Ultrathin Metal Film with Yb/Ag Electrode for Flexible Organic Devices

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ABSTRACT

We have studied on the fabrication of the ultrathin metal film with Yb/Ag for the electrode of flexible organic devices. It had a lower sheet resistance and a higher transmittance than conventional Al/Ag metal electrode. Yb/Ag film is a promising transparent conductive electrode for flexible device.

1 Introduction

Flexible displays are fabricated in a free form and can be applied not only to mobile phones and TVs, but also to e-books, fashions, medical electronics, and automotive displays. The transparent conductive electrodes (TCEs) play an important role in realizing the flexible organic devices. TCEs require high flexibility, high electrical conductivity, and high transparency [1, 2]. However, the common indium tin oxide (ITO) film, widely used TCE, cannot be applied to flexible substrates due to its brittleness properties which induce the sheet resistivity deteriorations by bending stress [3]. To replace ITO electrode, many researches have been carried out [1, 2]. The flexible TCEs can be classified into three types: (1) ultrathin metal films, (2) metal nanowire networks, and (3) metal meshes [1, 2]. The ultrathin metal film technology has the advantages of low surface roughness and simplification of process time. For ultrathin metal films, it is key technology to fabricate homogeneous metals such as Ag, Cu, and Al. The thickness of the transparent electrode should be less than 20 nm due to the penetration threshold range [1, 4]. The physical vapor deposition (PVD) method such as sputtering or thermal evaporation is typically used to deposit the TCEs. When depositing a homogeneous metal by the PVD, it follows the Volmer-Weber growth mode [5]. The deposited metal atoms became a thin film on the non-wetting substrate via isolated islands. However, the thin film of TCEs lower than 20 nm increase the resistance. To reduce the resistance, two fabrication methods were proposed: (1) a method to form a seed metal layer between the substrate and the ultrathin metal film, and (2) a doping method when depositing the ultrathin metal film [2].

In this paper, we proposed new seed metal of ytterbium (Yb) for the ultrathin metal film. We also demonstrate the electrical and optical properties of TCEs with Yb as the electrode of the flexible organic devices.

2 Experiment

To verify the electrical and optical properties of TCEs with Yb metal as a seed metal, first we fabricated the Al/Ag film and Yb/Ag film using thermal evaporation. Then, their characteristics such as the sheet resistance, transmittance, figure of merit (FoM), roughness image were compared.

To fabricate the TCEs, glass substrates were cleaned by an ultrasonic method with acetone and isopropyl alcohol for 15 min each, dried in a drying oven for at least 30 minutes. The Al, Yb, and Ag was deposited under high vacuum conditions of under 3×10^{-7} Torr using thermal evaporation. Al and Yb were deposited as the seed metal with the thickness of 2 nm on a glass substrate, respectively. Then, we deposited Ag with the thickness of 8 nm to 14 nm on the substrates which were deposited by the seed metal. Finally, 1,4,5,8,9,11-Hexaazatriphenylene hexacarbonitrile (HAT-CN) was deposited with the thickness of 10 nm on seed metal/Ag film.

After depositing Ag with the thickness of 8 nm to 14 nm on the seed metal film such as Al and Yb, the sheet resistance was measured with respect to the seed metal and thickness of Ag. Then, the transmittance of the seed metal/Ag/HAT-CN film was also measured by the spectroscope. The roughness of each film was compared by atomic force microscopy (AFM). Finally, the FoM data was evaluated by the sheet resistance data and transmittance data at the wavelength of 550 nm.

3 Results

We analyzed the electrical and optical properties of the TCEs of Al/Ag and Yb/Ag films.

Figure 1 shows the sheet resistance data with respect to the thickness of Ag. Although the thickness of Ag was reduced to 6 nm, both electrodes showed superior sheet resistance characteristics of approximately 20 Ω sq^{-1}.

Especially Yb/Ag film has better data more than Al/Ag film. It implies that Yb seed layer presents more effective suppression of the Vomer-Weber growth mode of Ag layer comparing with Al, hence, it can enhance the transmittance without the aggravation of sheet resistance property.

We also evaluated the transmittance of the TCEs. To maximize the transmittance characteristics of TCEs, HAT-CN was applied on each electrode as a capping layer in order to match the refractive indices between Ag and air. Figure 2 shows the transmittance curves of Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film. The transmittance curves also had better data for Yb metal. In particular, it is noteworthy that the transmittance was significantly improved in the longer wavelength region.

