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Properties of ITO films deposited on cholesteric liquid crystal layer by two-step DC magnetron sputtering

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Abstract Indium tin oxide (ITO) films were deposited on cholesteric liquid crystal (Ch-LC) layers at room temperature using one-step and two-step DC magnetron sputtering processes, respectively. The surface morphologies and electrical properties of the ITO thin films were analyzed using scanning electron microscopy, X-ray diffraction, three-dimensional microscopy, and a four-point probe. The results showed that the two-step deposition process prompted the formation of a polycrystalline structure and improved both the surface roughness and the electrical resistance of the ITO film. Specifically, compared to the bare Ch-LC layer, the surface roughness was reduced from 1.8 to 0.6 μm and the electrical sheet resistance was reduced from 165 to 100 Ω/sq.

Keywords Cholesteric liquid crystal · Magnetron sputtering · ITO

1 Introduction

Transparent conducting oxides (TCOs) have good electrical and optical properties, and are thus widely used in the fabrication of optoelectronic devices such as thin film transistor liquid crystal displays (TFT-LCDs), light emitting diodes (LEDs), organic light-emitting diodes (OLEDs), touch panels, and solar cells (Qi et al. 2013; Kim et al. 2000). Among the

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various TCOs available, indium tin oxide (ITO) is one of the most commonly used due to its low electrical resistivity (i.e., 1–3$\times$10^{-4} Ω cm) and high optical transmittance (i.e., >90 % in the visible region) (Cui et al. 2008; Lin and Hsu 2014). Various deposition methods have been used for the preparation of ITO films, including the sol–gel method (Yu et al. 2002), sputtering (Guillén and Herrero 2011; Lee et al. 2008), evaporation (Diniz 2011; Fallah et al. 2007), conductive coating (Yabuki et al. 2014), and pulsed laser deposition (PLD) (Quiñones-Galván et al. 2016; Tsai et al. 2014). Of these techniques, sputtering is commonly preferred due to its low-cost, versatility and low temperature operation. The thin film with good quality, repeatability and uniformity can be easily obtained. Flexible LCDs have attracted growing interest in recent years for such applications as smart watches, advertising displays, smart textiles, e paper, human health monitoring systems, and so on. Such devices typically consist of transparent conducting electrodes deposited on a color stacking structure (Khan et al. 2007; Lin et al. 2010). This stacking structure is generally fabricated of transparent conducting polymer layers since polymer has good flexibility and high physical robustness. However, the polymer layers have a high sheet resistance of 1–2 kΩ/sq (Betz et al. 2008), and hence the resistance of the transparent conductive film can affect the performance of the device. Electrical properties are very important for color stacking Ch-LCDs. Thus, great interest exists in the potential for replacing polymer color stacking structures in flexible LCDs with ITO/LCD structures. However, in doing so, it is desirable to reduce both the sheet resistance and the surface roughness of the ITO films in order to minimize their power consumption and improve their optical properties. Accordingly, the present study proposes a method for lowering the sheet resistance and surface roughness of ITO films on Ch-LC layers using a two-step magnetron sputtering process. The surface morphologies and electrical properties of the deposited ITO thin films are investigated and compared with those of bare Ch-LC layers and ITO films deposited on Ch-LC layers using a one-step sputtering process. It is shown that the proposed two-step sputtering process significantly reduces the surface roughness and electrical resistance of the deposited ITO films.

2 Experimental method

The ITO deposition process was performed using a DC magnetron sputtering system (ULVAC SIV-3040) with an In_2O_3-SnO_2 alloy target with a composition of 90:10 (wt%). Sputtering was performed at room temperature using base pressures of 5.2 $\times$ 10^{-8} Torr and 5.3 $\times$ 10^{-7} Torr in the load-lock chamber and process chamber, respectively. Prior to the sputtering process, Ch-LC layers with a thickness of 10 μm were coated on polyethylene terephthalate (PET) substrates (CPfilms-OC100) with a size of 3.5 $\times$ 4.5 inch^2 using a sheet coater. ITO layers with a total thickness of 100 nm were then deposited on the Ch-LC/ITO/PET substrates using one-step and two-step magnetron sputtering processes, respectively (see Fig. 1). For the two-step process, two different thicknesses of the ITO layers sputtered in each step were considered, namely 30 nm for Layer 1 and 70 nm for Layer 2 and 50 nm for Layer 1 and 50 nm for Layer 2. For both sputtering processes, the argon (Ar) and oxygen (O_2) flow rates were fixed at 50 and 0.45 sccm, respectively. Moreover, the feed speed was set in the range of 400–960 mm/min. The discharge power settings for the various deposition processes are summarized in Table 1.

