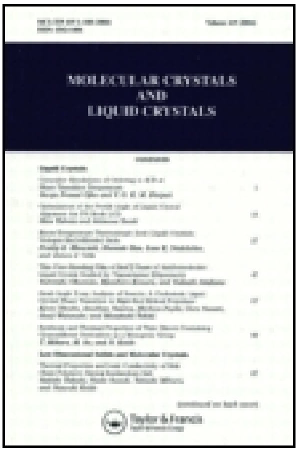

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Properties of ITO (Indium Tin Oxide) Film Deposited by Ion-Beam-Assisted Sputter

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Properties of ITO (Indium Tin Oxide) Film Deposited by Ion-Beam-Assisted Sputter

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The ITO films were deposited on polyethylenenaphthalate at the room temperature using dc magnetron sputtering system with Ar ion-beam assist. The dc sputtering power was maintained at 200 W, and the Ar ion-beam power was varied from 20 to 70 W. The change in the resistance of the ITO films in the cyclic bending tests was significantly delayed with the Ar-ion-beam power 40 W. Also, the ITO film showed relatively low resistivity (5.39 × 10^{-4} Ωcm). Thus. the ITO film showed good mechanical and electrical properties attributable to the effect of Ar ion bombardment on the thin film formation.

Keywords Magnetron sputtering; ion-beam assist sputtering (IBAS); indium tin oxide; electrical properties; cyclic bending test; transmittance

Introduction

Transparent conductive oxide (TCO) films are used in industrial fields such as transparent electrodes for flexible display (OLED), solar cells and touch panel [1]. Although several different types of TCO films have been reported in various applications, tin-doped indium-oxide (ITO) films are used most commonly on account of their high electrical conductivity and optical transparency in the visible region [2] During last decades, new and/or modified methods of TCO films preparation have been introduced in literature [3–6] aimed on precise control of the film properties, improvement of the functionalities providing new applications. These methods are chemical vapor deposition (CVD) [3], magnetron sputtering [4], evaporation [5], sol-gel synthesis [6], etc. Although there are several techniques for depositing a variety of TCO films,dc magnetron sputtering using ceramic targets is most preferred by industry owing to its high controllability, high deposition rate and potential for large area deposition. However, dc magnetron sputtering requires a relatively high process voltage to

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maintain the discharge through secondary electron emission at the cathode. On the other hand, the Ion-beam-assisted sputtering (IBAS) system through Ar ion beam assist during the film growth requires a lower discharge voltage than dc magnetron sputtering due to increased Ar ion in the plasma. Also, the advantage of the utilized ion beam technologies is the possibility to control precisely the technological process and finally material properties such as microstructure, non-stoichiometry, morphology, crystallinity, etc [7]. Currently, the dynamics of the film growth should account for several concepts of the ion-beam including ion assist deposition (IAD), hybrid ion beam, ion beam sputter deposition, and ion-assisted reaction (IAR) [7]. In the case of Ion-beam-assisted sputter (IBAS), simultaneous irradiation of a film by an ion beam during growth causes some significant changes in the film characteristics related to the electrical properties, surface morphology, film crystallinity, mechanical properties of the film.

In this study, we prepared the ITO films by developing a process involving Ar ion beam assist during the sputtering of a 200-nm-thick ITO film on polyethylene naphthalate (PEN) at the room temperature.We review the experimental results and discuss our research activities for improving properties of ITO film on PEN substrates by IBAS system.

Experimental

The ITO (10wt% SnO_2) films were grown on unheated PEN substrates using a Ion-beam-assisted sputter (IBAS) system. ITO target was sputtered by using dc magnetron sputtering and Ar ions were generated by using a end hall type 3-cm-gridded ion gun. The current density of the beam was changed from 0.7 to 1.01 A by changing the ion gun power supply current 0, 20, 30, 40, 50, 60, 70 W. The arrival ratio on substrate of Ar ion was converted into an average current density which was changed. The deposition rate was fixed at 0.1 nm/s and the final film thickness was about 200 nm. The ITO films were deposited at an Ar flow rate, working pressure and dc power of 20 sccm, 3mTorr and 200 W, respectively.

Electrical properties, resistivity (ρ), hall mobility (μ), and free carrier density (n) of the ITO films were measured by the Hall-effect measurement (HMS-3000, ECOPIA) in the van der Pauw geometry. The transmittance of the films were measured from 200 to 800 nm using a spectrophotometer [Lambda 950, Perkin Elmer].

The mechanical property of ITO film was estimated by resistance changes during the cyclic bending test, which were monitored by computer system with an digital multimeter [Agilent 34401A]. Samples used in the cyclic test have rectangular in shape, 20 mm $\times$ 50 mm. The bending tests were carried out at a 0.08 Hz frequency and maintaining a constant linear vertical movement with a 20 mm stroke. Using a moving jig, the cyclic bending stress was applied dynamically on the films.

