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Ultrathin Reflective Flexible Liquid Crystal Display Film

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In this investigation, we present a thin reflective liquid crystal film with a mixed-mode twisted nematic mode. A low-temperature alignment process is used to obtain good orientation of the liquid crystal molecules. A microcell process is utilized to maintain a uniform cell gap of the flexible display under various bending conditions. To simplify the structure of a flexible mixed-mode twisted nematic liquid crystal display film, a layer of Zeonor optical plastic material is used in place of conventional plastic substrates; this material exhibits quarter wave retardation. The ultrathin device exhibits good cell gap uniformity, a high reflectivity of 35%, and a short response time of 6.67 ms. © 2012 The Japan Society of Applied Physics

Recently, much research has focused on flexible displays because of their favorable characteristics, including light weight, thinness, and flexibility.[1–5)] Therefore, flexible displays have potential use in mobile phones, smart cards, e-paper, and other handheld products. Numerous display technologies, including organic light-emitting displays[6–8)] (OLEDs), electrophoretic displays[9–12)] (EPDs), and flexible liquid crystal displays[13–16)] (LCDs), can be used in flexible-display applications. The mature resources of conventional flat panel LCD markets help make flexible LCDs good candidates for various environmental applications based on cheap, flexible, large-area electronics fabricated by roll-to-roll manufacturing. One of the most interesting applications of plastic electronics is to the integration of flexible displays and smart card devices. Although several nontransmissive LCD technologies, including cholesteric, guest-host, and polymer-dispersed LCs, have been studied, all of these have some issues, such as their high driving voltages and low contrast ratios, which prevent them from being used in smart card applications. To satisfy the special requirements of smart cards, a plastic reflective mixed-mode twisted nematic (MTN) cell is fabricated. The MTN mode has higher reflectivity, higher contrast, a lower driving voltage, and weaker color dispersion under a single-polarizer configuration than the conventional TN mode.[17)] The total thickness of a reflective display cannot exceed 450 µm because of the standards for smart card devices. Therefore, a 45-µm-thick plastic substrate with multifunctional characteristics was utilized in the MTN cell.

Figure 1(a) shows the structure of the ultrathin flexible MTN cell. A 125-µm-thick film of polycarbonate (PC; Tejin) with an indium zinc oxide (IZO) layer was used as the bottom substrate. The PC material has a higher T_g (~180 °C) and weaker optical anisotropy than conventional poly(ethylene terephthalate) (PET) substrates. A 45-µm-thick quarter-wave plate (QWP) was used as the top substrate in the ultrathin MTN structure. The QWP was made of cycloolefin polymer and was developed by Zeon Corporation. Before the cell process, an 800-Å-thick IZO layer was grown on the QWP by room-temperature vacuum sputtering. The IZO layer has good conductivity in the amorphous phase so it can be easily coated at low temperatures, and IZO is easily etched with a weak acid, so the process cost is lower. Compared with the ITO layer, the IZO layer has few microcracks when bending the plastic substrate. Therefore, the IZO layer is a good candidate for the conducting layer on a plastic substrate.

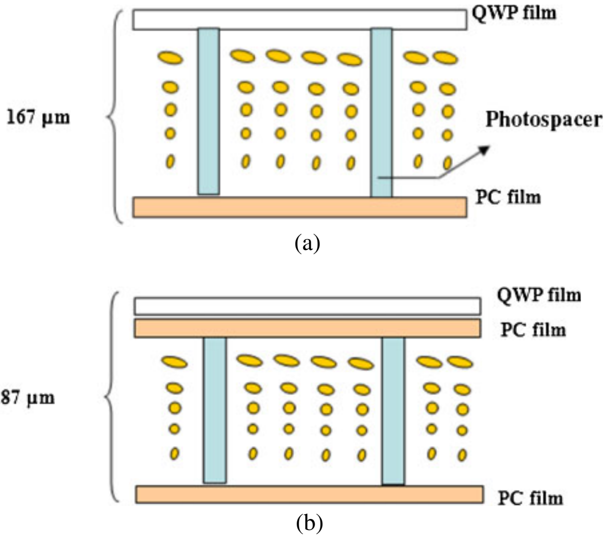

Fig. 1. (Color online) Cell structures of (a) ultrathin reflective LC film and (b) traditional reflective LC film.

A room-temperature sputtering process will cause the QWP to slightly bend but this does not affect the flexible LCD processes. Moreover, the IZO layer absorbs short-wavelength visible light. Therefore, the QWP becomes yellowish after IZO sputtering and the average transmittance for visible light decreases from 91 to 85%.

