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Investigation of surface energy, polarity, and electrical and optical characteristics of silver grids deposited via thermal evaporation method

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ABSTRACT

In this study, silver grid transparent conducting films are fabricated via the thermal deposition method. The proposed grid shows low sheet resistance and a good figure of merit. The sheet resistance decreased from 688 to 3.37 Ω/square when the thickness was increased from 30 to 70 nm. The samples are characterized in terms of the contact angle to calculate the surface energy and polarity. The surface energy and polarity of the samples increased from 8.15 to 58.029 mJ/m^2 and 0.024 to 0.067, respectively, when the sulfur content was increased from 6.67 to 9.26% (thickness increased from 50 to 70 nm). The fabricated Ag grid transparent conducting films show good optical and electrical characteristics and have potential for application in optoelectronics.

1. Introduction

Transparent conducting electrodes (TCEs) are important components in organic light-emitting diodes (OLEDs). ITO is currently the most popular TCE used in the electronics industry because it has excellent characteristics for OLEDs, such as low sheet resistance (as low as 10 Ω/square) and high transmission in the visible wavelength range (typically 85% on average from 400 to 700 nm) [1]. ITO also has been used in flexible substrates for flexible optoelectronics applications and the characteristics were investigated in the article [2]. For example, Gustafsson et al. [3] have demonstrated that ITO/PET can be used as anode in flexible LEDs and Yang et al. [4] fabricated the OLEDs based on the ITO/PET anode. However, ITO has some drawbacks that limit its future applications. For example, ITO is very expensive due to the scarcity of indium, its relatively high refractive index, which induce power lost to the total internal reflection at the ITO/glass and ITO/organic interfaces reflection at the ITO/glass and ITO/organic interfaces [5,6]. ITO also requires a high processing temperature and the migration of indium limits the lifetime of OLEDs.

Alternative TCEs are thus needed to replace ITO. TCEs used in optoelectronics must high transmission at the emission wavelength and low sheet resistance. Lowering the process time and cost is also desirable. Many transparent materials with good conductivity have been reported, such as poly (3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) [7], silver nanowires (NWs) [8], metal grids [9], carbon nanotubes (CNTs) [10], and graphene oxides [11,12]. However, poor uniform dispersion in most solvents of carbon nanotubes, inconvenient synthesis method and high surface roughness of metallic nanowires are major challenges in employing these electrodes. Besides, graphene oxides are highly sensitive to the film thickness of the GO due to its insulating property. A precise control of the thickness is required, which limits the repeatability of the device performance [13]. Meanwhile, the conductivity of pristine PEDOT:PSS is below 10 S cm^{-1}, much too low to be used as an electrode in an optoelectronics applications. Therefore, PEDOT:PSS films must combine with other auxiliary anode to increase the conductivity [13,14].

On the other hand, many metals, such as copper [15], gold [16], silver [17], aluminum [18], have been used to fabricate metal grids with novel characteristics, such as low sheet resistance (as low as 20 Ω/square), good ductility, and adjustable sheet resistance and transmission (controlled by the line width, spacing, or thickness [16]). However, these metal grids were deposited via sputtering deposition methods. Sputtering deposits films with good quality.

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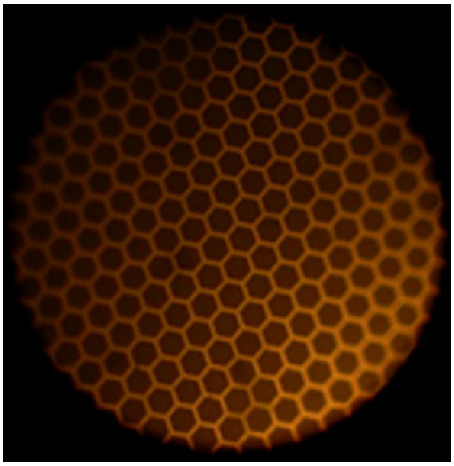

Fig. 1. Optical microscopy image of silver grid.

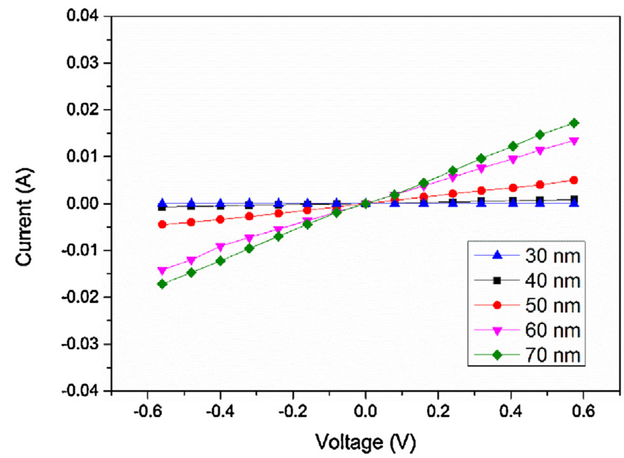

Fig. 2. Current–voltage curves for Ag grids with various thicknesses.

