Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp573-574

Advanced transparent conductive ZnO/ITO/ZnO multilayer thin films

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1. Introduction

Transparent conductive oxide (TCO) thin film has received extensive attention all the time due to its potential applications in various opto-electronic devices [1-2]. In order to achieve high conductivity and transmittance TCO films, multilayer TCO thin films have been extensively designed and fabricated, such as IZO/Al/GZO [3], AZO/Cu/AZO [4], ZnO/Ag/ZnO [5] tri-layer films etc. Notably, the most studies used metal layer to take as the middle layer to improve the electrical properties. However, the metal layer would be increased the optical transmittance.

Indium tin oxide (ITO) is not only an n-type wide-band gap semiconductor but also possess an excellent optical transmittance. In this work, the ZnO/ITO/ZnO tri-layer film was used to improve the optical and electrical properties.

2. Experimental procedure

The ZnO/ITO/ZnO multilayer was deposited on silica-glass substrate by RF sputtering. Finally, the multilayer was annealed at 500 ºC for 1 hour under the different atmosphere (Vacuum, O_2, Ar and N_2). Fig. 1 shows the structures of multilayer. The thickness of ZnO layer was 100 nm, and the thickness of ITO layer was varied from 0 to 17 nm.

3. Results and discussions

Fig. 2 shows the XRD pattern of ZnO/ITO/ZnO multilayer with different ITO interlayer thickness. All multilayer presented a ZnO hexagonal structure and preferred c-axis orientation of (002). Notably, the diffraction peak of (622) was also observed which associated with the ITO structure [6]. In addition, the intensity of (002) peak increased with increasing ITO thickness. As ITO interlayer thickness increased to 13 nm, the intensity of (002) peak decreased instead which indicated that the thicker ITO interlayer resulted in the deterioration of ZnO quality.

To understand the effect of ITO interlayer thickness on transmittance, the optical transmittance of multilayer with various ITO interlayer thicknesses is shown in Fig. 3. For ZnO films (ITO=0 nm), the average optical transmittance in the visible region (390- 800 nm) was about 92 %. With the ITO interlayer thickness increased to 17 nm, the average transmittance still possessed an excellent transmittance (~90 %). This result was indicated that the ITO was more suitable for interlayer comparing with other metal interlayer (Ag, Cu and Al etc.).

To understand the electrical properties and possible effects of various ITO interlayer thicknesses, ZnO/ITO/ZnO multilayer films were measured by Hall measurement. Table 1 shows the resistivity, mobility and carrier concentration of ZnO/ITO/ZnO multilayer films. The resistivity decreased and the carrier concentration of ZnO/ITO/ZnO multilayer films increased with increasing the ITO interlayer thickness (from 0 nm to 17 nm). Due to the indium would be gradually diffused to whole multilayer under the particular thermal treatment condition (>450 ºC) [7] resulted in improvement of multilayer films conductivity. In addition, the mobility of ZnO film was slowest due to ITO layer was not consisted in film. As ITO interlayer consisted in the multilayer, the electron mobility decreased with increasing the ITO interlayer thickness which indicated that the higher indium concentration resulted in the reduction of electron mobility.

According to Fig. 3 and Table 1, the synthetic analysis of ZnO/ITO/ZnO multilayer with different ITO interlayer thickness was shown in Fig. 4 using regression. The ZnO only possessed an excellent transmittance but ZnO/ITO/ZnO multilayer with 9 nm ITO interlayer not only had good transmittance but also possessed better electrical properties. In addition, the synthetic analysis of atmosphere of thermal treatment for ZnO/ITO/ZnO multilayer with 9 nm ITO interlayer was shown in Fig. 5 using regression. Under the vacuum condition, ZnO/ITO/ZnO multilayer with 9 nm ITO interlayer not only had good optical transmittance but also possessed excellent electrical properties.

4. Conclusion

The investigations of ITO interlayer on the structure, optical, and electrical properties of ZnO/ITO/ZnO multilayer films were performed. The ZnO/ITO/ZnO multilayer film not only had good optical transmittance but also provided good electrical properties. For these reasons, this ZnO/ITO/ZnO multilayer structure may be considered as a candidate for an advanced TCO material.

Acknowledgements

The authors are grateful to National Cheng Kung University, the Center for Micro / Nano Science and Technology (NCKU Project of Promoting Academic Excellence & Developing World Class Research Center: D97-2700) and NSC 97-2221-E-006-018; NSC 97-2622-E-006-009-CC3 for the financial support.