Results and Discussion

We prepared the ITO films by the IBAS system with different Ar ion-beam power from 0 to 70 W. The discharge voltage at an Ar ion-beam power 0 W corresponds to the general dc magnetron sputtering method. The discharge voltage decreased from -271 V to -243 V with increasing Ar ion-beam power from 0 to 70 W. This behavior was explained due to IBAS system. For example, dc magnetron sputtering requires a relatively high process voltage to maintain the discharge by secondary electron emission at the cathode. On the other hand, the IBAS system requires a lower discharge voltage than dc magnetron sputtering which is affected mainly by Ar ion that generate an ion gun. This relationship

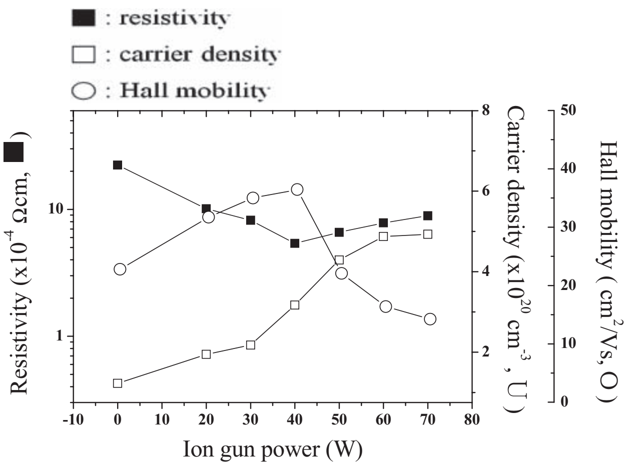

Figure 1. Resistivity, carrier density and Hall mobility for ITO films without Ar ion assist and ITO films with Ar ion beam assist as a function of ion beam assist power.

can be explained by increased electrons with increase of scattering motion in the plasma due to increased Ar ion. Therefore, the IBAS system has lower discharge voltage than dc magnetron sputtering due to the the high electron temperature.

Figure 1 shows the electrical properties of resistivity, carrier density, Hall mobility for ITO films deposited with Ar ion-beam assist. The low resistivity of the ITO film is 5.39×10^{-4} Ωcm with ion gun power 40 W compare to resistivity of ITO film deposited without Ar ion-beam-assist. The difference of electrical properties in the ITO films fabricated at each ion gun power is due to the energy dependence of ion bombardment effect on the thin film formation. Under a low energy ion current (power of ion gun: from 0 to 30 W), the primary effect of the ion bombardment is to enhance ad-atom mobility [8,9]. Thus, the assist beam effectively contributes to the ion-beam mixing of the sputtering atoms within the thin film and consequently reduces the film porosity and increases the film density to as much as that of the bulk material. In addition, the electron temperature of the IBAS system is higher than that in DC magnetron sputtering, resulting in a higher $V_p - V_f$, where V_p and V_f are the plasma and floating potentials, respectively. Therefore, surface migration of adatoms during the sputtering process is improved by the increased $V_p - V_f$. As a result, a gradual decrease in the resistivity with ion gun power up to 40 W is associated though Ar ion-beam assist [10–12].

However, in the case of high ion bombardment (power of ion gun: from 50 to 70 W), the radiation damage is more effective than the enhancement of ad-atom mobility, and the defect sites act as nucleation sites to form the fine grain structure. Thus, this behavior may be due to the adverse effects of the excessively high energy of Ar ion accelerated by $V_p - V_f$ near the growing film surface. Therefore, the relatively high resistivity properties of the ITO films can be attributed to the increase in film damage caused by the bombardment of highly energetic particles.

Figures 2 (a), (b), and (c) show the change in R/R_0 of the ITO films estimated under the dynamic stress mode, where R_0 and R represent the initial resistance and the difference between the initial and final resistances, respectively. Figures 3 (a), (b), and (c) show that the resistance of the ITO films is strongly affected by Ar ion gun power. In particular, it is clear that the resistance change observed for ITO films grown by ion gun power 40 W is

