

## Stability-Enhanced Liquid Crystal Mode for Flexible Display Applications

**Jong-Wook Jung, Se-Jin Jang, You-Jin Lee, Hak-Rin Kim, Min Young Jin,  
and Jae-Hoon Kim**

Department of Electronics and Computer Engineering, Hanyang University, Seoul, Korea

### Abstract

*We demonstrated stability-enhanced liquid crystal (LC) displays using pixel-isolated LC mode in which LC molecules are isolated in pixel by horizontal polymer layer and vertical polymer wall. The device shows good electro-optic properties with external pressure and bending due to the polymer structures. The polymer wall acts as supporting structure from mechanical pressure and maintains the cell gap from bending. Moreover, the polymer layer acts as adhesive for tight attachment of two substrates. We presented various methods to produce the polymer structures by using anisotropic phase separation from LC and polymer composites or patterned micro-structures.*

### 1. Introduction

Liquid crystals (LCs) have been extensively studied and used for display applications because of their efficient light-control capabilities with low power consumption<sup>1</sup>. These advantages come from hydrodynamic properties and high birefringence of LCs. In general, LC devices are prepared by sandwiching LC molecules between two glass substrates with transparent electrodes and alignment layers to obtain a specific configuration of the optic axis. One primary role of these substrates is supporting the LC molecular orientation from external bending or pressure, which alters the arrangement of LC molecules and diminishes the optical properties of the device.

In recent years, LC devices using plastic film substrates have drawn much attention for use in applications such as smart cards, PDA, and head mount displays because of their lighter weight, thinner packaging, flexibility, and lower manufacturing cost through continuous roll processing than other similar available devices<sup>2-4</sup>. However, fabrication of LC displays (LCDs) with plastic substrates raises two major problems; (i) plastic substrates can not give a solid mechanical support for the molecular alignment of LCs between them, (ii) two plastic substrates are easily detached by bending in large size LCDs.

To overcome these problems, polymer walls and/or

networks as supporting structures have been proposed and demonstrated<sup>5-7</sup>. These structures were fabricated using an anisotropic phase separation method from polymer and LC composite systems by applying 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 device.

In this presentation, we proposed new methods to produce stability-enhanced LC mode which is suitable for mass production of LCDs with plastic substrates through continuous roll processing.

### 2. Experimental Results

We fabricated stability-enhanced LC devices by forming inter-pixel walls which are produced by various methods such as photo-polymerization induced anisotropic phase separation, photolithography using photo-resist, or stamping method using poly(dimethylsiloxane) (PDMS).

#### 2.1 Pixel-isolated LC Mode

We fabricated pixel-isolated liquid crystal (PILC) mode with plastic substrates using anisotropic phase separation from LC and polymer composites.

ITO-coated poly-ether-sulfone (PES) films were used as substrates. For the alignment layers, we used RN1199 polyimide (Nissan Chemical). The alignment layers are spin coated on one substrate followed by rubbing to achieve homogeneous LC alignment. We note that the results of phase separation are greatly affected by alignment layer and prepolymer. The other substrate is untreated to enhance anisotropic phase separation. The cell gap was maintained using glass spacers of 3.5  $\mu\text{m}$ . A mixture of nematic LC (LC17) and photo-curable pre-polymer NOA65 (Norland Co.) with weight ratio of 75:25 was introduced into the cell by capillary action at a temperature higher than the clearing point of the LC. The cells are exposed to UV light of  $\lambda = 350 \text{ nm}$  to initiate polymerization. The source of UV light is a Xenon lamp operated at 200 W of electrical power. The photomask is placed on one of

glass substrates without the alignment layer. The cell with the LC+prepolymer mixture is irradiated with UV light for ~ 90 minutes. A second exposure is performed without the mask for 10 minutes to fully harden the polymer. During this process, the LC molecules which remain in polymer network after first UV exposure are expelled from the polymerized volume. During these first and second UV exposures, the anisotropic phase separation occurs in the horizontal and vertical direction, respectively, forming vertical polymer walls and planar polymer layers. Fig. 1 shows the resultant element after UV exposure. The LC molecules were isolated in the pixel surrounded by polymer wall which acted as supporting structures against external shock and maintain the cell gap from bending. Moreover, two substrates were tightly attached each other by polymer layer.

