**High-performance ITO thin films for on-cell touch sensor of foldable OLED displays**

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**ABSTRACT**

ITO thin films must have good electro-optical and mechanical characteristics to use them as integrated touch sensors for flexible OLED displays. We fabricated ITO thin films on a separation-layer-coated glass substrate under various deposition or annealing conditions, and then transferred them to cyclo-olefin polymer films to evaluate their electro-optical and mechanical characteristics. ITO films with a thickness of approximately 136 nm deposited at 250°C showed a sheet resistance of 36 Ω/□, light transmittance of 88%, and 2.4% of elongation at break. The 136 nm thick ITO films deposited at 150°C and transferred on 50 μm thick COP film survived 500 h of 85°C, 85% relative humidity under 180-degree bending preservation test, endured at 200,000-time repetitive bending test with a curvature radius of 1.5 mm. These high-performance ITO thin films can be applied to fabricate on-cell touch sensors for foldable OLED displays.

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**1. Introduction**

Transparent conducting thin-film indium tin oxide (ITO) is widely used as an electrode in touch sensors as well as in liquid-crystal displays, organic light-emitting diode (OLED) displays, and solar cells. In general, ITO has an energy band gap of approximately 2.5–4.5 eV with high light transmittance and low specific resistance [1–4]. The electro-optical and mechanical characteristics of ITO thin films are largely dependent on thin-film deposition conditions such as the In–Sn sputter target composition ratio, O₂ partial pressure, substrate temperature, and radio-frequency (RF) power. Furthermore, the crystal structure of the ITO thin film can be changed not only by the deposition temperature, but also by the annealing temperature after the deposition [5]. The transmittance and reflectance of visible light and sheet resistance change depending on the thickness of the thin film [6]. Therefore, the ITO thin-film fabrication conditions should be optimized under different conditions depending on the application device. Usually, the optical characteristics of the transmittance and reflectance are extremely important when an ITO with a large work function is used as the anode electrode of an OLED [7]. When used as an on-cell touch sensor electrode for flexible or foldable OLED displays, mechanical properties such as flexibility are required, along with high transmittance and low sheet resistance. We investigated not only the electro-optical characteristics, such as low sheet resistance and high transmittance at short wavelengths, but also mechanical characteristics that can be applied to integrated on-cell touch sensors for foldable OLED displays.

**2. Experiment**

To apply an ITO thin film to an OLED on-cell touch screen, the ITO should be transferred onto a flexible substrate. In this experiment, an ITO thin film was sputter-deposited on a 3-μm thick organic-separation-layer-coated alkali-free glass. The separation layer was prepared by curing a slab coated cyclo-olefin resin on glass substrate at 250 °C. The thicknesses of the ITO thin films deposited on the separation layer were 45–136 nm. After ITO thin-film deposition, the 45 nm ITO films were subjected to annealing at different temperatures ranging from 160 to 200 °C for 1 hr. Subsequently, a protective film of a 50-μm thick polyethylene terephthalate material coated with an adhesive (15 μm) was laminated on top of the ITO thin film. The roll-to-roll process was used for delamination between the glass and the separation...
layers. The separated ITO thin film and protection film were laminated on a cyclo-olefin polymer (COP) film with a thickness of 50 μm using an adhesive layer with a thickness of 1 μm. The adhesive layer was formed by slit coating and UV curing of photo-curable acrylate resin. Figure 1 illustrates the fabrication process and the cross-sectional structure of the ITO thin film sample that was tested in this experiment.

Several types of ITO thin films were deposited using a sputter target with an In–Sn ratio of 9:1 in a DC magnetron sputter system. The substrate temperature, RF power, and O₂ partial pressure were 25–250°C, 3.5–10.7 kW, and 3%–10%, respectively. ITO thin-film deposition was started at a base vacuum pressure of \( \sim 10^{-7} \) Torr. Film thickness was adjusted using the RF power and deposition time. An ITO thin film with a thickness of 30–136 nm is used in the evaluation, with the thickness of the deposited ITO thin film analyzed using scanning electron microscopy (SEM). Visible light transmittance was analyzed using a spectrophotometer. Crystallinity was analyzed using X-ray diffraction (XRD). Surface roughness was analyzed using atomic force microscopy (AFM). The elongation characteristics of the ITO thin film were evaluated by measuring the tensile strain at which microcracks occurred using an extensometer (Linkam TST350) and a curvature evaluation tester.

