Effect of Inductively Coupled Plasma on the Structural and Electrical Properties of Ti-Doped ITO Films Formed by IPVD

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In this study, we investigated Ti-doped ITO films formed through ionized physical vapor deposition (IPVD) using inductively coupled plasma (ICP). Ti-doped ITO thin films showed an enhanced mobility with ICP power; owing to the improved crystallinity, and the sheet resistance of the Ti-doped ITO (30 nm) largely decreased from 295.1 to 134.5 ohm/sq, even during at room temperature. Therefore, IPVD technology offers a useful tool for transparent electrodes with a large area window-unified touch-screen panel.

Keywords: TCO, IPVD, Ti-Doped ITO, ICP.

1. INTRODUCTION

Transparent conductive oxide (TCO) films with high conductivity and high transparency are of considerable research interest because of their applications in optoelectronic devices such as light emitting diodes (LEDs), organic light-emitting diodes (OLEDs), flat panel displays (FPDs), and touch-screen panels (TSP).¹⁻¹² Indium-tin oxide (ITO) is a representative TCO, which is a highly degenerate n-type semiconductor with a low electrical resistivity of 2⁻⁴ × 10⁻⁴ ohm·cm. The degeneracy is caused by both the intentionally doped Sn atoms and inherent oxygen vacancies, which create donor levels in the energy band gap.¹² To obtain high-qualified ITO films with low resistivity and high transmittance, the experimental conditions need to be optimized by several parameters such as the ITO target composition, substrate temperature, oxygen partial pressure, and thin film thickness.¹³⁻¹⁶

In particular, there have been several reports on the effects of dopants such as Zn, Ce, and Ti on the electrical and optical properties of ITO films.¹⁷⁻¹⁹ As a donor, a titanium atom can release one free electron by replacing an indium site in the In₂O₃ matrix of an ITO film, and thus a Ti-doped ITO film has good electrical properties compared to a conventional ITO film.¹⁸⁻¹⁹ Chung et al. reported that Ti-doping changes the structure of an ITO film from amorphous to crystalline, even at low temperature, by offering a small ionic radius of Ti⁴⁺.¹⁸ On the other hand, IPVDs with ICP reactors have improved the structural, electrical, and optical properties of transparent electrical materials, by showing a high ionization rate and plasma density.²¹⁻²⁵ For depositing ITO thin films, IPVD decreased the sheet resistance, and increased the transmittance of ITO thin films with deposited at the room temperature.²⁴

In this paper, we will investigate the effects of ICP power on the structural, electrical, and optical properties of Ti-doped ITO films using a specially designed IPVD at room temperature.

2. EXPERIMENTAL DETAILS

Using a Ti-doped ITO target (weight composition of 97.5% ITO and 2.5% Ti), Ti-doped ITO films were deposited on alkali-free glass (Corning 1737) substrates using a DC magnetron sputter system equipped with an ICP (IPVD system), as shown in Figure 1. The deposition was processed at 5 mTorr at room temperature, with gas flows of Ar (100 sccm) and O₂ (0.4 sccm). The DC power was fixed to 600 W during deposition, and the ICP...
power ranged from 0 to 450 W (with 150 W for each step). After deposition, the heat treatment of the films was carried out in a box furnace for 1 hour at up to 200 °C in a vacuum atmosphere. The thickness of the Ti-doped ITO films was measured using a surface profiler (Alpha- step-IQ, USA). The optical transmittance was measured at a wavelength range of 350 to 750 nm, using a UV-visible spectrometer (Hitachi U-3501, Japan). Hall-effect measurements (Accent HL5500PC, USA) were carried out in a van-der-pauw configuration at room temperature. The microstructures of the Ti-doped ITO films were examined by X-ray diffraction (XRD, Rigaku D/max-RC300, Japan).

3. RESULTS AND DISCUSSION

Figure 2 shows the X-ray diffraction of Ti-doped ITO films with ICP power and thickness. The Ti-doped ITO film (30 nm) deposited with no ICP power has an amorphous structure. However, the one formed at an ICP power of 450 W shows a preferred orientation along the (222) direction which is generally observed for near-stoichiometric poly crystalline Ti doped ITO as shown in Figure 2.

To confirm this ICP effect on the structural change of the Ti-ITO film, we deposited (a 100-nm thick) Ti-doped ITO film. In this case, (222) peak also appeared. The crystallization can be explained through mechanism in which the high energy of ions generated by ICP can compensate for the energy required for dopant-activation during deposition, by assisting the substitution of Sn or Ti into the In site of the ITO film, and thus improve the crystallization of the Ti-ITO films. Figure 3 shows AFM images of a Ti-doped ITO film deposited with/without ICP. The RMS roughness of Ti-doped ITO deposited without ICP was 0.395 nm, and Ti-doped ITO deposited with 300 W ICP was 0.345 nm. This result shows that the ICP did not impact on the roughness of the Ti-doped ITO films.