The surface morphologies of the Ch-LC layer and ITO films deposited on the Ch-LC layer were observed using a scanning electron microscope (SEM, Hitachi S-4800). The

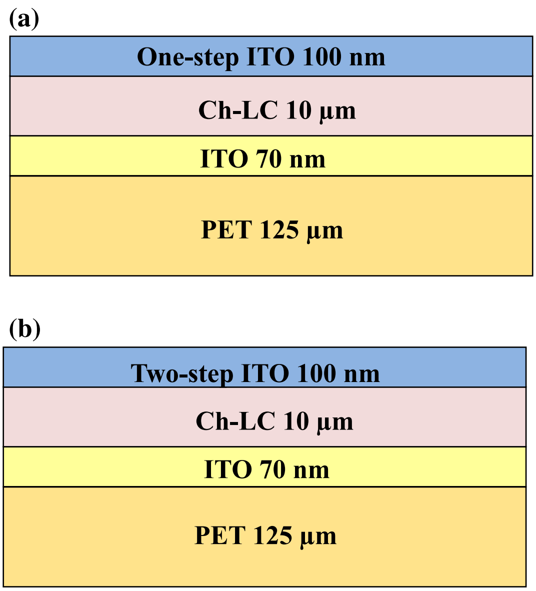

Fig. 1 Schematic diagrams showing: **a** one-step ITO sample and **b** two-step ITO sample

Table 1 ITO layer thickness and DC power conditions for various samples

Sample	Process	ITO layer 1		ITO layer 2	
		Thickness (nm)	DC power (kW)	Thickness (nm)	DC power (kW)
1	Without ITO	*		*	
2	One-step ITO deposition	100	2.3	*	
3	Two-step ITO deposition	30	1.0	70	2.3
4	Two-step ITO deposition	50	1.0	50	2.3

surface roughness of the Ch-LC layer and ITO films was evaluated using a three-dimensional microscope (SIS-1200) with a scanning area of 600 × 600 μm^2. The structures of the ITO films were also examined by grazing incidence in-plane X-ray diffraction (GIXD). Finally, the sheet resistance of the ITO films was analyzed using a four-point probe (RS meter HA6100/RG-1000E).

3 Results and discussions

Figure 2 shows the XRD patterns of the one-step (Sample 2) and two-step (Sample 3) ITO layers deposited on Ch-LC/ITO/PET substrates. For the one-step ITO film, a prominent diffraction peak occurs at 26° as a result of the Ch-LC layer. However, no other peaks are observed in the spectrum, and hence it is inferred that the ITO layer has an amorphous structure. The spectrum for the two-step ITO sample also contains a strong peak

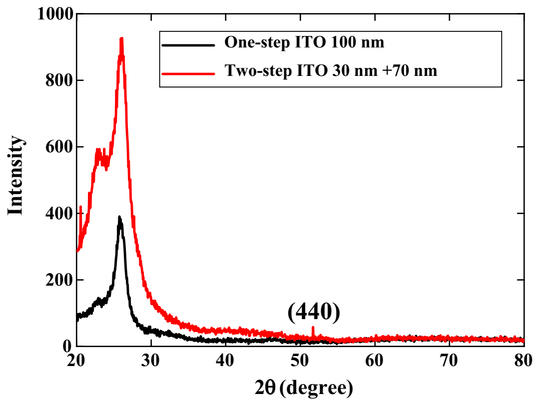

Fig. 2 X-ray diffraction profiles for one-step and two-step ITO samples

corresponding to the Ch-LC layer. However, an additional peak corresponding to the (440) plane of ITO is also observed, which indicates that the ITO layer has a polycrystalline structure. The SEM image in Fig. 3a shows that the bare Ch-LC layer on the ITO/PET substrate contains a large number of holes. The one-step ITO layer deposited on the Ch-LC/ITO/PET substrate also contains holes, as shown in Fig. 3b. However, the holes are both smaller in size and fewer in number than those in the bare Ch-LC layer. The size and number of the holes are further reduced in the two-step ITO samples, as shown in Fig. 3c, d, respectively. The reduction in the hole size and hole number is particularly evident in the ITO sample prepared with non-equal layer thicknesses (i.e., Sample 3 in Fig. 2). ITO films were deposited for the two-step process to minimize roughness due to the former had good step coverage. Overall, the results presented in Fig. 3 suggest that the use of a two-step deposition process is beneficial in reducing the surface roughness of the Ch-LC layer deposited on the ITO/PET substrate.