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Table 1 Electrical properties of ZnO/ITO/ZnO multilayer films with different ITO interlayer thickness

ITO thickness (nm)	Resistivity (Ω-cm)	Mobility (cm^2/V-s)	Carrier concentration (cm^{-3})
0	9.09	0.88	7.8×10^{17}
5	9.47×10^{-2}	5.83	1.13×10^{19}
9	5.71×10^{-2}	5.68	1.92×10^{19}
13	2.29×10^{-2}	5.11	5.32×10^{20}
17	1.23×10^{-2}	3.96	1.29×10^{20}

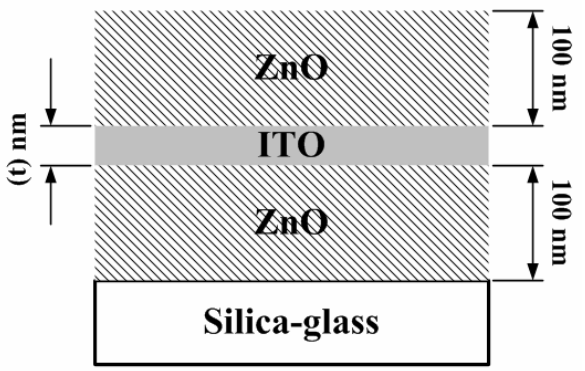

Fig. 1 Schematoc structure of ZnO/ITO/ZnO multilayers

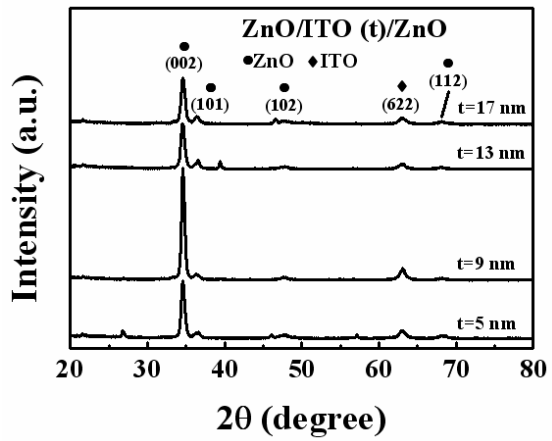

Fig. 2 XRD patterns of ZnO/ITO/ZnO multilayer film with different ITO interlayer thickness.

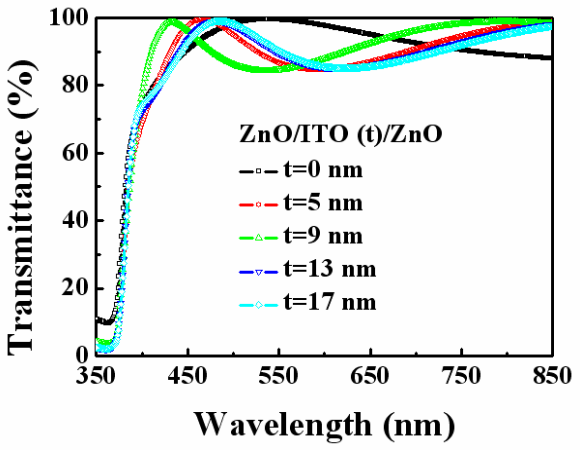

Fig. 3 Optical transmittance of ZnO/ITO/ZnO multilayer films with different ITO interlayer thickness

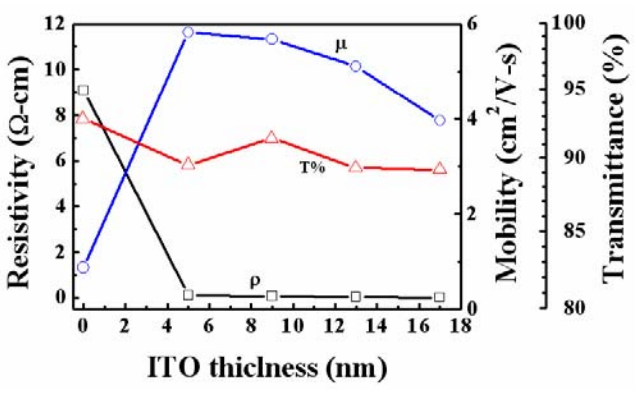

Fig. 4 The relation of ITO thickness of ZnO/ITO/ZnO multilayer films with the optical and electrical properties

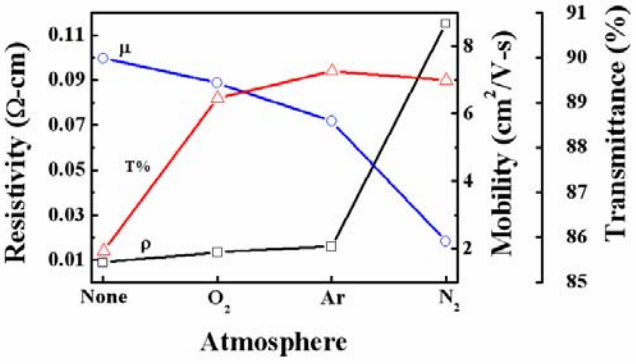

Fig.5 The relation of atmospheres with the optical and electrical properties