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Effect of the Cu Bottom Layer on the Optical and Electrical Properties of In_2O_3/Cu Thin Films

Daeil Kim*

School of Materials Science and Engineering, University of Ulsan, Ulsan 680-749

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Indium oxide (In_2O_3) single layer and In_2O_3/copper (Cu) bi-layer films were prepared on glass substrates by RF and DC magnetron sputtering without intentional substrate heating. In order to determine the effect of the Cu bottom layer on the optical, electrical and structural properties of In_2O_3 films, 3-nm-thick Cu film was deposited on the glass substrate prior to deposition of the In_2O_3 films. As-deposited In_2O_3 films had an optical transmittance of 79% in the visible wavelength region and a sheet resistance of 2,300 Ω/□, while the In_2O_3/Cu film had optical and electrical properties that were influenced by the Cu bottom layer. In_2O_3/Cu films had a lower sheet resistance of 110 Ω/□ and an optical transmittance of 71%. Based on the figure of merit, it can be concluded that the Cu bottom layer effectively increases the performance of In_2O_3 films for use as transparent conducting oxides in flexible display applications.

Keywords : In_2O_3, Cu, Magnetron sputtering, Sheet resistance, Optical transmittance

I. Introduction

Sn-doped indium oxide (In_2O_3), specifically an ITO thin film, is a highly degenerated, wide-gap semiconductor with good conductivity and high optical transmission across the visible spectrum. As a result, ITO films are used in many applications such as solar cells [1], light emitting electrochemical cells [2], and variant flat panel displays [3]. ITO films can be prepared with high reproducibility using methods including reactive evaporation, reactive DC or RF sputtering [4], ion beam assist deposition [5], and chemical vapor deposition (CVD) [6]. Among these methods, DC or RF magnetron sputtering are two of the most frequently used deposition methods in optoelectronic device manufacturing [4].

In conventional sputtering processes, substrate temperatures as high as 300°C are required for deposition and/or post-annealing to obtain high quality transparent conducting oxide (TCO) films with reasonably high conductivity ($\sim 2\times10^{-4}$ Ωcm) and transmittance (≥80% in the visible region) [7]. However, for certain applications, such as flexible optoelectronic devices, high substrate temperatures or high post-deposition annealing temperatures are undesirable due to the low thermal resistance of the polymer substrates.

One way to improve the optical and electrical properties of the transparent conducting oxide (TCO) films without substrate heating is to use TCO/metal/

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* [E-mail] dkim84@ulsan.ac.kr

TCO structures that have lower resistivity than TCO single layer films of the same thickness [8]. Recently Y. Kim reported ITO/Au/ITO multilayer films that have higher performance than that of ITO single layer films [9]. In this study, transparent and conducting In_2O_3/copper (Cu) bi-layered films were deposited on a glass substrate without intentional substrate heating by RF and DC magnetron sputtering, and the effect of the Cu bottom layer on the optical, electrical and structural properties of the In_2O_3 films were considered.

II. Experiments

In_2O_3 and Cu thin films were deposited on a glass (Corning 1737) substrate without substrate heating by RF and DC magnetron sputtering equipped with two cathodes. RF (13.56 MHz) and DC power were applied to the In_2O_3 (purity; 99.9%) and Cu (purity; 99.9%) targets, respectively. During deposition, the substrate temperature was monitored using a K-type thermocouple directly in contact with the substrate surface and was maintained at 70°C. Prior to deposition, the chamber was evacuated to a pressure of 2.0×10^{-4} Pa. Sputtering was performed at 1×10^{-1} Pa in argon (Ar) and the deposition distance between the target and substrate was maintained at 7 cm. By controlling the deposition time and sputtering power, the film thickness for In_2O_3 and Cu was maintained at 100 nm and 3 nm, respectively. For comparison, In_2O_3 single layer films without a Cu bottom layer were also deposited under the same deposition conditions.

After deposition, film thickness was confirmed with a surface profilometer (Dektak 150, Veeco) and atomic force microscopy (AFM, XE-100, Park Systems). The crystallization of the films was observed with high resolution X-ray diffraction (XRD, X' pert Pro MRD, Philips) at the Korea Basic Science Institute (KBSI, Daegu Center). The surface roughness was analyzed using AFM on 2×2 μm^2 sample areas. In addition, optical and electrical properties were assessed using a four-point probe (MCP-T360, Mitsubishi), a Hall automatic measuring system (HMS-3000, Ecopia) and a UV-Vis. Spectrophotometer (Cary 100 Cone, Varian), respectively. The glass substrates showed a 92% optical transmittance in the visible wavelength range. The performance of the In_2O_3 and In_2O_3/Cu films as transparent conducting films was evaluated using the figure of merit (FOM) [10].