Figure 4 shows the surface morphologies of the bare Ch-LC layer and sputtered ITO films, as evaluated using three-dimensional microscopy. The results confirm that the average surface roughness (Sa) reduces following the ITO sputtering process. Figure 5 shows the Sa values of the various samples. The Ch-LC layer has a high surface roughness of 1.8 µm due to the use of a sheet coater in depositing the LC layer on the ITO/PET substrate. However, the surface roughness falls to around 0.8 µm for the ITO layer deposited in a single-step process, and to around 0.6 and 0.7 µm for Samples 3 and 4 deposited in a two-step process with non-equal and equal ITO layer thicknesses, respectively. The present results are consistent with those of Lin et al. (2007), who showed that in the two-step RF magnetron deposition of ZnO films, the first step was beneficial in minimizing the surface roughness through achieving a good coverage of the underlying substrate, while the second step was beneficial in further reducing the surface roughness and achieving the preferred orientation.

Figure 6 shows the effect of the processing conditions on the electrical properties of the ITO films. As shown, the one-step ITO film has a sheet resistance of approximately 165 Ω/sq. However, the sheet resistance values of the two-step ITO samples are 100 Ω/sq (Sample 3) and 135 Ω/sq (Sample 4), respectively. It is noted that the results presented in Fig. 6 for the electrical resistance are consistent with those presented in Fig. 5 for the surface roughness. In other words, as reported in [17], the sheet resistance of the sputtered ITO films is directly related to the surface roughness.

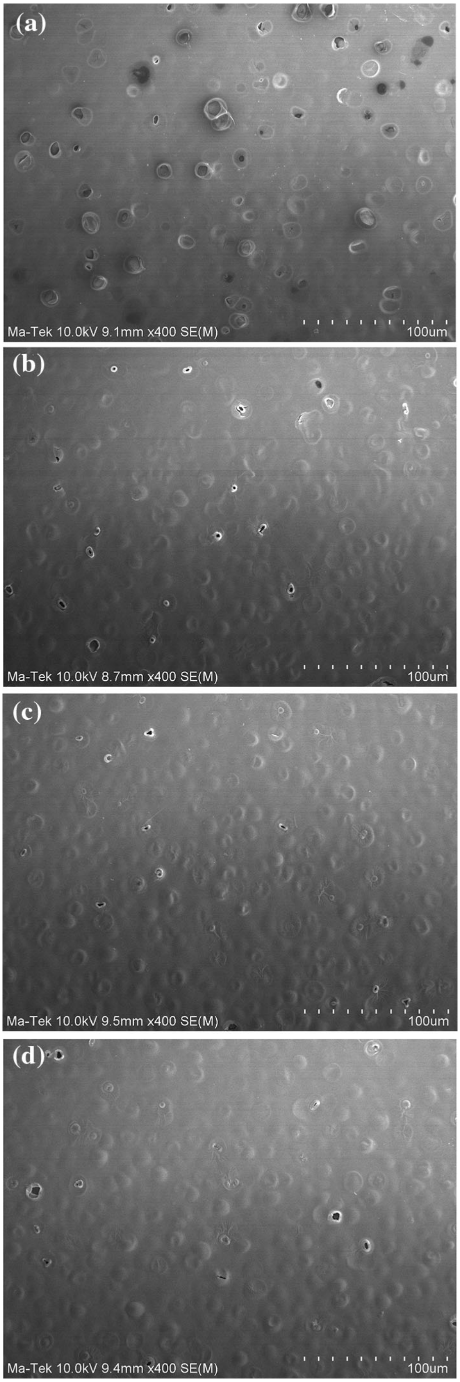

Fig. 3 Top view SEM images of: **a** bare Ch-LC layer, **b** one-step ITO layer (100 nm), **c** two-step ITO layer (30 + 70 nm), and **d** two-step ITO layer (50 + 50 nm)