Figure 4 shows the sheet resistance, carrier density, and mobility of Ti-ITO films as a function of the ICP power at room temperature. The sheet resistance of Ti-doped ITO film largely decreased from 295.1 to 134.5 ohm/sq as the ICP power increased from 0 to 450 W, respectively. The carrier density of Ti-doped ITO films deposited at an ICP of 450 W slightly increased from $4.7 \times 10^{20}$ cm$^{-3}$ to $5.6 \times 10^{20}$ cm$^{-3}$, but the mobility of the Ti-ITO films
dramatically increased from 15 to 27.8 cm²/Vs, as compared with Ti-ITO film deposited without ICP power.

Increased mobility with ICP power could greatly enhance the electrical conductivity of Ti-ITO film. The electrical conductivity \( \sigma \) depends on both the concentration \( n \) and mobility \( \mu \) of the free carrier, as shown in Eq. (1).

\[
\sigma = n \cdot e \cdot \mu
\]

where \( e \) is the electron charge. To obtain high conductivity, a high carrier concentration and mobility should be simultaneously realized.

Yang et al. reported that too many titanium atoms addition play as a role of ionized impurities scattering, thereby reducing the mobility and increase the resistivity, the carrier density increases with the titanium.\(^{19}\) In our case, the composition of Ti in ITO was fixed, and thus a small increase in the carrier density with ICP power was closely related with the crystallization effect of ICP power.\(^ {24}\) The sheet resistances of Ti-doped ITO deposited with ICP power were closely related with the crystallization effect of ICP power. Figure 5 shows the sheet resistance of Ti-doped ITO films as a function of the ICP power and post-annealing temperature (up to 200 °C). After 200 °C annealing, the sheet resistance of Ti-doped ITO film deposited at no ICP power decreased from 295.1 ohm/sq to 202.3 ohm/sq, while the one obtained at an ICP power of 450 W decreased from 134.5 ohm/sq to 75.65 ohm/sq.

From the viewpoint of the reduction ratio of the sheet resistance with the annealing temperature, the Ti-doped ITO film formed at the ICP power was more effective. It is considered that micro-crystallites made by ICP power at the room temperature easily initiate the crystallization process at higher temperatures, such that the larger grains were essentially attributed to the higher mobility. Figure 6 shows the transmittance of the Ti-doped ITO film/glass with the ICP power.

Ti-doped ITO film without ICP had a transmittance of 75% at a wavelength of 550 nm, while those with ICP had higher transmittances, e.g., the ICP of 300 W, had a transmittance of 78.9% before anneal process. Clearly, this shows that IPVD with an ICP increased the transmittance of Ti-ITO film.

Moreover, the transmittance of this Ti-doped ITO films increased to 81.6% at a wavelength of 550 nm after a 200 °C annealing process for 1 hour under a vacuum. In case of Ti-undoped ITO (25 nm) with ICP 450 W, transmittance of 78.8% at wavelength of 550 nm and sheet resistance of 190 ohm/sq has been achieved after 200 °C annealing for 1 hour (not shown). In this result, we can expect that using of Ti-doped ITO film with ICP is better than ITO film with ICP for transparent conductive material. To evaluate and compare the quality of the different ICP power, the figure of merit \( (\Phi_{TC}) \) was calculated from the sheet resistance and transmittance at a wavelength of 550 nm as shown in Figure 7. The \( \Phi_{TC} \) was defined by Haacke as the Eq. (2).\(^ {27}\)

\[
\Phi_{TC} = \frac{T^{10}}{R_{sh}}
\]

Where \( T \) is the transmittance and \( R_{sh} \) is the sheet resistance of the Ti-doped ITO film. It was shown that the \( \Phi_{TC} \) value of the Ti-doped ITO film increase with increasing
ICP power. The maximum $\Phi_{TC}$ value (1.62 $\Omega^{-1})$ of the Ti-doped ITO film was obtained at an ICP power of 450 W.

4. CONCLUSION

We investigated the effect of inductively coupled plasma on the electrical and optical properties of Ti-doped ITO films at room temperature. The Ti-doped ITO films obtained at ICP power showed an increased transmittance and decreased sheet resistance. The Ti-doped ITO film (30 nm) formed at an ICP of 450 W had a transmittance of 78% at a wavelength of 550 nm, and a sheet resistance of 134.5 ohm/sq, which was due to the improved crystallization from the IPVD.

Acknowledgment: This work was supported by R&D projects of MOTIE/KEIT. [10039263, Development of window-unified 30” touch sensor and A007700102, Development of multi-touch IC and module for next generation using by hybrid electrode].

References and Notes


Received: 11 November 2014. Accepted: 27 January 2015.