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Stability-Enhanced Pixel Isolation Method for Flexible Liquid Crystal Displays

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We proposed a new method of enhancing the stability of a liquid crystal (LC) mode for flexible display applications. In the device, LC molecules are isolated in pixels where LCs are surrounded by a microstructure produced by a stamping method with a durable elastomer such as poly(dimethylsiloxane) (PDMS). Two substrates are tightly attached by a solidified polymer layer produced by anisotropic phase separation from LC/polymer composites. The electrooptic characteristics of our sample are comparable to those of a normal sample without a PDMS microstructure. This method can be applicable to the fabrication of large plastic LCDs using a roll-to-roll process. [DOI: 10.1143/JJAP.44.6670]

KEYWORDS: flexible liquid crystal display, pixel isolation, anisotropic phase separation, roll-to-roll process

1. Introduction

In recent years, roll-up displays have drawn considerable attention for next-generation information displays because of their excellent portability such as light weight, thin packaging, and flexibility. Among several available technologies, it is expected that a liquid crystal display (LCD) using plastic film substrates is the most promising device because of its superior visibility with a low power consumption over other displays such as organic light-emitting device or electrophoretic displays.[1–3] However, there are still critical problems regarding the fabrication of commercially available plastic LCDs with current technologies obtained from the development of conventional LCDs with glass substrates. One of those problems is the instability of LC structures due to hydrodynamic properties of LCs at bending and another is the separation of two plastic substrates due to the flexibility of film substrates. Such problems do not exist in conventional glass-substrate-based LCDs since these substrates can sustain a stable LC alignment condition against external bending or pressure.

To solve these problems, several types of polymer wall and/or network as supporting structures have been proposed and demonstrated.[4–10] These structures were fabricated using an anisotropic phase separation method from polymer and LC composite systems by applying a patterned electric field or spatially modulated UV intensity. However, these methods require high electric field to initiate the anisotropic phase separation or remain residual polymers in an unexposed region that reduce optical properties and increase the operating voltage of the devices.[5,6,9] Moreover, these methods are not appropriate to a cost-effective roll-to-roll process, which is essential to fabricate large area plastic LCDs. Thus, an alternate fabrication method should be developed for the plastic LCDs to be commercialized.

In this report, we propose a new method of enhancing the mechanical stability of a plastic LCD using stamping and an anisotropic phase separation methods. The device shows a good mechanical stability and almost the same optical behaviors as conventional LC modes without wall structures.

2. Experimental

Pixel-isolating wall structures are fabricated by a stamping method using durable elastomeric poly(dimethylsiloxane) (PDMS), which can be applicable to a roll-to-roll process for the mass production of large flexible LCDs. Figure 1 shows the schematic illustration of procedures for fabricating our plastic LC device with a microtransfer molding method. The first step shown in Fig. 1(a) is to produce a master structure using the negative photoresist SU-8 (MicroChem) by a photolithographic method. On the master substrate, liquid PDMS is deposited and the excess liquid PDMS is removed by a PDMS block, as shown in Fig. 1(b). The PDMS wall structure produced by the patterned master structure can be effectively transferred to the covered bare indium–tin–oxide (ITO) substrate by heating under pressure, as shown in Fig. 1(c). In our experiment, the heating condition for transferring and solidifying the PDMS structure was 100°C for 10 min. By peeling off the master substrate, the bottom substrate with the PDMS wall structures is prepared. Since PDMS provides a very low interfacial free energy and a good chemical stability, the master substrate can be easily detached without the degradation of the micro-structure on both substrates.[11] Onto the prepared bottom substrate shown in Fig. 1(d), the homogeneous alignment layer RN1286 (Nissan Chemical Industries) is spin-coated and rubbed to promote a uniform LC alignment. After the mechanical rubbing process, the PDMS walls maintain the initial micropatterned structures attached to the ITO surface. The fourth step is the preparation of a LC cell. After dropping a LC/prepolymer composite onto the substrate with the microstructure, a LC cell is prepared by covering a bare ITO substrate on the bottom substrate. However, within only these fabrication steps, the cell gap cannot be stably sustained at bending since two substrates are not tightly adhered to each other.