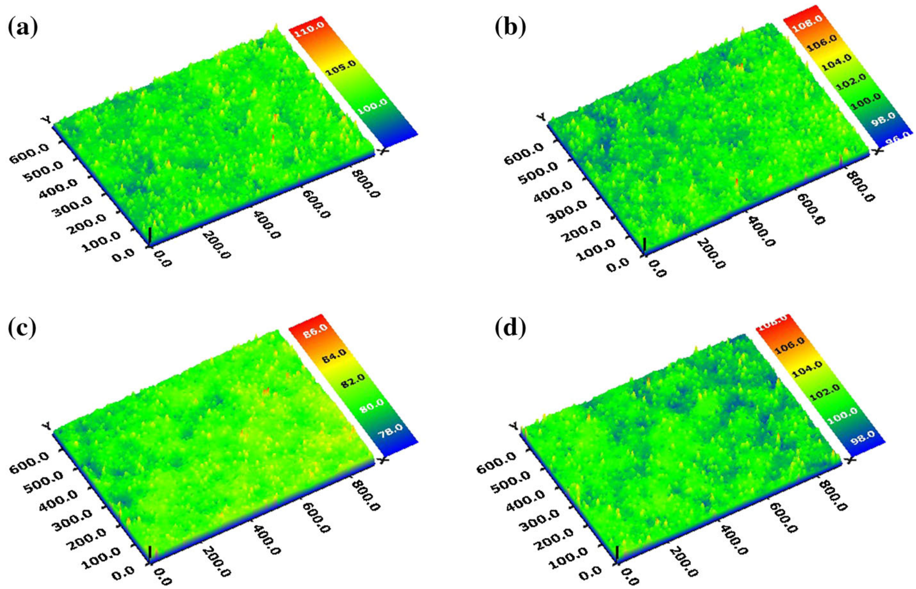

Fig. 4 Surface morphologies of: **a** bare Ch-LC layer, **b** one-step ITO layer (100 nm), **c** two-step ITO layer (30 + 70 nm), and **d** two-step ITO layer (50 + 50 nm)

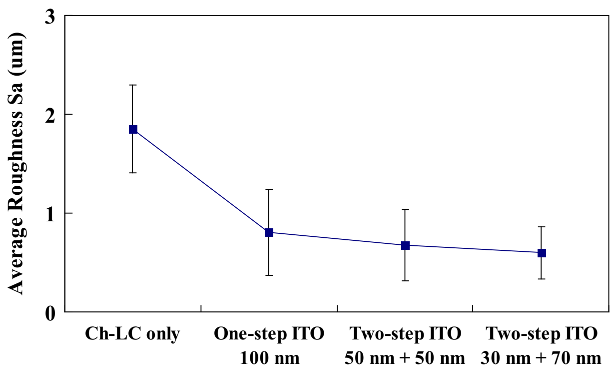

Fig. 5 Average surface roughness (Sa) values of various samples as measured using three-dimensional microscopy

As discussed above in relation to Fig. 2, the XRD spectrum for the two-step ITO film (Sample 3) deposited on the Ch-LC layer shows that the film has a polycrystalline structure. Previous studies on ITO thin films have shown that crystallization leads to both a low sheet resistivity and a high optical transmittance (Lin and Hsu 2014). Consequently, the present results suggest that the use of a two-step magnetron sputtering process is beneficial in improving both the electrical properties and the optical properties of ITO films deposited on Ch-LC/ITO/PET substrates.

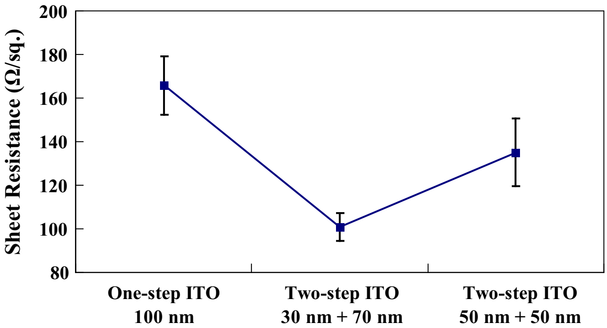

Fig. 6 Sheet resistance values of various samples as measured using four-point probe

4 Conclusions

ITO films have been deposited on Ch-LC/ITO/PET substrates at room temperature using single-step and two-step magnetron sputtering processes. It has been shown that the single-step sputtering process reduces the surface roughness of the bare Ch-LC layer and leads to a lower electrical resistance as a result. Moreover, the two-step sputtering process not only yields a further reduction in the surface roughness, but also prompts the formation of a crystalline structure, which is beneficial in further improving the electrical and optical properties of the sample. For a two-step ITO film with a total thickness of 100 nm, a surface roughness of 0.6 μm and a sheet resistance of 100 Ω/sq can be obtained given ITO layer thicknesses of 30 nm in the first step and 70 nm in the second step, respectively. Overall, the results suggest that the two-step magnetron sputtering process is an ideal solution for fabricating the electrode in the color stacking structures of flexible Ch-LCDs.