III. Results and Discussion

In XRD measurements, none of the films showed diffraction peaks in the patterns, indicating that they were all amorphous and the low substrate temperature prohibited crystallization. In a previous study, Kim reported that the Au bottom layer in ITO/Au bi-layered films promotes the crystallization of the upper ITO film without intentional substrate heating [11] or a post-deposition annealing process [12]. However, the Cu bottom layer in the present study did not effectively crystallize the upper In_2O_3 film.

Fig. 1 shows the three-dimensional AFM images of as-deposited Cu, In_2O_3 and In_2O_3/Cu films. The root mean square (RMS) roughness of the as-deposited Cu and In_2O_3 films was 0.3 and 1.1 nm, respectively, while the RMS roughness of the In_2O_3/Cu bi-layered films was 6.4 nm.

As shown in Fig. 1, though the thin Cu bottom layer had a flat surface morphology, it increased the surface roughness of the upper In_2O_3 film effectively in the bi-layered films. Since the rough surface morphology resulted in a wider film surface area, it can be inferred that the effect of the Cu bottom layer on the surface roughness is favorable for solar cells and gas sensor applications of In_2O_3 films.

Fig. 2(a) shows the optical transmittance in a

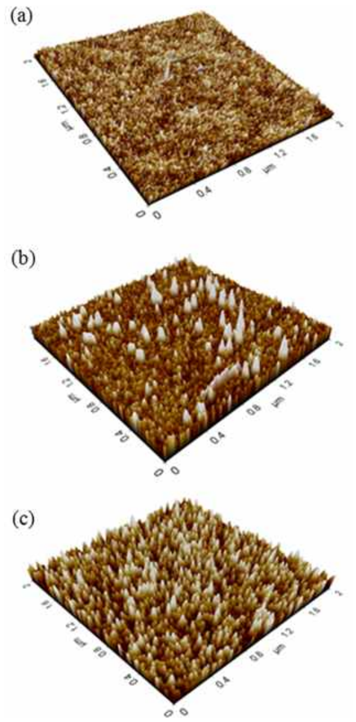

Figure 1. The three-dimensional AFM images of as-deposited Cu, In_2O_3 and In_2O_3/Cu films. (a) Cu thin film, (b) In_2O_3 film, (c) In_2O_3/Cu film.

wavelength range of 300～900 nm. The In_2O_3 and In_2O_3/Cu films had optical transmittances (with a glass substrate) in the visible wavelength region of 79% and 71%, respectively. Fig. 2(b) shows the optical absorption in the wavelength range of 300～900 nm. The In_2O_3/Cu films had greater absorption than that of the In_2O_3 single layer films.

The optical absorption at the interface between the In_2O_3 and Cu films reduced the optical transmittance of the In_2O_3/Cu films. In addition, the rougher In_2O_3/Cu surface increased the absorption of the incident light and may also have reduced the optical transmittance.

Along with the optical analysis, the electrical properties of the films were evaluated. Fig. 3 shows a parallel electrical resistance circuit model of the In_2O_3/Cu bi-layer films. Based on the amount of flowing electrical current, the bottom Cu layer had a thickness of 3 nm and a sheet resistance of 3.56×10^6 Ω/□. The electrical resistance can be calculated

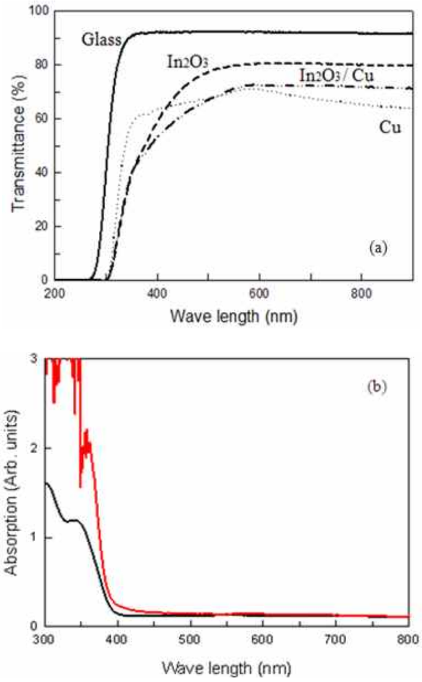

Figure 2. (a) Optical transmittance of In_2O_3 and In_2O_3/Cu films, (b) Optical absorption of In_2O_3 and In_2O_3/Cu films.

