Refractive-Index-Matched Indium–Tin-Oxide Electrodes for Liquid Crystal Displays

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Refractive-index-matched indium–tin-oxide (ITO) electrode for thin-film transistor liquid crystal displays is presented to reduce optical losses caused by Fresnel reflections. Simulations show a 24% improvement in optical transmittance when the conventional dense ITO is replaced with the refractive-index-matched ITO in a stack of glass/ITO/liquid crystal/ITO/glass. The refractive-index-matched ITO, fabricated by oblique-angle deposition technique, shows higher optical transmittance and smaller dependency on film thickness and wavelength than conventional dense ITO. © 2009 The Japan Society of Applied Physics

Liquid crystal display (LCD) technology is dominant for flat panel display applications ranging from low-power handheld mobile phones to large scale high-definition televisions. Core components of an LCD are the backlight unit (BLU), optical films, a liquid crystal (LC) panel with thin-film transistors (TFTs), polarizers, and color filters (CF). Light emitted by the BLU goes through all components of the LCD until it reaches the screen. However, due to optical loss mechanisms at each component, less than 5% of total light output from the BLU light source is usually available at the screen.[1] The LC is sandwiched between two indium–tin-oxide (ITO) electrodes which are used to induce a bias to the LC. The top and the bottom ITO electrodes should have properties of high optical transmittance and low sheet resistance. However, mismatch in refractive index between ITO, LC, and glass results in Fresnel reflection losses at each interface, as schematically shown in Fig. 1. It would be very desirable to reduce those optical losses without deteriorating other desired properties of each material. Fresnel reflection increases as the refractive index difference between two materials increases.[2] Therefore, refractive index-matched structures would minimize Fresnel reflection losses so that light from the BLU is transmitted through the LC more efficiently. In this study, refractive-index-matched ITO electrodes for a LCD system are shown to reduce the Fresnel reflection at the interfaces of TFT-LCD. The optimum refractive index of ITO electrodes is calculated. ITO electrodes which are refractive-index-matched to a glass substrate are experimentally demonstrated to have a more than 12% increase in optical transmittance.

At first, the optical transmittance of a multilayer constituting an LCD system is simulated by using the characteristic-matrix method with implementation in MATLAB.[3] In this method, any single layer in a multilayer stack is represented by a 2 × 2 characteristic matrix which contains physical properties such as incident angle of the plane wave, wave vector, and refractive index and thickness of each layer of the multilayer stack. By the iterated multiplication of the characteristic matrix of each single layer, the transmittance and reflectance through the multilayer stack can be calculated. A detailed discussion of this method can be found in ref. 2.
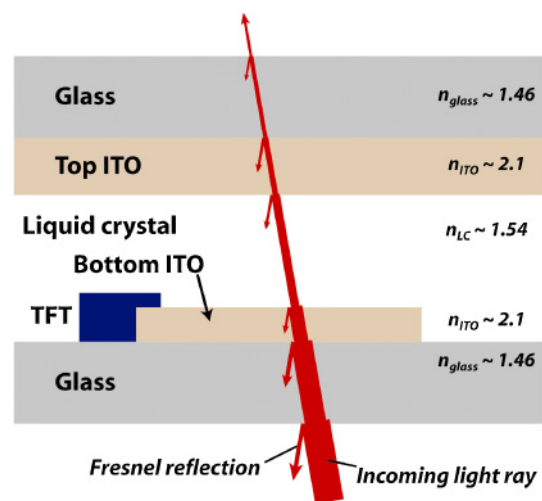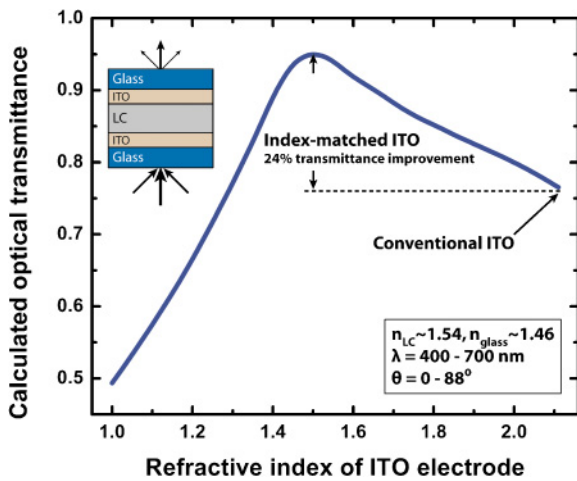
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Fig. 1. (Color online) Cross-sectional schematic illustration of glass/ITO/LC/ITO/glass structure of a LCD panel. Fresnel reflection happens at each interface as indicated by the red arrows.