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References

Betz, U., Olsson, M.K., Marthy, J., Escolá, M.F.: On the synthesis of ultra smooth ITO thin films by conventional direct current magnetron sputtering. Thin Solid Films **516**, 1334–1340 (2008)

Cui, H.N., Teixeira, V., Meng, L.J., Martins, R., Fortunato, E.: Influence of oxygen/argon pressure ratio on the morphology, optical and electrical properties of ITO thin films deposited at room temperature. Vacuum **82**, 1507–1511 (2008)

Diniz, A.S.A.C.: The effects of various annealing regimes on the microstructure and physical properties of ITO (In_2O_3:Sn) thin films deposited by electron beam evaporation for solar energy applications. Renew. Energy **36**, 1153–1165 (2011)

Fallah, H.R., Ghasemi, M., Hassanzadeh, A.: Influence of heat treatment on structural, electrical, impedance and optical properties of nanocrystalline ITO films grown on glass at room temperature prepared by electron beam evaporation. Phys. E **39**, 69–74 (2007)

Guillén, C., Herrero, J.: TCO/metal/TCO structures for energy and flexible electronics. Thin Solid Films **520**, 1–17 (2011)

Khan, A., Schneider, T., Montbach, E., Davis, D.J., Miller, N., Marhefka, D., Ernst, T., Doane, J.W.: Recent Progress in color flexible reflective cholesteric displays. SID **38**, 54–56 (2007)

Kim, H., Piqúe, A., Horwitz, J.S., Murata, H., Kafafi, Z.H., Gilmore, C.M., Chrisey, D.B.: Effect of aluminum doping on zinc oxide thin films grown by pulsed laser deposition for organic light-emitting devices. Thin Solid Films **377–378**, 798–802 (2000)

Lee, J., Jung, H., Lee, J., Lim, D., Yang, K., Yi, J., Song, W.C.: Growth and characterization of indium tin oxide thin films deposited on PET substrates. Thin Solid Films **516**, 1634–1639 (2008)

Lin, R.C., Chen, Y.C., Kao, K.S.: Two-step sputtered ZnO piezoelectric films for film bulk acoustic resonators. Appl. Phys. A **89**, 475–479 (2007)

Lin, H.K., Hsu, W.C.: Electrode patterning of ITO thin films by high repetition rate fiber laser. Appl. Surf. Sci. **308**, 58–62 (2014)

Lin, H.K., Li, C.H., Liu, S.H.: Patterning electrode for cholesteric liquid crystal display by pulsed laser ablation. Opt. Lasers Eng. **48**, 1008–1011 (2010)

Qi, J.H., Li, Y., Duong, T.T., Choi, H.J., Yoon, S.G.: Dye-sensitized solar cell based on AZO/Ag/AZO multilayer transparent conductive oxide film. J. Alloy. Compd. **556**, 121–126 (2013)

Quiñones-Galván, J.G., Lozada-Morales, R., Jiménez-Sandoval, S., Camps, E., Castrejón-Sánchez, V.H., Campos-González, E., Zapata-Torres, M., Pérez-Centeno, A., Santana-Aranda, M.A.: Physical properties of a non-transparent cadmium oxide thick film deposited at low fluence by pulsed laser deposition. Mater. Res. Bull. **76**, 376–383 (2016)

Tsai, J.R., Feng, W.S., Chien, P.H., Liu, K.C.: Optimization of electrical properties of Al/$LaAlO_3$/indium tin oxide capacitor by adjusting oxygen pressures in pulsed laser deposition and applying post-deposition annealing at low temperatures. Thin Solid Films **555**, 153–158 (2014)

Yabuki, A., Okumura, K., Fathona, I.W.: Transparent conductive coatings of hot-pressed ITO nanoparticles on a plastic substrate. Chem. Eng. J. **252**, 275–280 (2014)

Yu, D., Yu, W., Wang, D., Qian, Y.: Structural, optical, and electrical properties of indium tin oxide films with corundum structure fabricated by a sol–gel route based on solvothermal reactions. Thin Solid Films **419**, 166–172 (2002)