Low-Temperature Synthesis and Characterization of ITO Thin Films*

Wei-Chuan Fang† and Min-Sheng Leu
Materials and Chemical Laboratories, Industrial Technology Research Institute
195 Chung Hsing Rd., Sec.4 Chu Tung, Hsin Chu, Taiwan
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Low-temperature synthesis and characterization of ITO thin films prepared by cathodic arc ion plating (CAIP) have been demonstrated. The correlation between structural properties and electrical results are revealed in this work. At present, the in-house ITO films with the lowest resistivity and highest transparence of $4.8 \times 10^{-4}$ (Ω·cm) and 80% can be obtained. Such the low-temperature fabrication technique is very promising for the potential applications of flexible electronic devices or dye-sensitized solar cells. [DOI: 10.1380/ejssnt.2009.553]

Keywords: Indium tin oxide (ITO); Cathodic arc ion plating; Flexible electronic devices; Dye-sensitized solar cells

I. INTRODUCTION

Indium tin oxide (ITO) is an n-type degenerate wide band gap semiconductor. The degeneracy is caused by both oxygen vacancy and substitutional tin created during deposition. ITO thin films are widely used in optoelectronic devices such as solar cells, electroluminescence and liquid crystal displays as transparent electrode due to its high transmittance in the visible region and low electrical resistivity [1–3]. The high electrical conductivity of ITO films results in a high reflectivity in the infrared region, which gives applications to thermal insulation of windows, prevention of radiative cooling, etc. Many techniques have been used to deposit ITO films, such as sputtering, evaporation, sol-gel, and so on [4–6]. Another deposition method based on the anodic arc plasma technique [7–9] is utilized as the anode in arc discharge. It is more advantageous for synthesis of transparent conducting oxide (TCO) thin films with prompt deposition rate using this method. Cathodic arc discharge involves higher energy ions accompanied by a higher degree of ionization and more multi-charged ions. Hence, it is beneficial to have highly dense TCO thin films; nevertheless, only a few works on the cathodic arc deposition of TCO thin films have been testified.

In general, ITO thin films deposited by the techniques mentioned above involve a relatively high substrate temperature (over 200°C) or a postannealing process to obtain a reasonably high electrical conductivity and optical transmittance in the visible region [10, 11]. Recently, plastic materials are desirable in the flat panel display industry, where the demand for remote information access is driving the development of rugged, lightweight, power efficient displays. These applications need to deposit ITO thin films onto plastic substrate. However, it is necessary for ITO thin films to be deposited at a very low substrate temperature because of the poor thermal endurance of plastic substrate.

In this article, the theme is focused on the structural and physical properties of low-temperature ITO thin films using CAIP approach. Meanwhile, the correlation between electrical characteristics and structural properties is performed. This is very helpful for the precise manipulation of ITO thin films with superior electrical and supreme transmittance during low-temperature process.

II. EXPERIMENTAL

A. Preparation for ITO thin-film

The deposition equipment used in this study is a cathodic arc discharge ion plating system, as shown in Fig. 1. The wall of the vacuum chamber and the arc trigger constitute the anode of the arc discharge, and the target is the cathode. The target was an In-Sn (10 wt%) alloy target with a diameter of 100 mm. The glass substrate was ultrasonically cleaned in ethanol kept for 10 min. The substrate temperature is kept at 100°C during the experiment. Both base pressure and working pressure are $5 \times 10^{-3}$ Pa and 1 Pa, respectively. Before the ITO film deposition, the ion-bombardment procedure was performed to remove the surface impurity and increase in-
FIG. 2: (a) Sheet resistance and (b) resistivity of as-grown ITO thin film under various applied arc current.

FIG. 3: Cross-sectional scanning electron image of as-grown ITO thin film synthesized at (a) low and (b) high arc current.

B. Characterization of structural properties and physical behavior

For structural analysis, a JEOL-6500 field-emission scanning electron microscope (FESEM) was used. In electrical and optical measurements, a Mitsubishi MCP T-600 four-point probe and a Hitachi UV-Visible spectrometer were applied.

III. RESULTS AND DISCUSSIONS

As shown in Fig. 2(a), the sheet resistance of as-grown ITO thin film under various applied arc current is depicted. From the resultant correlation, it suggests that the sheet resistance is decreased with arc current raised, which means that the induced action from target source have more sufficient kinetic energy to deposit on substrate and lattice will be rearranged without any obstacle. Therefore, the crystalline is improved. Such the phenomenon is also found in resistivity as a function of arc current, as seen in Fig. 2(b). From the preliminary results, it could be suggestive that electrical performance of ITO thin film is associated with applied arc current.

To see the surface morphology, cross-sectional SEM images of ITO thin film is examined. The thickness of ITO thin film in Figs. 3(a) and (b) is 240 and 170 nm. Figure 3(a) shows the cross-sectional morphology of ITO thin film under low arc current. The inset is the corresponding top-view SEM image. As evidenced, the flatness of thin film is quite good and only a few particles on substrate are observed. However, the image looks a little bit fuzzy, which is probably generated from intrinsic low resistivity. Once the arc current is enhanced, the SEM image of ITO thin film becomes clear as displayed in Fig. 3(b). The inset reveals none of aggregates is found. From the SEM analysis, it infers that the surface roughness of ITO thin film is smooth under distinct current; however, the image quality is influenced by arc current.

For the further study of structural transformation, cross-sectional TEM images of ITO thin film under low and high arc current are testified. As revealed in Fig. 4(a), the TEM image shows the irregular lattice arrangement due to the insufficient ion energy induced by arc current. In Fig. 4(b), the magnified TEM image can explain the above phenomenon and the inserted picture tells
FIG. 4: Cross-sectional transmission electron microscope images of as-prepared ITO thin films synthesized at low (a, b) and high (c, d) arc current.

FIG. 5: Transmittance as a function of wavelength of as-grown ITO thin film synthesized at (a) low and (b) high arc current.

the ITO thin film structure is polycrystalline due to the ring-shaped diffraction pattern. As the arc current is increased, the structure arrangement becomes orderly in Figs. 4(c)-(d). Moreover, a highly-ordered grain can be found and diffraction pattern in the inset demonstrates the well-ordered lattice symmetry, which implies that current manipulation is quite crucial to crystalline of grown ITO thin film and so is electrical property.

In optical transmission properties, Fig. 5 show the transmission of ITO thin film as a function of wavelength under different arc current. In Fig. 5(a), the transmission of ITO thin film is decreased with the arc current raised
and the fluctuation induced by interference effect is also present. As higher current with shorter deposition interval is applied, the transmission spectrum of ITO thin film fabricated at arc current of 70 A has higher penetration ability than 80% at wavelength of 700 nm, as shown in Fig. 5(b). Meanwhile, the resistivity could be obtained about $5 \times 10^{-4}$ (Ω-cm). Due to the intrinsic properties of such the so-called CAIP technique, it could provide the dense film structure synthesized at low-temperature condition resulting from the generation of ions with high kinetic energy compared with sputtering method. It means that the in-house ITO thin film prepared at low temperature looks feasible in practical applications. The further improvement and detailed investigation would be processed in the future.

IV. CONCLUSIONS

Low-temperature synthesis and characterization of ITO thin films prepared by CAIP have been demonstrated. The correlation between structural properties and electrical results are revealed in this work. At present, the in-house ITO films with the lowest resistivity and highest transparence of $4.8 \times 10^{-4}$ (Ω-cm) and 80% can be obtained. Such the low-temperature fabrication technique is very promising for the potential applications of flexible electronic devices or dye-sensitized solar cells.

Acknowledgments

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