The phase retardation was measured with varying baking temperature. As shown in Fig. 2, the phase retardation of the QWP increased with baking temperature. When the baking temperature exceeded T_g, the phase retardation decreased markedly. To prevent the phase retardation from not matching the MTN LCD design, the baking temperature should be controlled to below 130 °C for flexible-LCD manufacturing processes.

The LC cell process was carried out by the sheet-to-sheet method. Therefore, both the PC substrate and the QWP were laminated on glass substrates after the cell processes, which included cleaning, polyimide (PI) printing, PI curing, rubbing alignment, assembly, and LC injection. 1000-Å-thick preimidized PI (Nissan Chemical SE8793) layers were printed onto the ITO and IZO layers of the PC and QWP substrates. PI layers were prebaked for 5 min at

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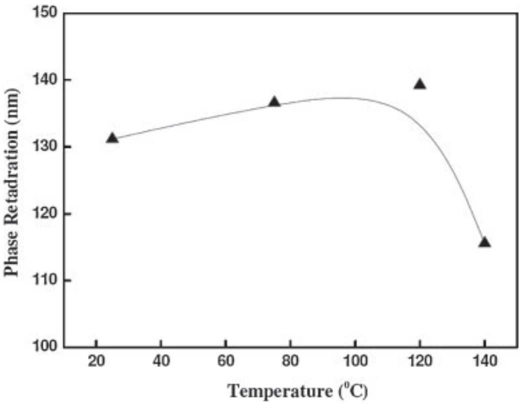

Fig. 2. Variation of phase retardation of QWP with baking temperature.

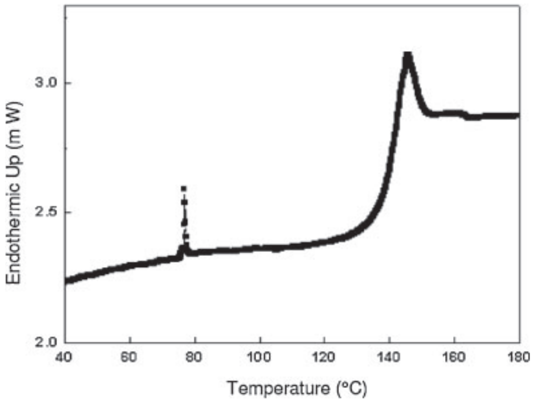

Fig. 3. Phase transition of QWP film.

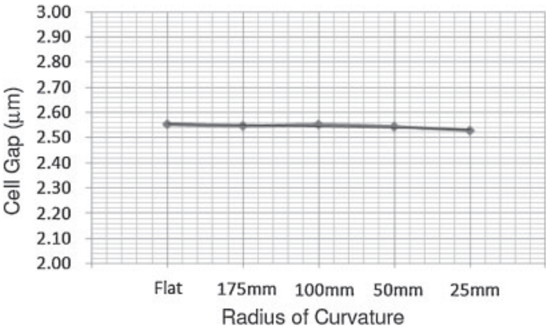

Fig. 4. Cell gap variation with radius of curvature.

80 °C and then hard-baked for 60 min at 130 °C. Figure 1(b) shows the traditional flexible MTN cell.

LC molecules (Merck MJ01744) with positive dielectric anisotropy were well aligned by the preimidized PI surfaces, and the directors exhibited a uniform 90° twist through the cell from the bottom substrate to the top substrate. Since the required cell gap of the MTN cell is smaller than the first Gooch–Tarry minimum[18)] of a TN cell, the uniformity of the cell gap between two flexible substrates strongly affects image quality. On the basis of the optical parameters of the injected LC molecules, a 2.55-µm-thick cell gap was found to be suitable for an ultrathin MTN cell. Therefore, to keep the cell gap constant, a microcell structure with high repeatability was used in the experiment. A microcell comprising crosslike spacers was grown by the photolithography and etching of an IZO surface. A 2.55-µm-thick layer of a positive photoresist (JSR PC403) was formed on the PC/IZO substrate. Crosslike structures were patterned using a g-line stepper. Then, the PC403 photospacers were baked at 160 °C to prevent the bending of the PC substrate. The length and width of the photospacers were 30 and 10 µm, respectively. The pitch between adjacent spacers was 300 µm. To prevent the thermal expansion of the substrates, we use UV-cured acrylic adhesive to seal the two substrates. The dominant wavelength of the adhesive is 365 nm and the exposure energy is 7.5 J/cm^2. The seal strength is 2 N/cm.