Figure 2 shows the numerically calculated optical transmittance as a function of the refractive index of ITO (n_{ITO}). The inset of Fig. 2 shows the simulated structure which is composed of a glass substrate, bottom ITO, LC, top ITO, and top glass in sequence. The thicknesses of bottom glass, top glass, and LC are equally set to 1 mm; the thicknesses of bottom ITO and top ITO are 50 and 150 nm. These thickness values are typically used in commercial applications as an industrial standard. A refractive index of 1.54 is used for LC. Refractive indices of ITO and SiO_2 are linearly interpolated from $n = 2.17$ ($\lambda = 400$ nm) to $n = 2.00$ ($\lambda = 700$ nm) for ITO,[4] and from $n = 1.47$ ($\lambda = 400$ nm) to $n = 1.45$ ($\lambda = 700$ nm) for SiO_2.[5] In the calculation, the wavelength range of interest is the visible spectrum (400–700 nm). The incident-angle range of interest is 0° (normal incidence) to 88° to reflect the real situation in which a BLU white light source is permitted to enter the liquid crystal from all directions. Figure 2 shows that the equally-weighted average optical transmittance increases from 50% at $n_{\text{ITO}} = 1$, to the maximum of 94% at $n_{\text{ITO}} = 1.5$, and then decrease to 76% at $n_{\text{ITO}} = 2.1$. So theoretically, about 24% improvement can be achieved by changing the typical dense ITO ($n_{\text{ITO}} = 2.1$) to low-refractive-index ITO ($n_{\text{ITO}} = 1.5$). The enhanced transmittance is due to the refractive index matching.

Fig. 2. (Color online) Calculated angle-averaged ($0 \leq \theta \leq 88°$) optical transmittance ($400 \leq \lambda \leq 700$ nm) versus the ITO refractive index showing improvement of the optical transmittance for low-refractive-index ITO.

To verify the simulation experimentally, ITO film with $n_{ITO} = 1.5$ is necessary. Even though the refractive index is one of the unchangeable material characteristic properties, a recently developed nano-structured deposition technique showed that the refractive index can be varied by controlling the porosity of the material.[6,7] Using this technique, refractive index of ITO can be gradually reduced from the value of dense ITO by increasing the porosity of films. Specifically, deposition of porous ITO is enabled by the oblique-angle deposition technique.[6] In oblique-angle deposition, a random growth fluctuation on the substrate produces a shadow region and the subsequent vapor flux incident at high angle cannot reach the shadow region, but deposits preferentially on a high edge (the tip) of a nano-pillar. In these films, the gaps between the nano pillars is sufficiently small ($\ll \lambda$) to limit optical scattering. The controllability of film thickness is excellent.[7,8] The refractive index of the porous ITO is given by the porosity-weighted refractive index of air and dense ITO. Based on the quantitatively tabulated data,[7,8] a deposition angle of $\theta = 75°$ is selected to achieve n_{ITO} of 1.5. Four porous ITO films and four dense ITO films are deposited on glass substrates with thicknesses ranging from 50 to 250 nm. After deposition, all of the samples are annealed at 550 °C for 1 min in an O_2 ambient to enhance the transmittance and the electrical conductivity. Ellipsometry measurements are used to determine the actual refractive index and the thickness of the porous and dense ITO films. All four porous ITO films have a refractive index of about 1.5, and actual thicknesses of 53, 100, 180, and 230 nm, respectively. For the dense ITO films, the thicknesses are 54, 98, 168, and 270 nm with a refractive index of 2.1. Normal incidence optical transmittance in an air ambient is measured to verify the effect of refractive index matching. Because the porous ITO film can reduce the refractive index contrast not only with LC but also with air ambient, optical transmittance measurement in air ambient was used to demonstrate the viability of the concept.

Figure 3(a) shows the transmittance as a function of wavelength for the 100-nm-thick ITO films. The index-

(a)

(b)
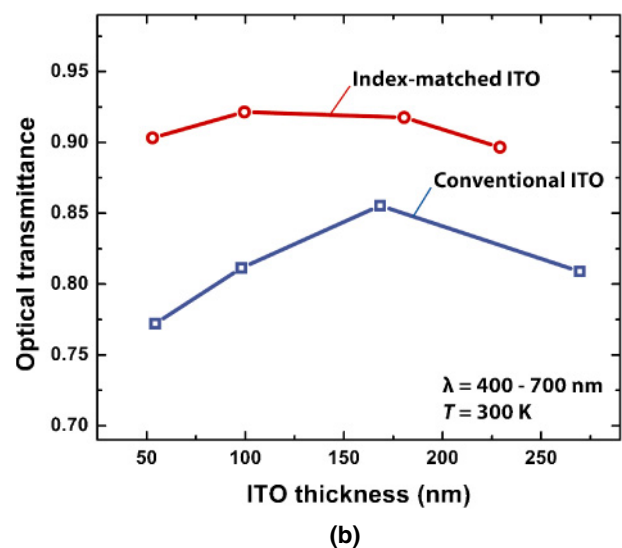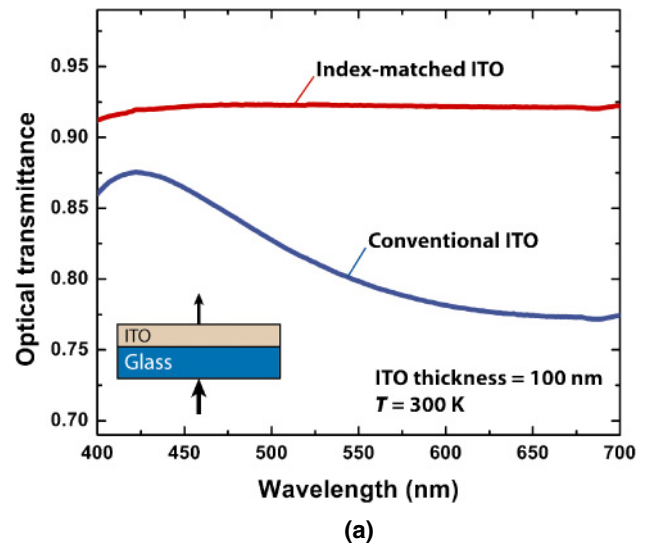
Fig. 3. (Color online) Measured normal-incidence optical transmittance of the index-matched porous ITO and the conventional dense ITO on a glass substrate: (a) optical transmittance as a function of incident wavelength for a 100-nm-thick ITO film and (b) wavelength-averaged transmittance from 400 to 700 nm at various ITO thicknesses.