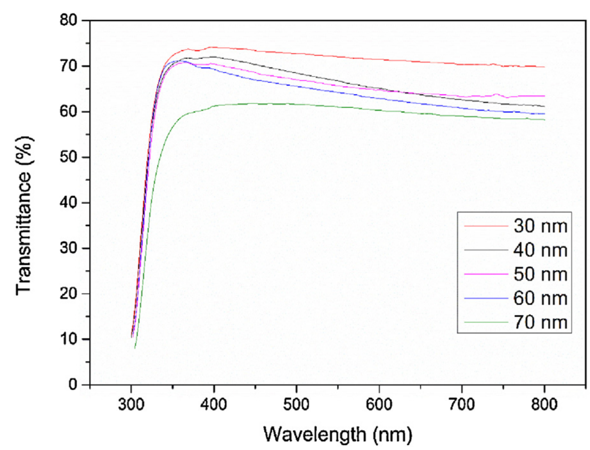

Fig. 3. Plots of transmittance for Ag grids with various thicknesses.

However, it has some drawbacks, such as a slow deposition rate and an inability to deposit organic films. Therefore, the sputtering deposition method is unsuitable for organic devices. The thermal deposition method is commonly used in industry due to its high deposition rate and good performance of fabricated devices. However, there have been no studies on the performance of metal grids deposited via the thermal evaporation method. In this paper, the electrical and optical characteristics of metal grids with various thicknesses deposited via the thermal evaporation method are investigated. The surface energy and polarity of films such as ITO [19] and polymer films [20,21] have been reported. However, the surface energy and polarity of metal grids have not been reported. These parameters are related to the surface roughness and contact between the metal grids and the organic layer. In this work, the surface energy and polarity are used to analyze surface characteristics.

2. Experiment procedures

Glass substrates were ultrasonically cleaned in detergent for 15 min and then washed in an ultrasonic bath of deionized (DI) water, isopropyl alcohol, and alcohol, each for 15 min. They were then rinsed in DI water and dried with nitrogen.

Photolithography was prepared in a lithography laboratory. The glass substrates were baked in an oven at 90 °C for 10 min. This process helps the photoresist adhere to the substrates. The photoresist was first spin-coated at 6000 rpm for 15 s and then spin-coated at 8000 rpm for 25 s (at the maximum acceleration). The photoresist was then baked in an oven at 90 °C for 10 min. After the samples had cooled to room temperature, the photoresist was exposed for 30 s and then developed for 30 s. The samples were then rinsed in DI water. An optical microscope was used to make sure that the patterns were well defined.

The samples were moved to the thermal evaporation system and Ag grids with various thicknesses were deposited under at pressure of 5×10^{-7} Torr. After deposition of the silver grids, the samples were sonicated in an ultrasonic acetone bath for 3 min. The samples were then rinsed and dried with nitrogen. The line width of the grids was 3 μm and the line spacing was 10 μm, as shown in Fig. 1.

The electrical performance and the transmittance of the metal grids were measured using a 4-point probe and an ultraviolet-visible system. The surface energy, polarity, and sulfur content were systematically investigated. The sulfur content, measured using energy-dispersive X-ray spectroscopy (EDS), affected the surface energy and polarity of the silver grids. The geometric mean expression was used to calculate the surface energy (γ_S) from the measured contact angle (θ) [22]:

$$\gamma_L(1 + \cos\ \theta) = 2(\gamma_S^p \times \gamma_L^p)^{1/2} + 2(\gamma_S^d \times \gamma_L^d)^{1/2} \quad (1)$$

where γ_L is the surface tension of the test liquid, γ_S is the surface energy of the solid, and superscripts *p* and *d* refer to the polar and dispersion components of the surface tension of the test liquid and/or the surface energy of the solid, respectively. The contact angle was measured using the sessile drop method. The test liquids were H_2O and CH_2I_2.

3. Result and discussion

3.1. Electro-optical characteristics of silver grid with different thicknesses

Fig. 2 shows the electrical properties of metal grids with various thicknesses (40–70 nm). The resistance of the sample with a thickness of 30 nm was too high to measure accurately. The resistance decreased from 6.88×10^3 (40 nm) to 33.7 (Ω) (70 nm). The area of the Ag grids was $2.5 \times 0.25\ cm^2$. The sheet resistance R_{sh} values were 688, 11.46, 4.25, and 3.37 Ω/square for grid thicknesses of 40, 50, 60, and 70 nm, respectively. The sheet resistance of a commercial ITO electrode is 10 Ω/square. Fig. 3 shows the transparency of the samples with various thicknesses. As shown, the transmittance values at 550 nm were 66.8–61% for samples with thicknesses of 40–70 nm (sheet resistances of 688–3.37 Ω/square). The figure of