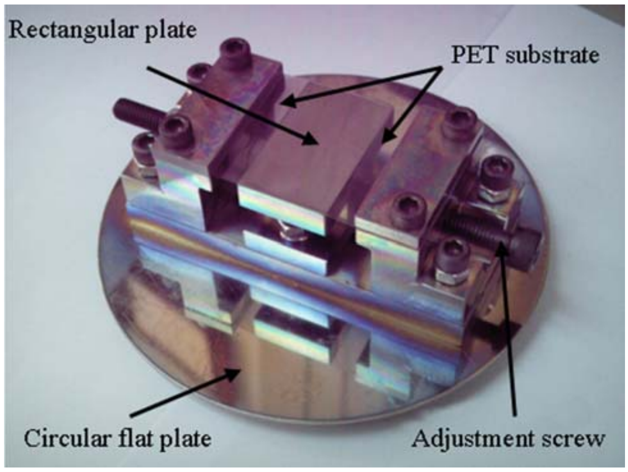


Fig. 1 Photograph of mold used to produce strain on PET substrate fixed on the rectangular area.

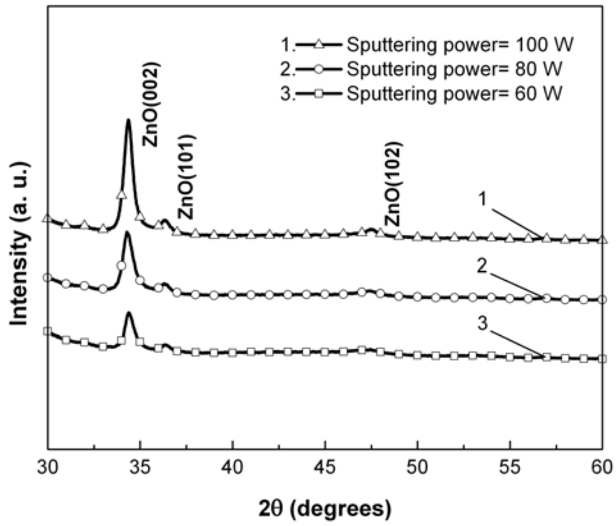
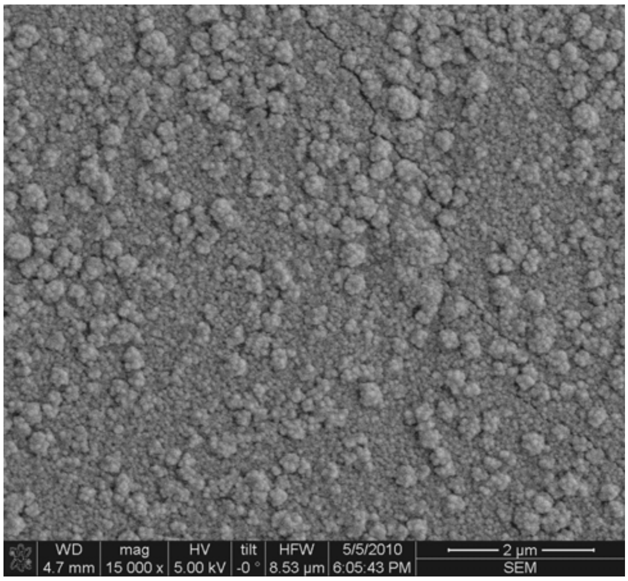
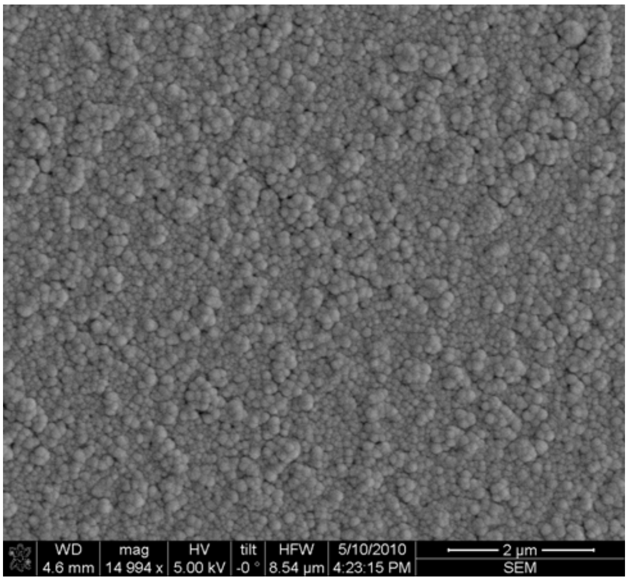


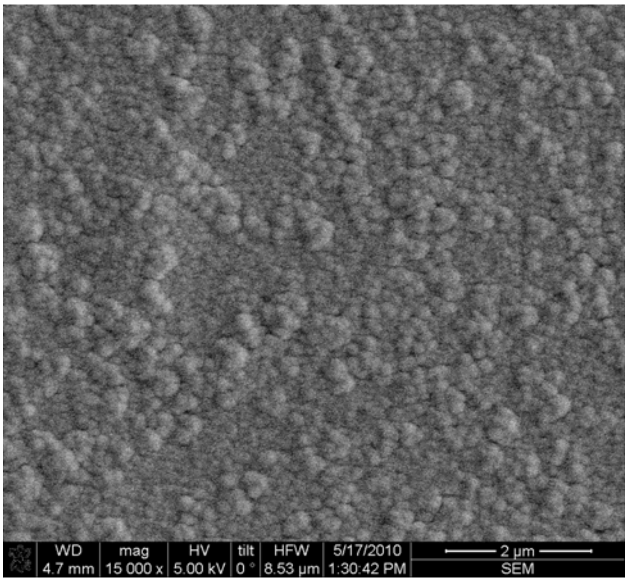
Fig. 2 XRD patterns of AZO thin film for various sputtering powers.