In our structure, such problems are eliminated by producing a uniformly solidified polymer layer on the bare ITO substrate using a complete anisotropic phase separation of the prepolymer/nematic LC (NLC) mixture by UV exposure. The materials used are E48 (Merck) for the NLC and the UV curable epoxy NOA-72 (Norland) for the prepolymer. A solution of the LC and prepolymer with a weight ratio of 95 : 5 is deposited on the substrate with the microstructure and covered by a bare ITO substrate, as shown in Fig. 1(d). The UV light is exposed to the bare ITO substrate. In our experiment, the source of the UV light is a Xenon lamp of $\lambda = 350$ nm, operated at an electrical power of 200 W, and the exposure time for making the thin polymer layer fully cured is 20 min. The solidified polymer

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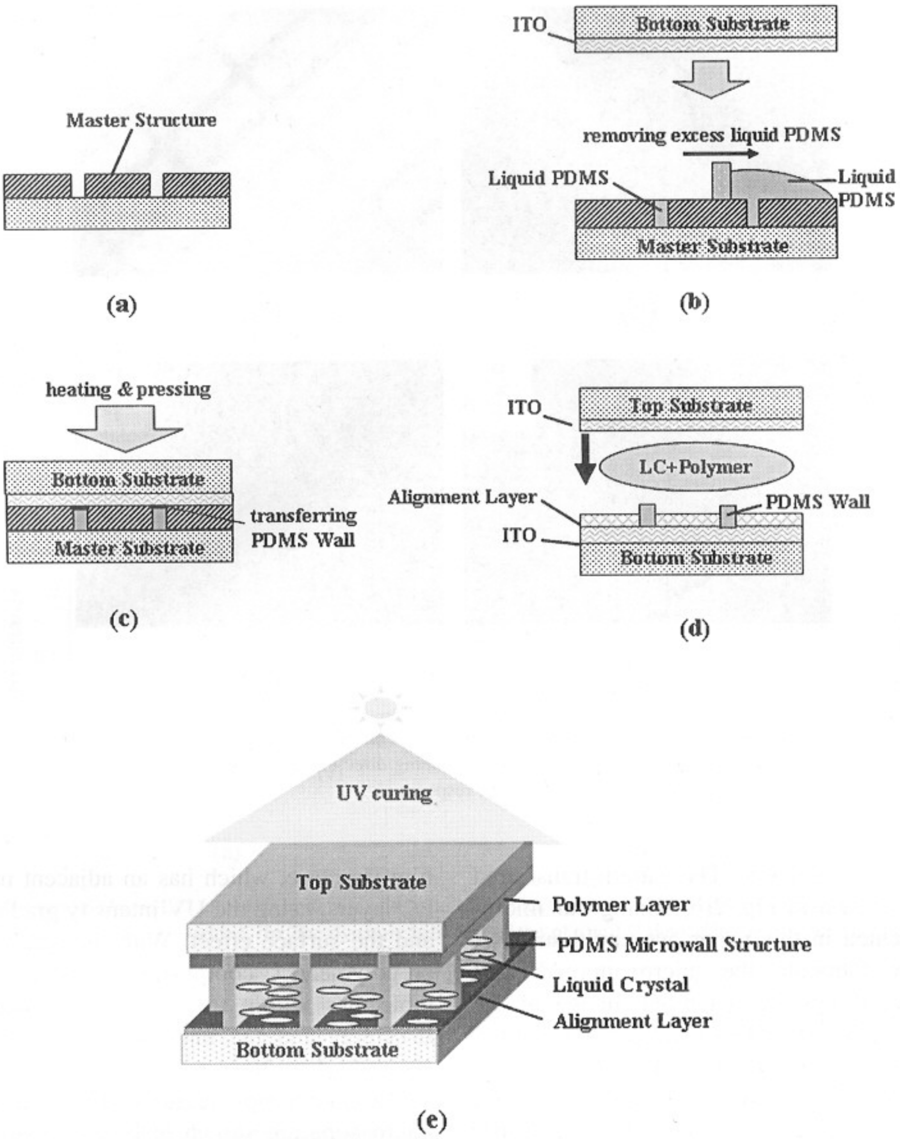


