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Ti-doped In_2O_3 transparent conductive thin films with high transmittance and low resistivity

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Ti-doped In_2O_3 thin films have been prepared on glass substrate by radio frequency (RF) sputtering with different sputtering powers (90, 120, 150, and 180 W) at 330 °C. The influence of sputtering power on the structural, electrical and optical properties of the deposited thin films is investigated. The average transmittance of the thin films in the wavelength range of 500–1100 nm is over 90%. Low resistivity of 7.3×10^{-4} Ωcm is also obtained based on our thin films, suggesting that Ti-doped In_2O_3 is a good candidate for transparent conductive thin film.

Keywords: sputtering, In_2O_3, transparent conductive oxide, thin films.

1. Introduction

Transparent conductive oxide (TCO) thin films have received much attention because of their wide applications in the field of thin-film solar cells, touch display panels, flat panel displays, heaters and defrosters [1–6]. With the development of these optoelectronic devices, the pursuing of novel TCO materials with improved electrical and optical properties which may contribute to better device performances is continuing [7–11]. Ti-doped oxide, such as Ti-doped ZnO, CdO and MgO, have emerged as one of the most useful transparent conducting films, becoming increasingly used in the aforementioned applications [12–14]. These thin films have been prepared by different techniques including continuous direct current (DC), pulsed mid-frequency (MF) and radio-frequency (RF) sputtering from either metallic, alloyed or ceramic targets. Among these techniques, RF sputtering has gained special attention owing to a good product quality and high yield. Extensive scientific technological efforts have been made in this technique in order to improve the transmittance and conductance of the thin films [15–17]. However, Ti-doped In_2O_3 is a novel material which can be employed for TCO thin films, and its optoelectronic properties have been investigated in a few papers only [18, 19].

In this paper, Ti-doped In_2O_3 film is deposited by efficient RF sputtering technique, and its crystalline structure and surface morphology are studied. The In_2O_3 has been chosen in our experiment for its unique properties in optoelectronic devices, sensors and transducers [20]. Simultaneously, Ti-doping has been proved to be of benefit in improving the transmittance and conductance of semiconducting metal oxides [12–14]. The Ti-doped In_2O_3 thin film exhibits low resistance and high transmission in our optoelectronic investigations, indicating its potential applications in TCO thin films.

2. Experimental details

Ti-doped In_2O_3 thin films were deposited on the conventional glass substrates by a RF sputtering system at 330 °C. The high purity TiO_2/In_2O_3 (99.99%) target was used in our experiments. The percentage of titanium in the target was 2 wt%. The base pressure in the chamber was below 5×10^{-4} Pa and the sputtering deposition was carried out at a pressure of 1 Pa with pure Ar gas. Four sputtering powers 90, 120, 150 and 180 W were used. Before deposition, the target was pre-sputtered in Ar atmosphere for 15 min in order to remove any impurity on the surface of the target. After deposition, the thin films with the thickness of 540–570 nm were obtained.

X-ray diffraction (XRD) analysis was conducted on a Rigaku D/max-2500 X-ray diffractometer with Cu Kα radiation (λ = 1.5418 Å). The component of the sample was determined by an energy dispersion X-ray (EDX) spectroscopy equipped with scanning electron microscopy system (HITACHI S-4700). The surface roughness was analyzed by an atomic force microscopy (AFM, Solver P47-PRO). The thin film thickness was measured by a step profiler (AMBIOS Technology INC XP-2). The optical transmission measurements were carried out in a spectrophotometer (UV-1700, SHIMADZU). The measurements of Hall effect were carried out in the Van der Pauw configuration with indium ohmic electrodes by Bio-Rad Microscience HL5500 Hall System at 25 °C.

3. Results and discussion

The Ti content in the thin films is about 2.6%, as determined by EDX, which is higher than that in the target. The thin film thickness is measured to be about 550 nm. The XRD pattern of the Ti-doped In_2O_3 thin film prepared at different sputtering powers is given in Fig. 1.