### 3. Results and discussion

The transmittance versus wavelength, total transmittance and sheet resistance as functions of the film thickness of the ITO deposited at room temperature are shown in Figure 2. In general, the light transmittance of the multiple layer structure is a function of the wavelength due to the optical interference effects by the reflective lights from interfaces between ITO and adjacent layers as shown Figure 2 (a). This interference effect strongly depends not only on the wavelength but also on the layer thickness and the difference of reflective index between the ITO and adjacent layers. The transmittance of the ITO films deposited at room temperature and unannealed depends on the wavelength, while the total light transmittance of the ITO films is a U-shaped curve, depending on the thickness of the ITO. As shown in Figure 2 (b), the total transmittance of 84% at a thickness
of 40 nm decreased to 74% (minimum) at 96 nm, and then increased again to 84% at 136 nm because of the optical interference effect.

Results showed that ITO thin films with a thickness of 40 nm or less, or approximately 136 nm, are required for high usable transmittance. In contrast, as shown in Figure 2 (b), sheet resistance decreased as thickness increased, with a value of approximately 60 Ω/□ at a thickness of 136 nm. ITO with a thickness smaller than or equal to 40 nm is unsuitable for touch sensors, although it has a high transmittance characteristic because its sheet resistance is greater than or equal to 100 Ω/□.

Figure 3 shows the ITO surface and cross-sectional SEM images according to the ITO thickness. The grain size exhibits an increasing trend as the thickness of the ITO film increases.

The ITO elongation and cracking characteristics were tested using commercially available equipment, such as TST350 of Linkam Co. for elongation control, and VK9500 of Keyence Co. for 3D microscopic image of crack.

Figure 4 shows the ITO elongation and cracking characteristics according to the thickness of the ITO. For the ITO deposited at room temperature and subsequently annealed, the elongation at cracking (%) increases as the thickness increases from 30 to 136 nm upon which cracking of the ITO starts to occur. As shown in Figure 4 (a), if the thickness of the 30-nm thick ITO is increased by 0.7%, cracking occurs, whereas in the case of ITO with a thickness of 136 nm, cracking occurs when the thickness is increased by 2.6% or more, which is 3.7-times higher. Figure 4 (b) shows images of microcracks in the ITO thin film caused by the elongation for each thickness. At the time of cracking, several thin cracks occurred on the ITO thin films (30–50 nm), but the number of cracks decreased to one in the ITO with a thickness of 136 nm, which is thick. Therefore, sheet resistance, light transmittance, and elongation characteristics should be considered for ITO film applications to the on-cell touch sensor of a foldable OLED display requiring flexibility. A schematic diagram of the bending test tool for the thin film and the definition of the parameters are shown in Figure 5.

The thicknesses and elasticities of the COP film, used as a substrate for the ITO thin film, and the ITO thin film itself are $d_s$, $d_f$, $E_s$, and $E_f$, respectively. The effective elastic modulus of the COP film and ITO film layer can be expressed as follows:

$$\bar{E}_s = \frac{E_s}{1 - \nu_s}$$

$$\bar{E}_f = \frac{E_f}{1 - \nu_f}$$

where $E$ and $\nu$ denote the modulus and Poisson ratio, respectively.