matched porous ITO film on glass shows better transmittance than the conventional dense ITO film on glass. Moreover, the porous ITO film has uniform transmittance of about 92% for all wavelength, while the transmittance of the dense ITO film with the same thickness fluctuates between 77 and 87%. From Fig. 3(b), the index-matched porous ITO films on glass substrate with all of the four thicknesses have higher transmittance compared to the conventional dense ITO films. The transmittance enhancement ranges between 10 and 17% dependent on the film thickness and averages to 12%. Considering the much larger refractive contrast at the air/porous ITO interface than that at the LC/porous ITO interface in a real LCD system, the effect of the index matching would be about doubled in the LCD system.

In addition, it should be noted that the transmittance of the porous ITO films on glass substrate is generally less sensitive to the film thickness and the wavelength than that of the dense ITO films. In case of the dense ITO, conditions for constructive or destructive interference can easily occur
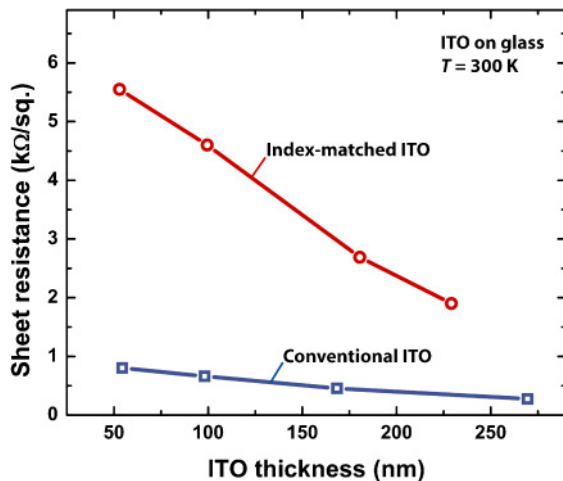
Fig. 4. (Color online) Measured sheet resistance of the index-matched porous ITO and the conventional dense ITO on glass substrate versus ITO film thickness.

and be significant due to the large refractive index difference, which may result in a modulation of transmitted light compared with incident light. However, the porous ITO film matches the refractive index of glass and thus reduces interference effects and is insensitive to a variation of film thickness and wavelength. Therefore, this characteristic can make design of TFT-LCD more flexible and reliable.

Sheet resistance, as a critical feature of ITO electrode, is measured for both the index-matched porous ITO and the conventional dense ITO structures by the Eddy-current method. Figure 4 indicates that the sheet resistance of dense ITO films is between 300 to 800 Ω/sq with an ITO film thickness range of 50–270 nm. The sheet resistance of the porous ITO films ranges from 1000 to 5500 Ω/sq. A decrease of the sheet resistance versus thickness, for both the porous and the dense ITO films, are clearly shown in Fig. 4. The porous ITO films show higher sheet resistance than the dense ITO films. This can be explained by the porous ITO having more restrictions for current flow than the dense ITO because of a porosity of 55% and low lateral connectivity between ITO nano pillars structures. However, the high sheet resistance of the index-matched porous ITO can be compensated by increasing the film thickness without deteriorating the transmittance, as shown in Fig. 3. Also, some techniques can also be applied to reduce the sheet resistance such as an additional blanket layer of ITO.[9]

In summary, refractive-index-matched porous ITO replacing conventional dense ITO as the electrode of TFT-LCD significantly increases the optical transmittance of the glass/ITO/LC structures. Simulation shows an improvement of 24% of the optical transmittance when the refractive index of ITO is reduced from 2.1 to 1.5. The refractive-index-matched ITO, fabricated by oblique-angle deposition technique, is shown to have improved optical transmittance, averaged 12%, for every film thicknesses in the visible spectrum and a low dependency on the variation of the film thickness and wavelength. Although the refractive index-matched ITO shows higher sheet resistance than that of the conventional ITO, it can be compensated by increasing the film thickness without a reduction of the optical transmittance.

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