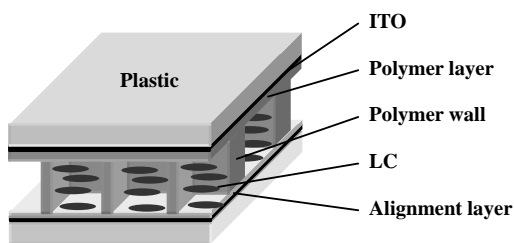


Fig. 1 Schematic diagrams of PILC structure

Fig. 2 shows the cross section images of PILC cell using scanning electron microscope (SEM). It is clear that the polymer wall is formed between two substrates by the first UV exposure. The residual pre-polymers are completely expelled from the bulk LC layer by second UV exposure forming thin polymer layer onto the bare ITO-coated PES substrate. Due to this second step of UV exposure, our PILC mode can show the good electro-optic (EO) properties and the enhanced mechanical stability with good adhesion of the plastic substrates and the polymer walls.

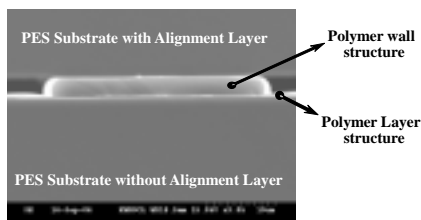


Fig. 2 Cross section image of PILC sample using scanning electron microscope.

We tested the mechanical stability of PILC cell against an external pressure and bending. Fig. 3 shows polarizing microscopic textures of a normal and PILC samples with plastic substrates in the presence of an

external point pressure by a sharp tip. The alignment texture of the normal sample was severely distorted by the distortion of LC alignment due to the cell gap variation in a relatively large area as shown in Fig. 3(a). However, that of the PILC sample showed no appreciable changes since the LC molecular reorientation is restricted and the cell gap are sustained by the polymer wall structure shown as dark lines in Fig. 3(b).

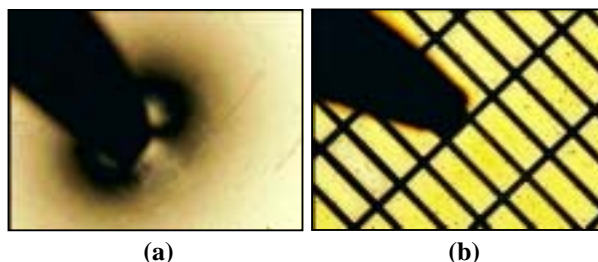


Fig. 3 Alignment textures of (a) a normal and (b) a PILC sample fabricated using plastic substrates. The polarizing microscopic textures are taken in the presence of an external point pressure with a sharp tip.

Fig. 4 shows the EO properties of a normal and PILC cell with an external bending as a function of applied voltage. As applying bending stress on normal plastic LC cell, the transmittances are decreasing as increasing the degree of bending. However, our PILC cell shows almost same transmittance with various degree of bending in whole range of applied voltages.

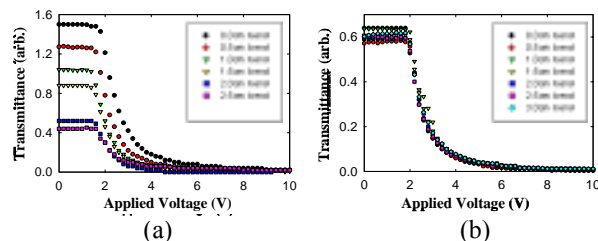


Fig. 4 EO properties of (a) a normal and (b) a PILC sample depending on degree of bending.

Fig. 5 shows 3" prototype plastic LCD with PILC mode in bending state.



Fig. 5 3" Plastic LCD sample using PILC mode.

## 2.2 Stability enhancement using micro-structure

We fabricated PILC mode using patterned micro-structure produced by photolithography for mechanical stability and LC+polymer composites for adhesion of two substrates. We used a SU-8 (Micro-Chem) negative photo-resist. SU-8 layers were spin coated on substrate and polymer walls are patterned by UV exposure through a photo-mask. The pixel size is  $100\mu\text{m} \times 300\mu\text{m}$  and the distance between pixels is  $20\mu\text{m}$  [Fig 6(a)]. The alignment layers are spin coated on the micro-structure followed by rubbing to achieve homogeneous LC alignment. In order to attach two substrates, we used anisotropic phase separation<sup>5</sup>. The materials used were E7 (Merck) for nematic LC and UV curable epoxy NOA-65 (Norland) for prepolymer. A solution of the LC and prepolymer with weight ratio 95:5 was dropped on the microstructure and covered by bare ITO substrate. The cell gap was maintained by the height of microstructure. In our case, we controlled the cell gap about  $6\mu\text{m}$  [Fig 6(b)].