The compressive strain of the $R_{bottom}$ part for the bending radius $R$ and elongation of $R_{top}$ can be calculated as follows [8]:

$$\varepsilon_{bottom} = -\frac{d_s^2 \bar{E}_s + d_f^2 \bar{E}_f + 2d_sd_f}{2R(d_s \bar{E}_s + d_f \bar{E}_f)} \text{(compressive)}$$

$$\varepsilon_{top} = -\frac{d_s^2 \bar{E}_s + d_f^2 \bar{E}_f + 2dMd_f}{2R(d_s \bar{E}_s + d_f \bar{E}_f)} \text{(elongation)}$$

The elongation of $R_{top}$ calculated in this manner is shown in Figure 6. A difference may occur in this strain, depending on the elasticity of the COP film used as a substrate. However, when the thickness of the COP film is 50 μm, an elongation of approximately 3% occurs at a bending radius of 1.0 mm (1R). However, when the COP film thickness increased to 200 μm, the elongation of the ITO layer at a bending radius of 1R increased to 12%. Considering that the elongation of a typical ITO is smaller than
Figure 4. (a) Elongation characteristics before cracking as a function of the ITO thin film thickness, and (b) microscopy images of cracking at elongation with different film thicknesses.

Figure 5. Schematic of the bending test tool and defined parameters.

3%, the thickness of the COP substrate film should be less than or equal to 100 μm. Furthermore, the position of the neutral plane, where the stress from the curvature reaches zero, changes depending on the structure of other thin films laminated on the top of the ITO film. This indicates that the electro-optical and mechanical characteristics of the ITO thin film must be considered in optimizing the overall structure of the application device for on-cell sensors of foldable devices. As shown in Figure 4 (a), if the thickness of ITO is smaller than 50 nm, the elongation at cracking is less than 1%. Thus, it is challenging to reduce the bending radius of ITO to below 5R. In general, if the ITO has a thickness of 50 nm or smaller, resistance will be too high, and the required electrical properties of the touch sensor cannot be provided.

Figure 7 shows the effect of the treatment according to the annealing conditions of the ITO thin film with a thickness of 45 nm. The sheet resistance of the deposited ITO thin film can be reduced through annealing, as shown in Figure 7 (a), thereby improving the electrical properties. As the thickness of the ITO film decreases, sheet resistance can be reduced by increasing the annealing temperature. The lowest sheet resistance is obtained at an annealing temperature of 200 °C or higher. For application to touch sensors, the sheet resistance of the ITO thin film should be 100 Ω/□ or less, with high light transmittance and flexibility. As shown in Figure 7 (b) and (c), the crystallization of the ITO increases, the sheet resistance decreases, and the transmittance increases as the annealing temperature increases. However, as shown
Figure 7. (a) Sheet resistance, (b) XRD peak intensity, (c) elongation at cracking, and (d) light transmittance versus annealing temperature characteristics of the 45-nm thick ITO films deposited at room temperature.

in Figure 7 (d) the elongation decreases. Figure 7 (d) shows the elongation rate at the point where the cracks start to occur according to the annealing temperature of the ITO thin film with a thickness of 40 nm. In the case of the deposited ITO thin film (40 nm) with an amorphous state, an elongation of approximately 1.1% was observed. However, if the crystallization increases as the annealing temperature increases, the elongation rate decreases significantly. Therefore, for an ITO thin film with a thickness of 50 nm or smaller, the annealing temperature should be set such that it ensures the required elongation properties while satisfying the sheet resistance according to the usage. To improve the electromechanical properties of the ITO thin film with a thickness of 136 nm and high light transmittance, we applied split evaluation by setting the deposition temperature of the ITO thin film to 150°C, 200°C, and 250°C. The light transmittance of the ITO thin film according to the deposition temperature is shown in Figure 8 (a) and was evaluated using a spectrophotometer (Konica Minolta, CM3500D). The light transmittance of the ITO thin film increases as deposition temperature increases. In particular, there is a significant increase in the short-wavelength region. Improvement in light transmittance is considerably larger when the deposition temperature is 250°C when compared to 200°C. This can be explained by evaluating the crystallization behavior of the ITO thin film using XRD (Figure 8 (b)). Crystallinity and grain size improve when the deposition temperature is high.