Fig. 1. Schematic illustration of fabrication procedures with stamping method: (a) formation of micropatterned master structure, (b) printing PDMS layer using master structure, (c) transferring PDMS wall structure to ITO-coated substrate by baking under pressure, and (d) forming LC alignment layer on microstructured substrate, then dropping or injecting polymer/LC composites. The pixel-isolated LC structure is prepared by sandwiching the other ITO substrate. (e) schematic diagram of pixel-isolated LC device after UV exposure.

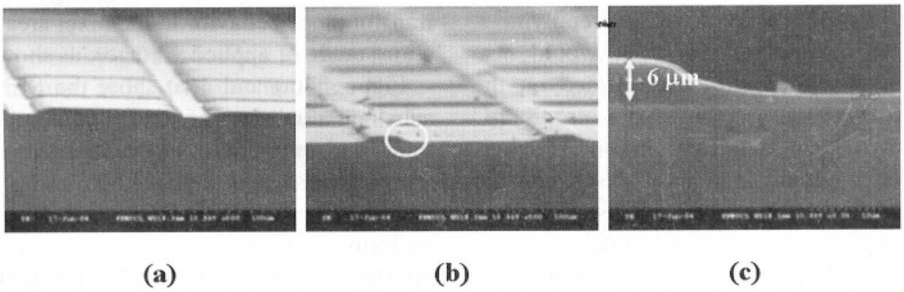


Fig. 2. SEM images of micropatterned substrate: (a) master structure of SU-8, (b) wall structures of PDMS on bottom substrate shown in Fig. 1(d), which are pattern-transferred from master structure shown in Fig. 1(a), and (c) cross-sectional image magnified in circular region in (b).

layer makes the patterned wall structures strongly attach to the opposite substrate and enhances the mechanical strength of the pixel-isolated LC device, as shown in Fig. 1(e).

3. Results and Discussion

Figure 2(a) shows the scanning electron microscopy (SEM) images of the master structure of SU-8 with a size

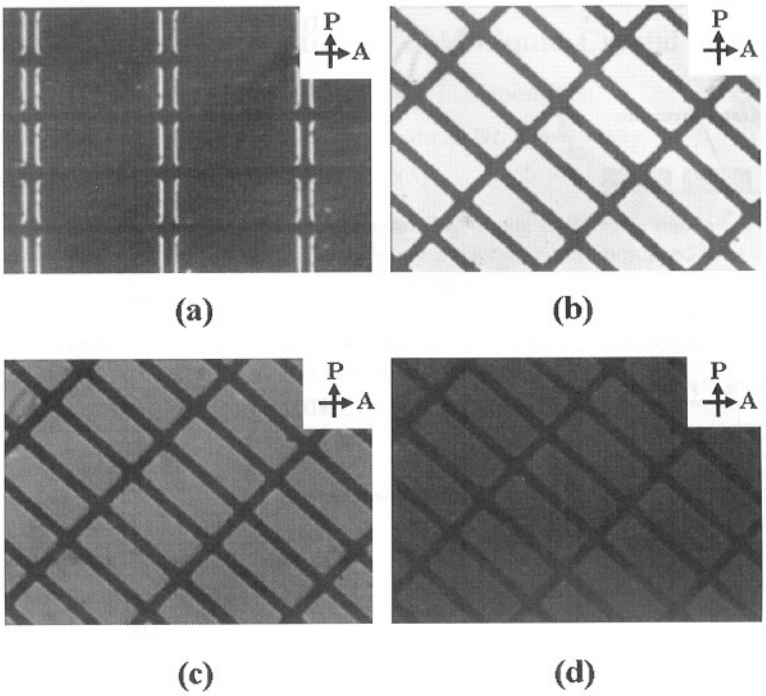


Fig. 3. Microscopic textures observed under polarizing microscope: (a) is obtained when the rubbing direction of the sample is parallel to one of the polarizers. (b), (c), and (d) are obtained when the rubbing direction of the sample is rotated by 45° with respect to the polarizer in the presence of applied voltages of 0, 3, and 6 V, respectively.