As shown in Fig. 1, two cells were assembled. One was an ultrathin reflective MTN cell and the other was a traditional MTN cell. The two substrates in the traditional cell were PC/IZO plastic substrates, and the QWP film was attached to the outer surface of the cell. The QWP film was utilized directly as the upper substrate of the ultrathin reflective MTN cell. Before the manufacture of the ultrathin MTN cell, the glass transition temperature (T_g) of the QWP film was measured using a differential scanning calorimeter (DSC), the result of which is shown in Fig. 3. From the measurements, the T_g of the QWP film was 136 °C. Therefore, to prevent the deformation of the QWP film at high temperatures, an attempt was made to lower the temperature of the manufacturing processes, including the growth of the conductive layer and the PI. Preimidized PI was chosen herein because the imidization process was finished before the spin coating on the QWP. The baking temperature of PI was reduced. The preimidized PI layer was cured at 130 °C for 1 h to evaporate the organic solvent on the IZO/QWP substrate and it prevents the structural deformation of QWP during baking.

The polar anchoring energies of the PI films were calculated by the retardation–voltage (R–V) method,[19)] and an optical heterodyne interferometer setup was utilized to measure the phase retardation (R) of LC cells as a function of applied voltage (V). The polar anchoring energy for a 130 °C/1-h-baked antiparallel cell was measured. The anchoring energy was 3×10^{-4} J/m^2. We can conclude that the preimidized PI can operate very well at a baking temperature of 130 °C.

Voltage holding ratio (VHR) and residue DC (RDC) voltage measurements were used to determine the electrical properties of LCDs. The VHR is 98.34% and the RDC voltage is 315 mV for a 130 °C/1-h-baked test cell. Although the baking temperature of the PI film is lower than that of the traditional film, the results still meet the specifications for passive matrix LCDs.

Finally, to optimize the optical performance of reflective MTN cells and maintain the uniformity of the cell gap, 2.55-µm-thick cross-type photospacers were formed by photolithography on IZO/PC substrates. The chosen pitch of the photospacers was 300 µm. To study the deformation of the cell gap, which was maintained by photospacers, a test sample with two PC substrates was bent at various curvatures. Figure 4 shows a plot of the cell gap against the radius of curvature. Although the cell gap varies with the radius of curvature, the variation is only approximately 1%, for all radii of curvature. Figure 5 shows plots of the

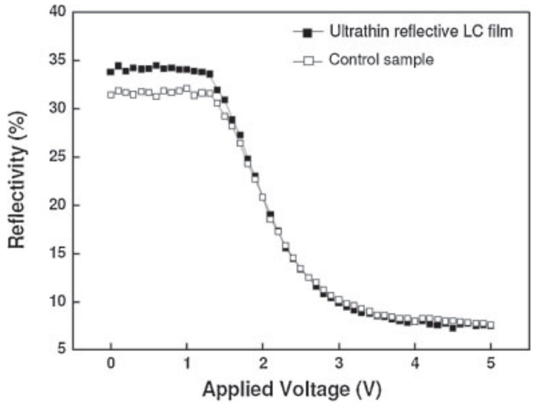

Fig. 5. Measured voltage-dependent reflectivity of ultrathin reflective and traditional reflective LC films.

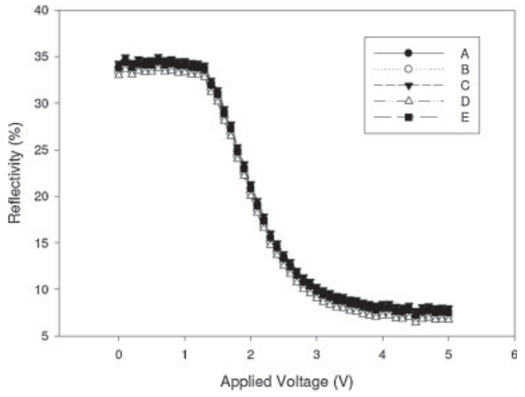

Fig. 6. Spatial uniformity of V–R curves.

Table I. Dynamic properties of ultrathin MTN cell and traditional MTN cell (unit: ms).

Sample	τ_{on}	τ_{off}	τ_{total}
Ultrathin cell	2.77	3.90	6.67
Traditional cell	2.32	3.91	6.23

measured voltage-dependent reflectivity (V–R) of the ultrathin reflective and traditional reflective LC films. The reflectivity of the LC cells was measured using an Otsuka LCD5100 system. Light was normally incident onto the samples, and the reflection was detected by a photodetector. The angle between the light source and the detector was set to 30°. From Fig. 5, the two LC films exhibited almost the same optical characteristics. The threshold voltages of the two samples were 1.4 V. Although the dΔn parameter of the cells was set to approximately 230 nm, which was close to the optimal parameter in the MTN mode,[20] the external metal reflector still slightly reduced the reflectivity of the ultrathin MTN cells. However, the elimination of one PC layer of the ultrathin reflective MTN cell minimized the interface scattering and increased the brightness by approximately 4%. Table I shows the measured response times of the reflective cells. The turn-on and turn-off voltages were set to 5.5 and 0 V, respectively. The driving frequency was 1 kHz. The behavior of the ultrathin reflective LC film was similar to that of the traditional film. The total response time ($\tau_{\mathrm{on}} + \tau_{\mathrm{off}}$) of the ultrathin reflective LC film was approximately 6.6 ms, which was close to the theoretical value.

