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# Effect of Cu layer thickness on the structural, optical and electrical properties of AZO/Cu/AZO tri-layer films

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ABSTRACT

Highly conducting AZO/Cu/AZO tri-layer films were successfully deposited on glass substrates by RF magnetron sputtering of Al-doped ZnO (AZO) and ion-beam sputtering of Cu at room temperature. The microstructures of the AZO/Cu/AZO multilayer films were studied using X-ray diffraction (XRD), field emission scanning electron microscopy (FE-SEM) and atomic force microscope (AFM). X-Ray diffraction measurements indicate that the AZO layers in the tri-layer films are polycrystalline with the ZnO hexagonal structure and have a preferred orientation with the *c*-axis perpendicular to the substrates. With the increase of Cu thickness, the crystallinity of AZO and Cu layers is simultaneously improved. When the Cu thickness increases from 3 to 13 nm, the resistivity decreases initially and then varies little, and the average transmittance shows a first increase and then decreases. The maximum figure of merit achieved is $1.94 \times 10^{-2}\ \Omega^{-1}$ for a Cu thickness of 8 nm with a resistivity of $7.92 \times 10^{-5}\ \Omega$ cm and an average transmittance of 84%.



## 1. Introduction

Transparent conducting oxides (TCOs) have received great attention because of their various technological applications, such as solar cells, organic light emitting diodes (OLEDs) and flat panel displays [1–4]. The efficiency and performance of these devices depend on the optical and electrical properties of the TCO materials. Indium tin oxide (ITO) film is the most widely used TCO film due to its high transparency, low resistivity and high work function [5,6]. However, ITO film is not stable and shows degradation at temperatures above 700 K [7,8]. Doped ZnO such as Al-doped ZnO (AZO) [9–11], In-doped ZnO (IZO) [12], Ga-doped ZnO (GZO) [13], Zr-doped ZnO (ZZO) [14] and Mo-doped ZnO (MZO) [15] have been widely investigated due to their excellent properties, and AZO film is mostly studied among them. Moreover, ZnO is thermally stable [16], nontoxic, cheap and abundant. However, the resistivity of these TCOs is still not low enough in some cases for improved practical applications [17]. In order to improve the conductivity of transparent conducting films, it is necessary to try new materials or constructions. It is well known that the conductivity of metal films is very high, but their transmittance is relatively low [18]. It had been reported [19] that when a metal mirror layer was embedded between two dielectric layers, the dielectric/metal/dielectric tri-layer film could suppress the reflection from the metal in the visible range and achieve a selective transparent effect. From then on, there were more and more studies on the tri-layer films, such as ITO/Ag/ITO [20,21], ZnO/Ag/ZnO [22,23] and ZnO/Cu/ZnO [24,25], and all of them possessed fine photoelectric performance, especially high conductivity.

The optical and electrical properties of the thin metal layer depend considerably on its thickness and deposition conditions [26]. The metal layer should be thin, uniform, and continuous for high transmittance and low resistivity. The tri-layer films mentioned above were prepared using different methods, such as low energy thermal evaporating and magnetron sputtering. However, the metal layer in the tri-layer film has been rarely prepared by ion-beam sputtering. As a widely used method of depositing films, ion-beam sputtering can prepare films with high quality due to high energy of incoming ions, and the film thickness can be easily controlled because of the low deposition rate. Furthermore, to our knowledge, there are few reports on AZO/Cu/AZO tri-layer films.

We have reported the preparation of AZO/Cu/AZO tri-layer films using RF magnetron sputtering of AZO and ion-beam sputtering of

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Cu method, and studied the properties with the variation of AZO thickness in our previous paper [27]. Thus, the AZO thickness for tri-layer and bi-layer films in this paper is fixed to 40 nm. In this paper, the effect of Cu thickness on the structural, electrical and optical properties of the films was investigated in detail.

## 2. Experimental details

AZO/Cu/AZO tri-layer, Cu/AZO bi-layer and AZO single layer films were prepared on glass substrates by RF magnetron sputtering of AZO using an AZO target (purity: 99.99%, diameter: 7.62 cm, thickness: 0.5 cm, $Al_2O_3$: ZnO = 3: 97 wt.%) and ion-beam sputtering of Cu using a Cu target (purity: 99.99%, area: 7 cm × 7 cm, thickness: 0.5 cm) at room temperature. Prior to deposition, the substrates were ultrasonically cleaned and degreased in acetone. The RF magnetron sputtering and ion-beam sputtering chambers were initially pumped down to $1.5 \times 10^{-4}$ Pa. The deposition of AZO layers was performed in an argon (purity: 99.99%) atmosphere and the deposition pressure was maintained at 0.5 Pa and the RF power was kept at 70 W. The distance between the substrate and the target was 4.5 cm. The deposition of Cu layers was carried out in an argon (purity: 99.99%) atmosphere and the working pressure was $5 \times 10^{-2}$ Pa.

The thickness of films was measured using a surface profiler (Ambios Technology Company, USA). The structural property was analyzed by the X-ray diffraction (XRD) using a Rigaku D/MAX 200V/PC diffractometer with a Cu-Kα1 radiation source. The surface morphologies and cross-section view were analyzed by using a JSM-6700F field emission scanning electron microscopy (FE-SEM). Surface roughness and surface images were taken by atomic force microscope (AFM, Digital Instruments Inc., Nanoscope Multimode and NanoScope Dimension 3100, USA). The sheet resistance ($R_S$) was determined by four-point probe measurements. The optical transmittance measurements were performed with a Cary100 UV–VIS spectrophotometer (Varian Company) in the range of 300–800 nm.