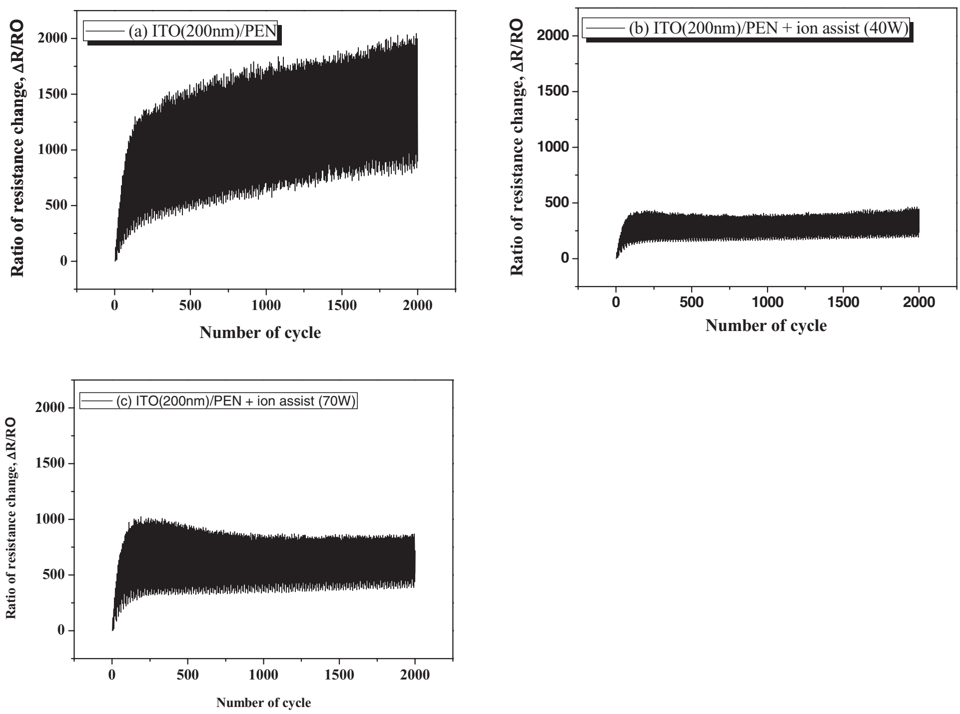

Figure 2. Change in the resistance of the ITO films deposited under Ar ion beam assist with various Ar ion gun power, (a) ITO film without ion assist, (b) ITO film with ion beam assist power 40 W, and (c) ITO film with ion beam assist power 70 W.

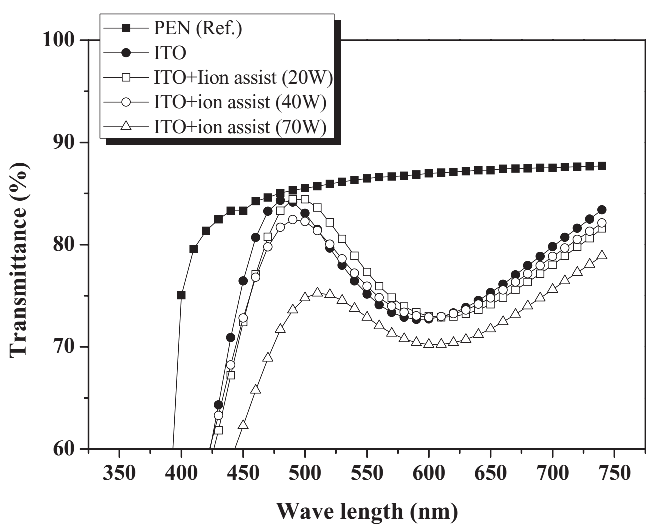

Figure 3. Change in the optical transmittance of ITO films prepared with the various Ar ion gun power.

significantly lower than that in the case of ITO films grown without Ar ion assist. This can be explained by effect of highly energetic particles (Ar^o, O^-) during the films grown using conventional dc magnetron sputtering processes. It is generally believed that bombardment of the growing surface with highly energetic particles (Ar^o, O^-) suppresses the surface migration of adatoms during the sputtering process, [13,14] which results in the formation of low-density films. This led to poor bending performance for the sputtered ITO films because of the formation of a large number of cracks even under a small induced stress. Also, the Ar ion beam assist effectively contributes to ion-beam mixing of the sputtering atoms within the thin film and consequently reduces the thin film porosity and increase the film density, which leads to an increase the internal compressive stress in the thin film. Generally, regarding the bending properties, the induced tensile stress continuously increases with the cyclic bending. Thus, cracks are formed when the compressive stress in the thin film is overcome by the tensile stress [15]. Therefore, increasing the internal compressive stress by Ar ion assist can improve the strength of the ITO film by improving the resistance of the film to tensile cracking failure.

In the case of Fig. 3 (c), the change in the resistance of ITO film grown was increased than that shown in Fig. 3 (b). This might be due to the damage caused by high energy particles, which is affected by the excessively high energy of Ar ion accelerated by $V_p - V_f$ at the substrate.

Figure 3 shows the optical transmittance of the ITO films deposited using different ion gun power. In the 550 nm wavelength, the ITO films deposited at Ar ion gun power of 0, 20, 40 W showed a transmittance of about 80%. The film transmittance decreased in the 550 nm with increasing Ar ion gun power to 70 W. It is believed that bombardment of the growing surface with highly energetic particles (Ar^o, O^-) suppresses the surface migration with increasing Ar ion, which results in the decrease of partial crystallization of ITO film. Therefore, it is confirmed that the decrease of transmittance with increasing Ar ion gun power could be attributed to the decrease in partial crystallization of ITO film, which shows a good agreement with the results of Figs. 1 and 2.

Conclusions

The ITO films were characterized by measuring their discharge voltage, electrical properties, optical transmittance, and resistance in cyclic bending tests. The growth of the ITO film was assisted by treatment with Ar ion beams of various DC powers (from 20 to 70 W). A low resistivity value of 5.39×10^{-4} Ωcm was obtained for the ITO film prepared with the Ar ion beam assist power 40 W. The change in the resistance of the ITO films in the cyclic bending tests was significantly delayed by the Ar-ion-beam-assist-induced improvement of the film's resistance to the internal compressive stress. These results show that IBAS method is an attractive process for producing high quality ITO films compared with conventional DC magnetron sputtering.

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