A $5 \times 5\,\mathrm{cm}^2$ sample was prepared for spatial uniformity measurement. The average uniformity of the cell gap was $2.75 \pm 0.3\,\mu\mathrm{m}$ for five measurement points. As shown in Fig. 6, the V–R curves show that the R-MTN sample exhibits good uniformity of the optical characteristics.

In summary, an ultrathin reflective MTN LCD film with good optical properties was fabricated by a low-temperature process. The reduced structure has a wider range of applications in flexible displays than the unreduced structure. A high-performance flexible display for use in smart cards that meet the ISO standards will soon be realized.

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1) F. Matsumoto, T. Nagata, T. Miyabori, H. Tanaka, and S. Tsushima: SID ’93 Dig., 1993, p. 965.
2) J. L. West, M. Rouberol, J. J. Francl, J. W. Doane, and M. Pfeiffer: Asia Display ’95 Conf. Pap., 1995, p. 55.
3) R. Buerkle, R. Klette, E. Lueder, R. Bunz, and T. Kallfass: SID ’97 Dig., 1997, p. 109.
4) S. C. Jeng, K. H. Chang, J. M. Ding, L. P. Hsin, C. Y. Lin, Y. R. Lin, K. H. Liu, C. C. Lu, Y. A. Sha, H. L. Wang, and C. C. Liao: J. Soc. Inf. Disp. **13** (2005) 475.
5) G. P. Crawford: *Flexible Flat Panel Displays* (Wiley, Chichester, U.K., 2005).
6) G. Gu, P. E. Burrows, S. Venkatesh, S. R. Forrest, and M. E. Thompson: Opt. Lett. **22** (1997) 172.
7) A. B. Chwang, M. A. Rothman, S. Y. Mao, R. H. Hewitt, M. S. Weaver, J. A. Silvernail, K. Rajan, M. Hack, J. J. Brown, X. Chu, L. Moro, T. Krajewski, and N. Rutherford: Appl. Phys. Lett. **83** (2003) 413.
8) A. Sugimoto, H. Ochi, S. Fujimura, A. Yoshida, T. Miyadera, and M. Tsuchida: IEEE J. Sel. Top. Quantum Electron. **10** (2004) 107.
9) Y. Chen, J. Au, P. Kazlas, A. Ritenour, H. Gates, and M. McCreary: Nature **423** (2003) 136.
10) R. C. Liang, J. Hou, H. M. Zang, J. Chung, and S. Tseng: J. Soc. Inf. Disp. **11** (2003) 621.
11) R. Hattori, S. Yamada, Y. Masuda, and N. Nehei: J. Soc. Inf. Disp. **12** (2004) 75.
12) R. Hattori, S. Yamada, Y. Masuda, N. Nehei, and R. Sakurai: J. Soc. Inf. Disp. **12** (2004) 405.
13) P. Slikkerveer, P. Bouten, P. Cirkel, J. D. Goede, H. Jagt, N. Kooyman, G. Nisato, R. V. Rijswijk, and P. Duineveld: SID Symp. Dig. Tech. Pap. **35** (2004) 770.
14) S. J. Jang, J. W. Jung, H. R. Kim, M. Jin, and J. H. Kim: Jpn. J. Appl. Phys. **44** (2005) 6670.
15) K. H. Liu, W. Y. Chou, C. C. Liao, C. T. Ho, and H. P. D. Shieh: Jpn. J. Appl. Phys. **45** (2006) 7761.
16) K. H. Liu, C. Y. Lee, C. T. Ho, H. L. Cheng, S. T. Lin, H. C. Tang, C. W. Kuo, C. C. Liao, H. P. D. Shieh, and W. Y. Chou: Electrochem. Solid-State Lett. **10** (2007) J132.
17) S. T. Wu and C. S. Wu: Appl. Phys. Lett. **68** (1996) 1455.
18) C. H. Gooch and H. A. Tarry: J. Phys. D **8** (1975) 1575.
19) Yu. A. Nastishin, R. D. Polak, S. V. Shiyanovskii, V. H. Bodnar, and O. D. Lavrentovich: J. Appl. Phys. **86** (1999) 4199.
20) S. T. Wu, C. S. Wu, and C. L. Kuo: Jpn. J. Appl. Phys. **36** (1997) 2721.