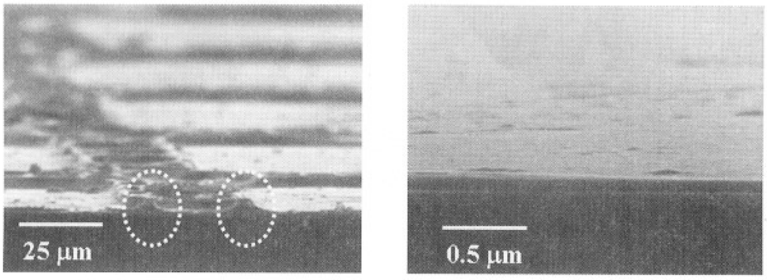
of $100 \times 300\,\mu\text{m}^2$ for the pixel area. The pattern-transferred PDMS structures are shown in Fig. 2(b). Using our microtransfer method presented in this paper, we could successfully and repeatedly fabricate the micropatterned wall structures. Figure 2(c) shows the magnified image of the circular region in Fig. 2(b). The SEM image shows that the height of the wall structure in our cell is about $6\,\mu\text{m}$.

In the device structure, we have to prevent the degradation of electrooptic (EO) properties which is common in polymer and LC composite systems. To obtain a uniform polymer layer, certain fabrication requirements, such as the relative surface wetting properties between the prepolymer and the LC molecules, the UV intensity gradient, and the mixing ratio of the composite, should be satisfied.[4,10] A complete theory of the anisotropic phase separation by UV exposure would describe the evolution of the structure in terms of the spatial and temporal distributions of LCs, prepolymers, polymers, and all intermediate oligomers. It would also include the effects of a rubbed substrate surface on the induction of nematic ordering in otherwise isotropic LC mixtures and the polymer morphology. In our previous report,[10] we presented a simple model for describing the anisotropic phase separation due to the UV intensity gradient in the sample thickness direction (z-axis direction) using the mean-field kinetic theory. In this model, the LC molecules are expelled from the polymerized volume by the polymerization of the prepolymer by UV light, namely, the contraction effect. We also discussed the effect of the surface interaction between the LC/prepolymer and the alignment layer on the anisotropic phase separation.[8] In this experiment, we used the commercially available polyimide RN1286 to promote the surface-induced anisotropic phase separation in the sample thickness direction. As a result, we successfully fabricated a phase-separated composite organic film structure, which has an adjacent uniform polymer and LC layers, using the UV intensity gradient in the z-direction and the surface effect. With the small mixing ratio of our prepolymer/LC composite, we successfully isolated the LC molecules within the pixel surrounded by the microwall structures and the uniformly solidified polymer layer, as shown in Fig. 1(e).

The microscopic textures of our cell under the polarizing microscope are shown in Fig. 3. Figure 3(a) was obtained when the rubbing direction of the bottom surface of the sample was parallel to one of the polarizers and Figs. 3(b)–3(d) were obtained when the rubbing direction was rotated by 45° with respect to the polarizer in the presence of applied voltages of 0, 3, and 6 V, respectively. The slight light leakage in Fig. 3(a) indicates that the PDMS wall surface has weak LC anchoring. However, the overall transmittance behavior in the pixel area is not affected in the entire range of applied voltages, as shown in Figs. 3(b)–3(d).