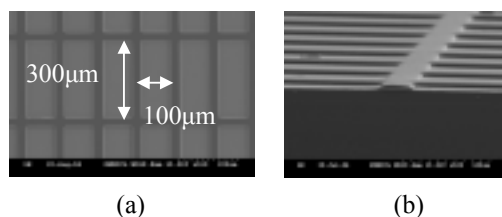


Fig. 6 The SEM images of the patterned micro-structures in (a) top view and (b) side view.

The cells were exposed to UV light of  $\lambda = 350\text{nm}$  to initiate polymerization. The source of UV light is a Xenon lamp operated at 200W of electrical power. The UV exposure was exposed onto the bare ITO substrate without micro-structure. Due to the surface wetting property and UV intensity gradient, NOA65 molecules first undergo polymerization near the top substrate and the LC molecules are expelled from the polymerized volume, forcing them to diffuse away from the UV source<sup>8,9</sup>. As a result uniform polymer layer is formed and tightly attaches two substrates as shown in Fig. 7(a). Fig. 7(b) and (c) show SEM images of cross section of the cell and the surface after removing top substrates. It is clearly observed that the place of tear-off polymer layer at the attached point. As a result, the LC molecules are successfully isolated into the pixel surrounded by microstructure and solidified polymer layer. And the solidified polymer layer tightly attached the micro-

structure to the top substrate.

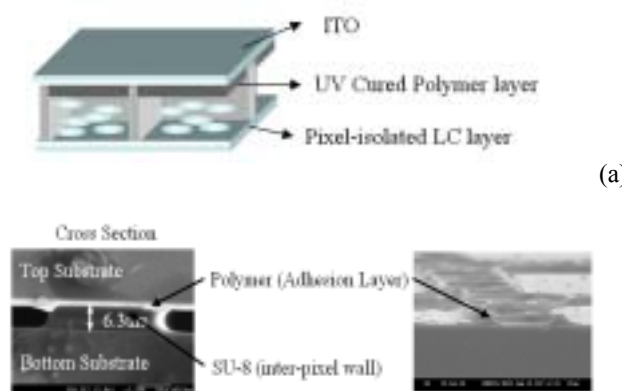


Fig. 7 (a) The schematic diagram of the pixel-isolated LC device using microstructure, (b) SEM image of cross-sectional view, and (c) side view after opening the cell.

## 2.3 Stamping method for micro-structure

We fabricated micro-structure using stamping method which is applicable to mass production of plastic LCDs through continuous roll processing. Fig. 8 shows the fabrication process. The first step is to produce a master structure using SU-8 photo-resist by normal photolithographic method [Fig. 8(a)]. The second step is pattern-transferring process to PDMS by stamping. The PDMS is coated on a patterned SU-8 structure, and covered by bare ITO glass [Fig. 8(b)].

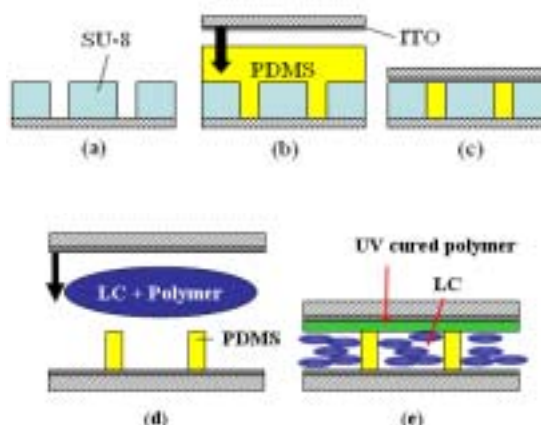


Fig. 7 Schematic illustration of the fabrication process: (a) master structure using SU-8 photo-resist, (b) & (c) pattern transferring step, (d) LC cell fabrication, (e) structure of LC cell after UV exposure.