The Haccke FoM equation used as an index to compare the electrical and optical characteristics based on the sheet resistance data and the transmittance data can be calculated as follows;

$$\text{FoM: } \mathrm{T}^{10}/\mathrm{R_s} \quad (1)$$

where T and R_s mean transmittance and sheet resistance, respectively [6]. The FoM of Yb/Ag/HAT-CN film was improved about 1.7 times comparing with that of Al/Ag/HAT-CN film. Table 1 summarizes the sheet resistance, transmittance, and FoM data comparison sheets of Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film. The sheet resistance of TCEs with the Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film was 22.46 $\Omega\ sq^{-1}$ and 16.44 $\Omega\ sq^{-1}$, respectively.

The Transmittance at 550 nm of TCEs with the Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film was 87.85% and 89.85%, respectively.

The FoM of TCEs with the Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film was $1.22\times10^{-2}\ \Omega^{-1}$ and $2.09\times10^{-2}\ \Omega^{-1}$, respectively. The FoM of Yb/Ag/HAT-CN film is 1.7 times higher than the FoM of Al/Ag/HAT-CN film.

Finally, as shown in Fig. 3, roughness was analyzed via AFM. The root mean square (RMS) values of TCEs with the Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film were 1.026 nm and 1.763 nm, respectively.

This confirms that the Yb metal can serve as a seed metal. There was no significant difference in the data.

4 Conclusions

We have studied on the fabrication of the ultrathin metal film with Yb/Ag for the electrode of flexible organic devices. The sheet resistance of TCEs with the seed metal by Al film and the seed metal by Yb film was 22.46 $\Omega\ sq^{-1}$ and 16.44 $\Omega\ sq^{-1}$, respectively. The Transmittance at 550 nm of TCEs with the seed metal by Al film and the seed metal by Yb film was 87.85% and 89.85%, respectively. The FoM of TCEs with the seed metal by Al film and the seed metal by Yb film was $1.22\times10^{-2}\ \Omega^{-1}$ and $2.09\times10^{-2}\ \Omega^{-1}$, respectively.

Yb/Ag film is a promising transparent conductive electrode for the next-generation flexible display device.

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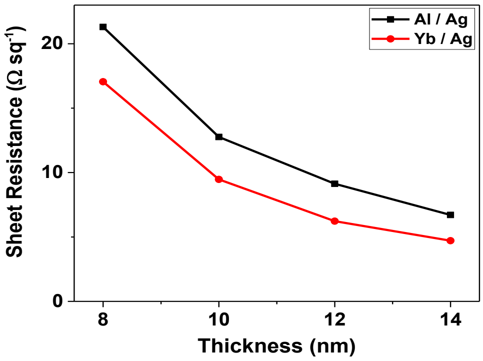

Fig. 1 Sheet resistance of flexible transparent conductive electrodes based on Al/Ag film and Yb/Ag film.

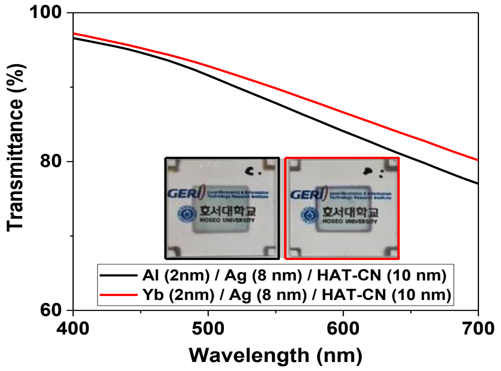

Fig. 2 Transmittance of flexible transparent conductive electrodes based on Al/Ag/HAT-CN film and Yb/Ag/HAT-CN film and photographs of both electrode (inset).

Table. 1 The opto-electrical properties of flexible TCEs based on Al /Ag/HAT-CN film and Yb/Ag/HAT-CN film at 550 nm wavelength.

Structure	R (Ω sq^{-1})	T (%)	FoM (10^{-2} Ω^{-1})
Al(2 nm) /Ag (8 nm) /HAT-CN (10 nm)	22.46	87.85	1.22
Yb (2nm) /Ag (8nm) /HAT-CN (10 nm)	16.44	89.85	2.09

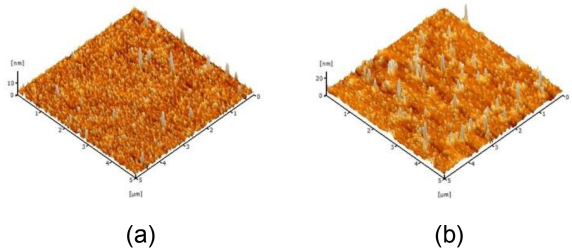

Fig. 3 AFM images of flexible transparent conductive electrodes based on (a) Al/Ag/HAT-CN film and (b) Yb/Ag/HAT-CN film.