The relatively thick ITO (136 nm) has a lower sheet resistance and higher transmittance and flexibility even without annealing compared to the ITO thin film with a thickness of 50 nm or smaller. At a temperature of 200°C or lower, the crystal structure of ITO is amorphous. However, at temperatures of above 200°C, crystallinity gradually increases. Figure 8 (c) shows the sheet resistance of the ITO thin film transferred onto the COP substrate according to the deposition temperature. Sheet resistance decreases as deposition temperature increases. At deposition temperatures of higher than 200°C, the increment becomes smaller. An amorphous ITO is obtained at a deposition temperature of lower than 200°C, No large changes in the electrical property were observed with the deposition temperature. However, as the deposition
temperature increases above 200 ℃, the crystallization of ITO increases. In addition, as the grain size increases, the surface roughness of the ITO also increases. Figure 8 (d) shows the elongation rate at which ITO cracking occurs according to the deposition temperature. In the case of the relatively thick ITO film (136 nm), crystallization increases with the deposition temperature. Accordingly, the decreasing trend in the elongation rate has the same form. For the ITO thin film transferred on the COP film with a thickness of 50 nm at 250 ℃, elongation decreases by 1.5% compared to that of the ITO deposited at or below 200 ℃. However, in the case of the relatively thick ITO (136 nm), the elongation rate is higher than that of the thinner 45-nm film. The elongation rate does not change considerably with the deposition temperature.

For foldable display applications, high-temperature and high-humidity preservation characteristics under 180-degree bending, and a repetitive bending reliability are essential. The high-temperature and high-humidity preservation characteristics under 180-degree bending were investigated by checking the crack occurrence rate.

The crack occurrence rate characteristics were investigated using a test zig as shown in Figure 9 (a). The test samples, shown in Figure 9 (b), were completely fixed at 180-degree bending zig using 5 μm thick of adhesive layer. Test samples were retained at 85% relative humidity, 85 ℃ chamber for 500 h then crack occurrence was checked by VK9500 of Keyence. The crack occurrence rate was calculated according to the number of cracked samples out of 20 test samples.

Figure 10 shows the high-temperature and high-humidity preservation test results using a 180° bending zig with a bending radius of 1.5R and 3R for each of the 20 samples. As shown in Figure 10 (a), the thinner ITO (45 nm) was evaluated by annealing at different temperatures under normal pressure. The thickness of the COP film used as a substrate for the ITO thin film was maintained at 50 μm. In the case of the 45-nm film, the same trend as that of the elongation at cracking shown in Figure 7 (c) was observed. The ITO thin films annealed at a temperature of 185 ℃ or higher exhibited cracks. In contrast, the ITO thin films that were 45 nm thick and

**Figure 8.** (a) Light transmittance, (b) XRD measurement, (c) sheet resistance, and (d) elongation at cracking characteristics for the 136-nm thick ITO films obtained at different deposition temperatures.
Figure 9. Schematic diagram of the bending preservation characteristics test zig and (b) test sample structure. The test samples were attached completely to test zigs using a 5 μm thick adhesive film.

Figure 10. (a) ITO cracking occurrence rate as a function of the annealing temperature and (b) ITO cracking occurrence rate as a function of the deposition temperature. $R$ is the bending radius [mm].

were not annealed did not exhibit cracks. This demonstrates that the amorphous ITO crystal structure is more favorable in relation to cracks. Figure 10 (b) shows the crack occurrence for thick ITO films (136 nm). Unlike in the ITO films with a thickness of 45 nm, no cracks occurred under any of the conditions at a bending radius of 3R. The elongation of the ITO thin film at a bending radius of 3R on the 50-μm COP film is expected to be approximately 1%, as shown in Figure 8 (d). However, in the case of a relatively thick ITO film (136 nm), it is expected that cracks will not occur by bending because its elongation is 2% or higher. However, when the bending radius is reduced to 1.5R, cracks started to occur with a small probability. As the deposition temperature increases, the occurrence rate of cracks also rises. Despite the cracks occurring at a high bending radius of 1.5R, the

Figure 11. Schematic diagram of the repetitive bending test tool and (b) test sample structure with neutral strain plane at the ITO layer. The test sample was partially attached to test zig using a 5 μm thick adhesive film.
level of occurrence is low compared to that of the thinner ITO film (45 nm). This trend is the same as that of the elongation with the thickness of the ITO. The thicker ITO films (136 nm) have a lower sheet resistance and higher transmittance and flexibility than those of the ITO thin films with thicknesses of 50 nm or less. Thus, an ITO thin film with a thickness of approximately 136 nm is optimal for application to the on-cell touch sensors of foldable display devices.