(a) 60 W



(b) 80 W



(c) 100 W

Fig. 3 Surface morphologies of AZO films on a pre-strained substrate with sputtering power at (a) 60 W, (b) 80 W, and (c) 100 W.

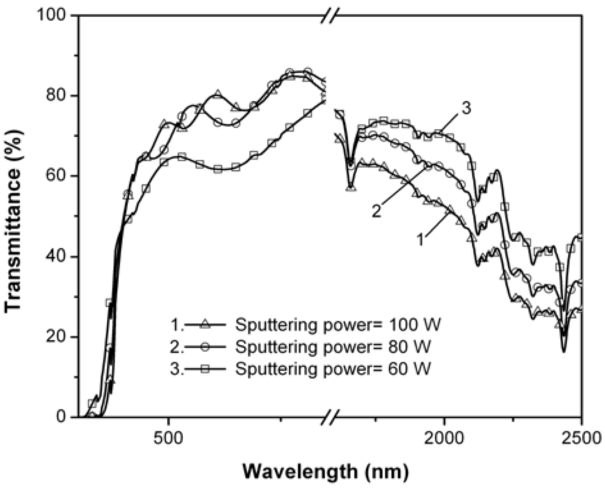


Fig. 4 Transmittance of AZO films on a pre-strained substrate with various sputtering powers.

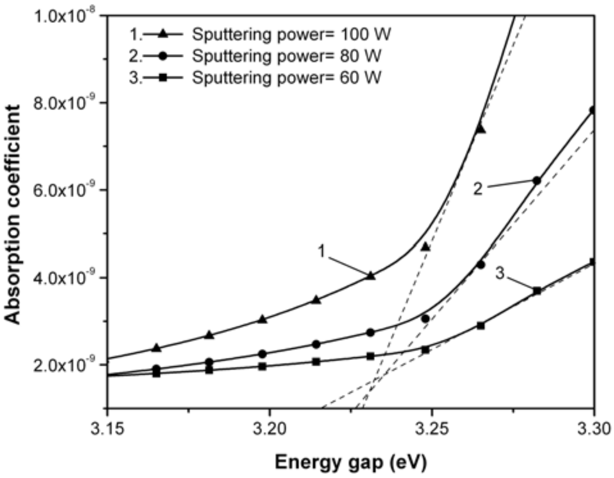


Fig. 5 Energy gaps of AZO films on a pre-strained substrate with various sputtering powers.

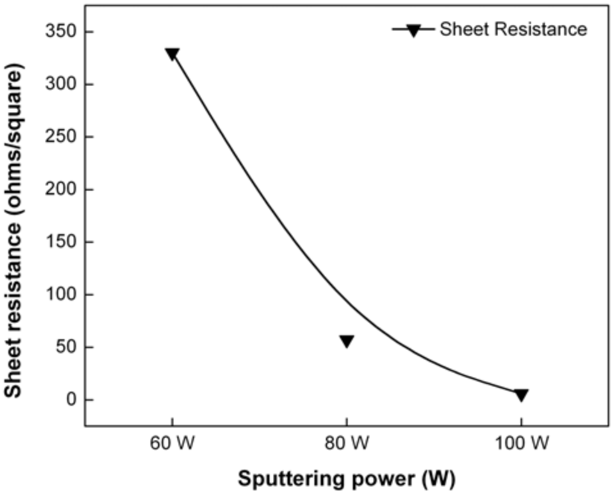


Fig. 6 Sheet resistances of AZO films on a pre-strained substrate with various sputtering powers.

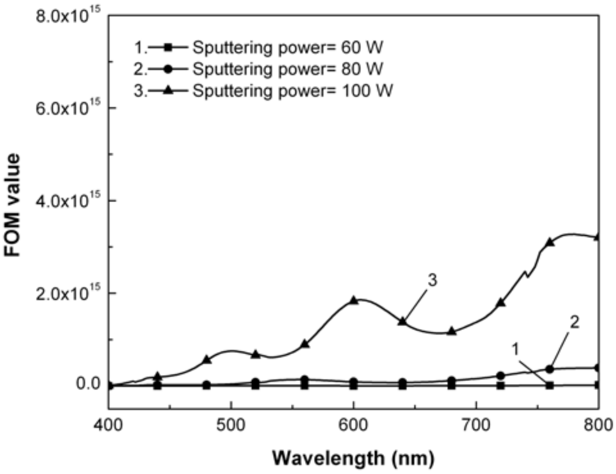


Fig. 7 FOM values of AZO films on a pre-strained substrate with various sputtering powers.