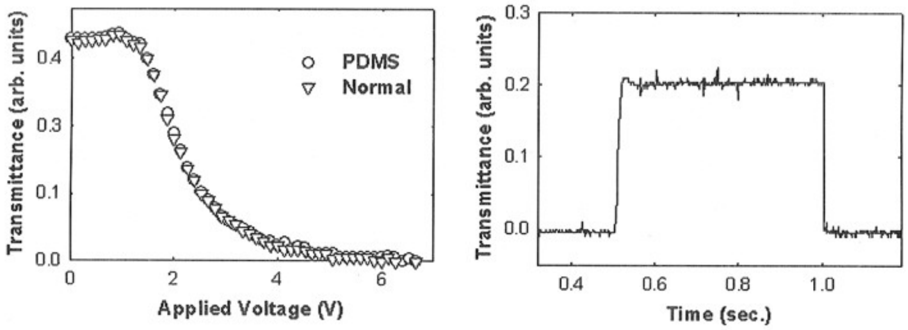
Figures 4(a) and 4(b) show the SEM images of the top substrate after opening the cell and removing the LCs in the inter- and intrapixel regions, respectively. The areas where the polymer layer was attached to the microwall structures were obviously shown in the dotted regions of Fig. 4(a). A uniform polymer layer of 30 nm thickness was formed in the interpixel region, as shown in Fig. 4(b). This thickness depends on the mixing ratio of the LC and prepolymer.

Figure 5 shows the EO properties of our sample. The transmittance of our cell as a function of an applied voltage from 0 to 7 V had the same behavior as that of a normal LC sample fabricated by a conventional method using spacers. Thus, the proposed pixel-isolation method can be easily applicable to several types of plastic LC device without varying the EO properties of normal LC devices. The contrast ratio and response time were about 100 : 1 and



(a) (b)

Fig. 4. SEM images of bottom substrate with microstructure after removing LCs: (a) interpixel regions and (b) intrapixel regions.



(a) (b)

Fig. 5. EO properties of plastic LCD: (a) transmittance of plastic LC device as a function of applied voltage. For comparison, an EO property of a normal LC device is added. (b) The dynamic behavior of the plastic LC device in the presence of the unipolar square pulse with 6 V is shown.

27 ms, respectively, which were comparable to those of normal samples.

We have to note that these methods can be applicable to a continuous roll-to-roll process. With the stamping roller, the microwall structures can be easily produced. After depositing the polymer/LC composite on the bottom substrate with microstructures and assembling the top and bottom flexible substrates in a continuous process, the tight adhesion of two substrates can be achieved by the solidified polymer layer produced by UV exposure.

4. Conclusions

We demonstrated a method of fabricating flexible LCDs with the stamped polymer wall structure and the phase-separated polymer layer. The stable LC structure could be achieved by isolating LC molecules into the pixel surrounded by the micropatterned PDMS wall structures. Using the interfacial properties of PDMS, such pixel-isolating wall structures could be fabricated on one of the substrates easily and repeatedly with the same master substrate. The adhesion of two substrates was achieved by the solidified polymer layer produced by anisotropic phase separation from polymer/LC composites. Experimental results showed that our device has almost the same EO properties as normal LC modes without microwall structures. It is expected that our proposed method is applicable to the fabrication of large plastic LCDs with a good mechanical stability and a superior visibility using the cost-effective roll-to-roll process.

Acknowledgements

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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) V. Vorflusev and S. Kumar: Science **283** (1999) 1903.
5) Y. Kim, J. Francl, B. Taheri and J. L. West: Appl. Phys. Lett. **72** (1998) 2253.
6) H. Sato, H. Fujikake, Y. Iino, M. Kawakita and H. Kikuchi: Jpn. J. Appl. Phys. **41** (2002) 5302.
7) J.-W. Jung, C.-J. Yu, S.-D. Lee and J.-H. Kim: SID '04 Dig., 2004, p. 606.
8) J.-W. Jung, S.-K. Park, S.-B. Kwon and J.-H. Kim: Jpn. J. Appl. Phys. **43** (2004) 4269.
9) H. S. Kitzerow, H. Molsen and G. Heppke: Appl. Phys. Lett. **60** (1992) 3093.
10) T. Qian, J.-H. Kim, S. Kumar and P. L. Taylor: Phys. Rev. E **61** (2000) 4007.
11) Y. Xia and G. M. Whitesides: Angew. Chem., Int. Ed. **37** (1998) 550.