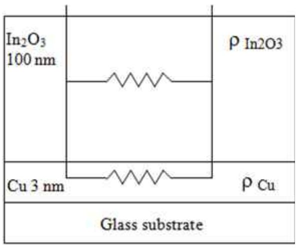

Figure 3. A parallel electrical resistance circuit model of In_2O_3/Cu bi-layer films.

with the simple equation:

$$1 / R_{Total} = 1 / R_{Cu} + 1 / R_{In2O3},$$

where R_{Total}, R_{Cu} and R_{In2O3} refer to the total resistance, the resistance of the Cu bottom layer and the resistance of the In_2O_3 upper layer in the In_2O_3/Cu films, respectively. The relationship between resistance (R) and resistivity (ρ) is expressed as R = (ρl)/A, where l is the length and A is the cross-sectional area.

Table 1 shows the electrical properties of In_2O_3 and

Table 1. The electrical properties of In_2O_3 and In_2O_3/Cu bi-layered films.

Film	Resistivity (Ω cm)	Mobility (cm^2/Vs)	Carrier concentration (cm^{-3})
In_2O_3	0.24×10	4.93×10^{-1}	5.34×10^{18}
In_2O_3/Cu	1.19×10^{-3}	8.26×10^{2}	6.29×10^{18}

Table 2. Comparison of optical, electrical properties and figure of merit (FOM, Ω^{-1}) of In_2O_3 and In_2O_3/Cu bi-layered films.

Properties	In_2O_3/Cu	In_2O_3
Optical transmittance (%)	71	79
Sheet resistance ($\Omega/\square$)	110	2,300
Figure of merit (Ω^{-1})	2.9×10^{-4}	4.1×10^{-5}

In_2O_3/Cu film and the In_2O_3/Cu bi-layered Film shows the lower resistivity than that of the In_2O_3 films.

Table 2 shows the optical and electrical properties of the films. The In_2O_3/Cu films had a lower sheet resistance than that of the In_2O_3 single layer films. The figure of merit (FOM) is an important index for evaluating the performance of transparent conducting oxide (TCO) films [13]. The FOM is defined as FOM= T^{10}/R_s, where T is the optical transmittance and R_s is the sheet resistance. The FOM reached a maximum of 2.9×10^{-4} Ω^{-1} for the In_2O_3/Cu layered films, which is greater than the FOM for the In_2O_3 single layer films prepared in this study, which was 4.1×10^{-5} Ω^{-1}.

As higher FOM indicates better quality TCO films, the In_2O_3/Cu layered films will likely perform better in TCO applications than In_2O_3 single layer films.

IV. Conclusions

Both In_2O_3 and In_2O_3/Cu bi-layered films were deposited without intentional substrate heating on glass substrates using RF and DC magnetron sputtering. In this study, the optical and electrical properties were highly dependent on the Cu bottom layer in the In_2O_3/Cu films. A TCO that had a sheet resistance of 110 $\Omega/\square$ and a high optical transmittance of 71% in the visible wavelength region was obtained from the 100 nm In_2O_3/3 nm Cu films.

Figure of merit for the In_2O_3/Cu films reached a maximum value of 2.7×10^{-4} Ω^{-1}, which was greater than that of the In_2O_3 single layer films. This result indicates that the 3-nm-thick Cu bottom layer in the In_2O_3/Cu films results in better performance than conventional In_2O_3 single layer films.

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구리 기저 층이 In_2O_3/Cu 박막의 광학적, 전기적 특성에 미치는 영향

김대일*

울산대학교 첨단소재공학부, 울산 680-749

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유리 기판 위에 RF와 DC 마그네트론 스퍼터링 방법으로 100 nm 두께의 In_2O_3 단층 박막과 In_2O_3 100 nm/Cu 3 nm의 두께를 갖는 적층박막을 증착하고, 구리 기저 층 증착에 따른 상부 In_2O_3 박막의 광학적, 전기적 특성의 변화를 연구하였다. 상온에서 증착 된 In_2O_3 박막의 가시광 투과도와 면 저항은 79%와 2,300 Ω/□이었다. 구리 기저 층의 광 흡수에 의하여, In_2O_3/Cu 적층박막의 가시광 투과도는 71%로 감소하였으나, 면 저항은 110 Ω/□로 측정되어 상대적으로 우수한 전기적 특성을 구할 수 있었다. 본 연구에서 Figure of Merit 분석을 통하여 구리 기저 층이 상부 In_2O_3 투명전극의 전기적, 광학적 특성을 개선 할 수 있음을 확인하였다.

주제어 : 인듐옥사이드, 구리, 광투과도, 마그네트론 스퍼터링, 면저항

* [전자우편]: dkim84@ulsan.ac.kr