## 3. Results and discussion

In order to study the role of every layer on the properties of the AZO/Cu/AZO tri-layer films, Cu/AZO bi-layer and AZO single layer films were prepared as well as AZO/Cu/AZO tri-layer films. Fig. 1 shows the XRD patterns of Cu/AZO bi-layer films with different Cu thickness. It is observed that all the films are polycrystalline with the (0 0 2) preferred orientation belonging to ZnO hexagonal wurtzite. The intensity of (0 0 2) peak increases with the increase of Cu thickness indicating that the crystallinity of AZO layer is improved, which should be due to the enhancement of the quality of Cu layer. However, the peaks corresponding to Cu are not detected.

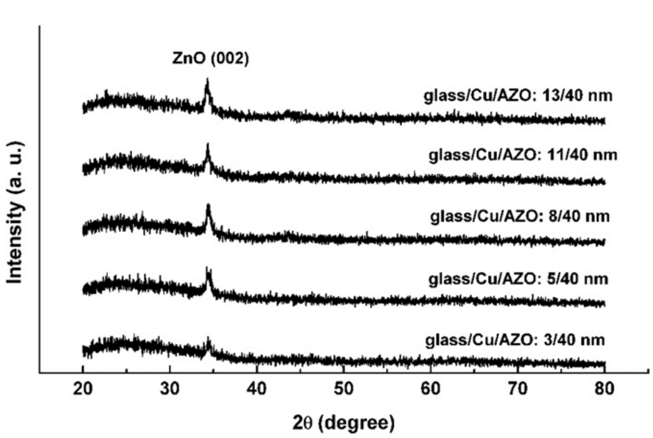


**Fig. 1.** XRD patterns of Cu/AZO bi-layer films with different Cu thickness.

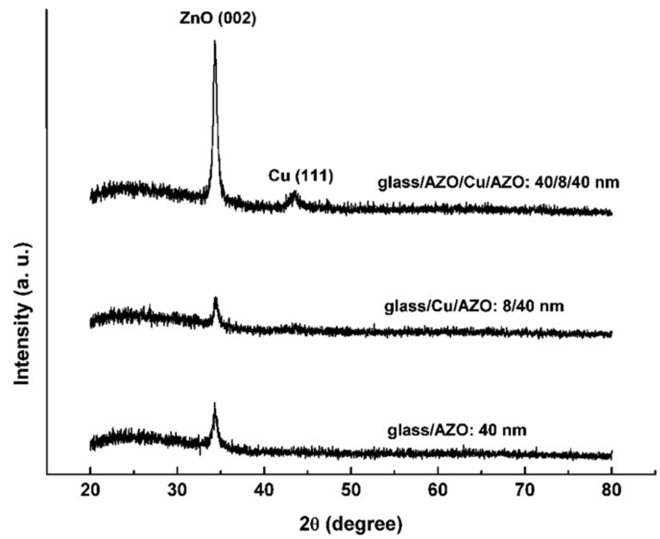


**Fig. 2.** XRD patterns of AZO/Cu/AZO tri-layer, Cu/AZO bi-layer and AZO single layer films.

Fig. 2 displays the XRD patterns of AZO/Cu/AZO tri-layer, Cu/AZO bi-layer and AZO single layer films. For Cu/AZO and AZO films, only ZnO (0 0 2) peak is observed. The intensity of (0 0 2) peak of the Cu/AZO film is weaker than that of AZO single layer film implying that the crystallinity of AZO layer in the Cu/AZO film is worse than that of the AZO single layer film, which should be due to the poor quality of Cu layer. For the tri-layer film, the intensity of (0 0 2) peak is strong, and a Cu (1 1 1) peak is simultaneously observed, which indicates that the AZO and Cu layers have good crystallinity. The ZnO grain sizes for AZO, Cu/AZO and AZO/Cu/AZO films are 17.9, 16.6, and 19.7 nm, respectively. Based on the grain sizes of AZO and AZO/Cu/AZO films, the grain size of the top AZO layer in the tri-layer film can be evaluated to be about 21.5 nm, which is larger than

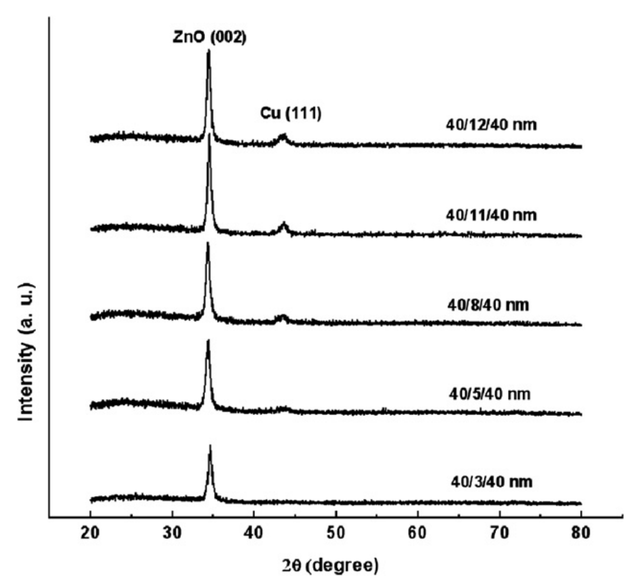


**Fig. 3.** XRD patterns of AZO/Cu/AZO tri-layer films with different Cu thickness.