All of the diffraction peaks can be indexed to the cubic In_2O_3 with lattice constant of a = 1.011 nm (JCPDS card no. 06-0416) [21]. No peaks corresponding to Ti are observed, indicating that titanium gets incorporated into the In_2O_3 lattice. The XRD pattern also indicates that the grains are randomly oriented. The average particle size t of the thin films was calculated using the Scherrer equation [22]:

$$t = \frac{0.9\lambda}{\beta\cos\theta} \tag{1}$$

where λ is the X-ray wavelength, β is the full-width at half-maximum of the (222) diffraction line and θ is the diffraction angle of the XRD spectra. The particle size

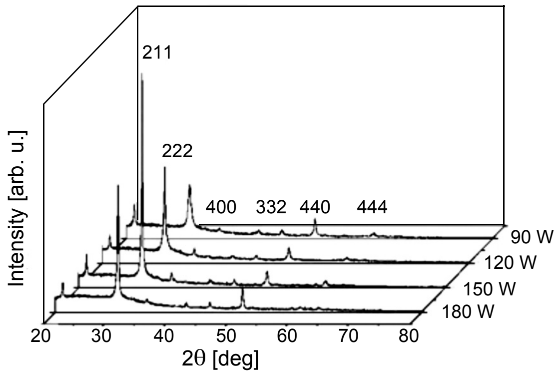

Fig. 1. XRD pattern of the Ti-doped In_2O_3 film prepared at different powers.

calculated from this equation is found to be 35, 43, 59 and 44 nm in the cases of 90, 120, 150 and 180 W, respectively. It can be observed that the crystallite sizes increase on elevating the sputtering power because the ions or ion clusters can obtain more energy prior to collision with the substrates [23].

The AFM morphology image of the Ti-doped In_2O_3 thin film prepared at 150 W on a scale of 2×2 μm is shown in Fig. 2. The scan was carried out in the contact mode, and the atomic force was set as 2 nN and scan frequency of 1 Hz. The thin film has a very smooth surface, which is beneficial for their optoelectronic application in transparent conductive layers or transparent electrodes. The root mean square (RMS) surface roughness of the film is about 2.17 nm which is much superior to the commercially available indium tin oxide films (~4 nm) [24]. The other thin films obtained at different powers exhibit similar morphologies to this sample.

The variation of electrical resistivity ρ, carrier concentration n and mobility μ as a function of sputtering power is shown in Fig. 3. As the sputtering power increases from 110 to 150 W, both Hall mobility and carrier concentration increase respectively, which leads to a decrease of resistivity. This trend is based on the sputtered species

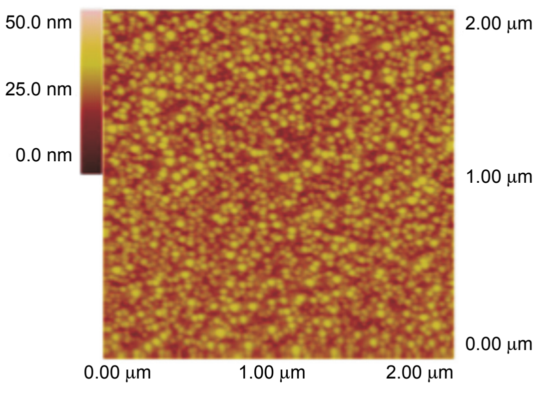

Fig. 2. AFM micrograph of Ti-doped In_2O_3 thin film prepared at 150 W.

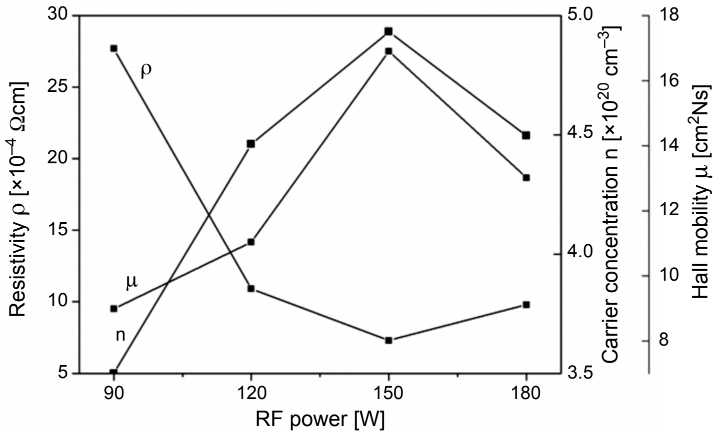

Fig. 3. Resistivities, carrier concentrations and Hall mobility as a function of sputtering power.