The repetitive bending test, 180-degree in-bounding, for 136 nm ITO on COP films was also carried out using 50 mm thick polarizer attached test samples as shown in Figure 11 (a). Foldable displays have a multi-stacking display structure. However, in this experiment as shown in Figure 11 (b), a 50 μm thick polarizer film was laminated to the top of the ITO on COP film using a 5 μm thick adhesive film to form a neutral strain plane [9] at the ITO layer. The ITO film with thickness of 136 nm and deposition temperature of 150 °C ITO endured at 200,000-time repetitive bending test with a curvature radius of 1.5 mm.

4. Conclusion
We evaluated the electrical, optical, and mechanical properties of ITO thin films that were transferred to COP films according to the ITO thickness and deposition conditions. Results confirmed that the crystallinity of ITO has a significant effect. The optical, electrical, and mechanical properties suitable for application to the on-cell touch sensors of foldable OLED devices were provided when thicker ITO films (136 nm) were deposited at 150 °C or below. The 136 nm thick ITO films deposited at 150 °C and transferred on a 50 μm thick COP film survived from 180-degree bending preservation test with 500 h of 85 °C, 85% relative humidity, endured at 200,000-time repetitive bending test with a curvature radius of 1.5 mm. We confirmed that these high-performance ITO thin films transferred on COP film can be applied to fabricate on-cell touch sensors for foldable OLED displays.

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Disclosure statement
No potential conflict of interest was reported by the author(s).

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References

[1] O.N. Mryasov, and A.J. Freeman, Electronic band structure of indium tin oxide and criteria for transparent conducting behavior, Phys. Rev B64, 233111 (2001).
[2] F. Martino, L. Persano, V. Arima, D. Pisignano, R.I.R. Blyth, R. Cingolani, and R. Rinaldi, Electronic structure of indium-tin-oxide films fabricated by reactive electron-beam deposition, Phys. Rev B72, 085437 (2005).
[3] G.J. Exarhos, and X.D. Zhou, Discovery-based design of transparent conducting oxide films, Thin Solid Films 515, 7025 (2007).
[4] I. Hamberg, C.G. Granqvist, K.-F. Berggren, B.E. Sernelius, and L. Engstrom, Band-gap widening in heavily Sn-doped InO, Phys. Rev B30, 3240 (1984).
[5] M. Nisha, S. Anusha, A. Antony, R. Manoj, and M.K. Jayaraj, Effect of substrate temperature on the growth of ITO thin films, Appl. Surf. Sci 252, 1430 (2005).
[6] D.P. Seo, J.E. Heo, T.H. Jang, and C. Kim, Crystalline state and temperature-dependent conductivity of annealed ITO thin films, New Physics Sae Mulli 66 (4), 392 (2016).
[7] E.K. Nam, Y.-H. Kang, D.-J. Son, D.G. Jung, S.-J. Hong, and Y.S. Kim, Electrical and surface properties of indium tin oxide (ITO) films by pulsed DC magnetron sputtering for organic light emitting diode and anode material, Surf. Coat. Technol. 205, S129 (2010).
[8] C.-C. Lee, Y.-S. Shih, C.-S. Wu, C.-H. Tsai, S.-T. Yeh, Y.-H. Peng, and K.-J. Chen, Development of robust flexible OLED encapsulations using simulated estimations and experimental validations, J. Phys. D: Appl. Phys 45, 275102 (2012).
[9] T. Kim, D. Stryakhilev, D. Jin, J. Lee, S. An, H. Kim, Y. Kim, Y. Pyo, S. Seo, K. Kang, H. Chung, B. Berkeley, and S.S. Kim, Highly Robust Bendable a-IGZO TFTs on Poly-imide Substrate with New Structure, IMID Symp. Dig. 998 (2009).