With pressing the ITO glass, the cell is baked  $100^\circ\text{C}$

for 10 min [Fig. 8(c)]. Then the glass with PDMS is separated from the patterned SU-8 structure. The third step is preparation of LC cell. The alignment layers are spin coated on the PDMS microstructure followed by rubbing to achieve homogeneous LC alignment. The materials used in fabrication of LC cell were E7 (Merck) for nematic LC and UV curable epoxy NOA-65 (Norland) for prepolymer. A solution of the LC and prepolymer mixture with weight ratio of 95:5 was dropped on PDMS and covered by bare ITO glass [Fig. 8(d)]. The cells were exposed to UV light onto the bare ITO substrates to initiate polymerization. Fig. 8(e) shows the resultant element after UV exposure. The LC molecules are isolated in the pixel surrounded by PDMS which act as supporting structures from external shock. Moreover, two substrates are attached each other by UV cured polymer.

Fig. 9(a) and (b) are SEM images of the SU-8 and PDMS microstructures, respectively. The width and height of SU-8 microstructure is 300  $\mu\text{m}$  and 6  $\mu\text{m}$ , respectively. It is clear that the patterned structure of SU-8 is well transferred to PDMS.

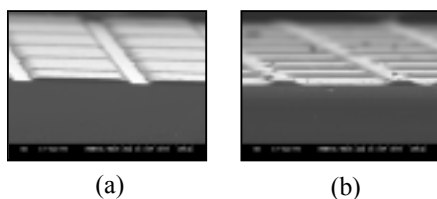


Fig. 9 (a) Master structure of SU-8, (b) PDMS structure after pattern-transferring

Fig. 10(a) and (b) show microscopic textures of the cell in black and white state, respectively. The light leakage in black state is due to the distortion of molecular alignment on PDMA wall.

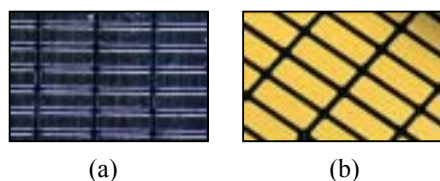


Fig. 10 Microscopic textures of PDMS sample under polarizing microscope: (a) black and (b) white state.

Fig. 11 shows EO properties for normal and PDMS samples. In both samples, transmittance as a function of applied voltage show almost same behavior which is different from polymer network structure [Fig. 11(a)]. The dynamic property of PDMS is also same as that of normal sample as shown in Fig. 11(b). The measured response time (field driven + relaxation

time) is about 20 ms.

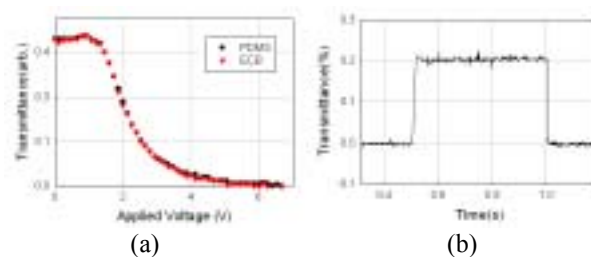


Fig. 11 EO properties: (a) Transmittances as a function of applied voltage of normal and PDMS sample, and (b) dynamic behavior of PDMS sample.

### 3. Concluding Remarks

Mechanical stability is a key issue in application of flexible LCDs using plastic substrates. We demonstrated stability-enhanced LCDs using PILC mode in which LC molecules are isolated in pixel by horizontal polymer layer and vertical polymer wall. The device shows good EO properties with external pressure and bending due to the polymer structures. The polymer wall acts as supporting structure from mechanical pressure and maintains the cell gap from bending. Moreover, the polymer layer acts as adhesive for tight attachment of two substrates. The polymer structures were fabricated by anisotropic phase separation from LC+polymer composites, or microstructures by photolithography or stamping method. Among the method, micro-structure using stamping method is the most applicable to mass production of plastic LCDs through continuous roll processing as shown in Fig. 12.

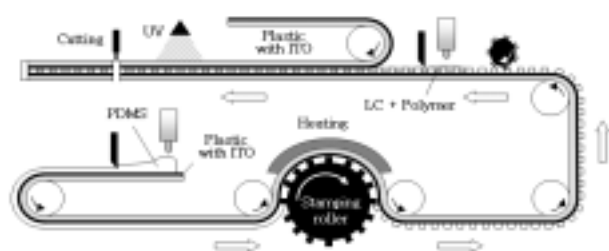


Fig. 12 Schematic diagram shows the continuous roll processing for fabrication of the plastic LCDs with the methods presented here.

### 4. Acknowledgements

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Industry and Energy of Korean government.

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