and has low surface mobility on the substrate at low sputtering power, which results in degraded crystallinity and few In substitutions, thus the thin film has low Hall mobility and carrier concentration [25]. With the sputtering power increasing, the species kinetic energy increases, which improves the thin film crystallinity and In substitution. The minimum resistivity is 7.3×10^{-4} Ωcm based on the thin film prepared at 150 W.

A comparison of the transmittance of films prepared at different sputtering powers is presented in Fig. 4. It is clear form the figure that the average transmittance of the thin films is more than 90% for wavelengths in the 500−1100 nm range, indicating the good transparency of the thin films. With the sputtering power changing from 90 to 180 W, a sharp UV-off shifts to shorter wavelength with an increase of carrier concentration, known as the Burstein−Moss shift [26].

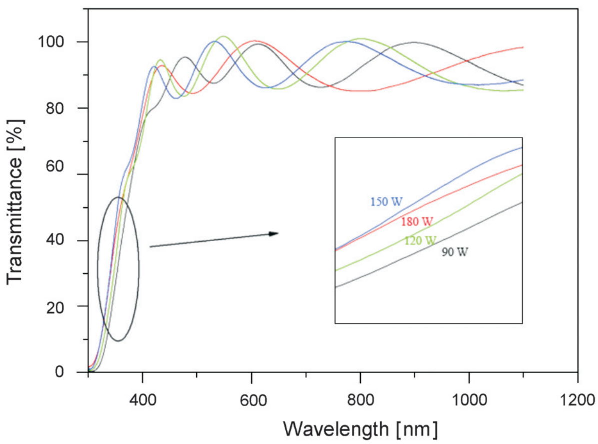

Fig. 4. Transmittance spectra for the Ti-doped In_2O_3 thin films obtained at different sputtering powers.

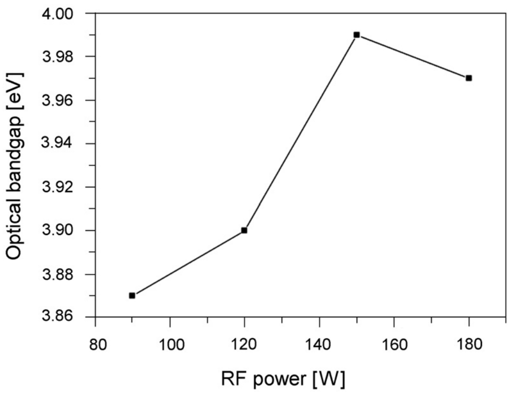

Fig. 5. Optical bandgap of the Ti-doped In_2O_3 thin films deposited at different sputtering powers.

The dependence between the optical gap E_g and the absorption coefficient α of the thin films can be obtained from the following equation [27]:

$$(\alpha h\nu)^2 = A(h\nu - E_g) \tag{2}$$

where A is a constant and $h\nu$ is the photon energy. E_g can be determined by extrapolations of the linear portion of the curve to the $h\nu$ axis. The optical bandgaps for the TCO thin films deposited at sputtering power of 90, 120, 150 and 180 W are 3.87, 3.90, 3.99 and 3.97 eV, respectively (Fig. 5). The optical bandgaps obtained for these thin films are much larger than that of undoped In_2O_3. The widening of the bandgap is in good agreement with the carrier concentration due to the Burstein–Moss effect [26].

4. Conclusions

In summary, TCO thin films of Ti-doped In_2O_3 are deposited on conventional glass substrates by RF sputtering at 330 °C, showing good crystallinity with a preferential orientation of (222). The lowest resistivity of 7.3×10^{-4} Ωcm is obtained for our thin films, and the average transmission between 500 and 1100 nm is over 90%. These experimental results reveal the potential applications of Ti-doped In_2O_3 in fields of TCO thin films.

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