Fabrication of a highly bendable LCD with an elastomer substrate by using a replica-molding method

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A highly bendable liquid-crystal display was fabricated by using a multi-functional elastomer substrate of self-aligning LC molecules without any surface treatment. One of the two substrates is a plastic substrate while the other is a multi-functional elastomer substrate produced by a replica-molding technique. The multi-functional elastomer substrate has pixel-encapsulating walls that serve as spacers and provide mechanical stability and reproducibility against bending deformations. The highly bendable LCD demonstrates great flexibility, durability, and excellent electro-optic performances in a highly bent state.

Keywords — Flexible LCD, multi-functional elastomer substrate, replica molding.

1 Introduction

Recently, flexible displays have attracted a great deal of interest due to their many advantages, such as lighter weight, better durability, and greater portability than existing displays. They open up new application areas including wearable computers, smart cards, and display systems in small packages for more freedom in design. Several types of flexible displays using liquid crystals (LCs),1–5 organic light-emitting materials,6,7 or electrophoretic materials8 as active layers have been developed thus far. Among them, the LC-based flexible displays are the most promising because relevant technologies have been rapidly developed in recent years. As an example, various approaches to the mechanical stability of the LC layer through the formation of polymer walls or polymer networks4,5,9,10 have been reported for flexible applications. However, these approaches may not be applicable for large panels and mass production. For instance, the image quality and uniformity in the electro-optic (EO) performances are not guaranteed due to anisotropic phase separation and non-uniform distribution of residual polymers.9,10 Although alternative technologies have been suggested, most of them are too complex and expensive to be commercialized in the flexible-display market. Therefore, a new technology capable of cost reduction and time savings in mass production needs to be developed.

In this paper, we describe a highly bendable liquid-crystal display (LCD) having a multi-functional elastomer substrate in a vertically aligned (VA) configuration.11,12 The multi-functional elastomer substrate, produced by a replica-molding technique13–15 that has large impact on enormous time savings and cost reduction, provides vertical alignment for the LC molecules without any surface treatment, pixel-encapsulated microstructures to prevent the LC flow under bending as well as to maintain a uniform cell gap as spacers, and mechanical stability. It was found that our highly bendable LCD preserves well the EO performances in a highly bent environment.

2 Experimental

Flexible LCDs require either plastic or other flexible substrates instead of conventional glass substrates. However, most of the plastic substrates have disadvantages in terms of flexibility, durability, process handling, and price. Thus, one alternative may be a multi-functional elastomer substrate. The fabrication process of the multi-functional elastomer substrate, used as a top substrate for a flexible LCD, is schematically shown in Fig. 1. This elastomer substrate was produced by a replica-molding technique which can easily duplicate information such as the shape, morphology, and structure present in the master. The replica-molding technique is very powerful in duplicating three-dimensional topologies in a single step, whereas the photolithography is not able to replicate such topologies.13 It has been used for mass production of surface-relief structures. As shown in Fig. 1(a), we prepared a master with microstructures that provide a uniform thickness for the LC layer and prevent the LC flow under deformation. The microstructures were first produced on the Si wafer by a conventional photolithographic process using a photosensitive resin (SU-8).16,17 The elastomer material, poly(dimethylsiloxane) (PDMS, GE Silicones),13–15 was then spin-coated onto the master at a spinning rate of 1000 rpm for 120 sec, resulting in a film thickness of 40 µm. The PDMS elastomer was subsequently cured at 130°C for 1 hour. The cured PDMS elastomer was peeled off from the master as shown in Fig. 1(a). Several properties of the PDMS are instrumental in the formation of high-quality patterns and structures for replica molding. First, the PDMS is an elastomer, and therefore conforms to the surface of the substrate over a relatively large area. It is sufficiently deformable so that the conformal contact can be achieved even on surfaces that are non-planar on the micro-

Revised extended version of a paper presented at the 2006 SID Symposium held June 6–9, 2006 in San Francisco, California.
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meter and nanometer scale. The elastic characteristics of the PDMS also allow it to be released easily even from complex and fragile structures. Second, the PDMS provides a surface that has a low interfacial free energy and is chemically inert and durable. Third, the PDMS is homogeneous, isotropic, and optically transparent like a glass or plastic down to about 300 nm in wavelength. In addition, the PDMS surface induces the vertical alignment of the LC without any surface treatment. An image of a scanning electron microscope (SEM) of the duplicated PDMS substrate from the master is shown in Fig. 1(b). This indicates that the PDMS is a good substrate for a flexible display on which the spacers can be simultaneously formed.

A schematic diagram of our highly bendable flexible LC cell is illustrated in Fig. 2(a). The electrodes made of aluminum were patterned on the polyethersulfone (PES) plastic substrate by thermal evaporation, a subsequent photolithography process, and an etching process. The width and the thickness of each electrode are 10 µm and 1000 Å, respectively. The spacing between two adjacent electrodes is 10 µm. The vertical LC alignment layer, JALS 684 (Japan Synthetic Rubber Co), was coated on the PES substrate with patterned electrodes. The LC, ZLI 2293 (Merk), was filled between the top (PDMS) elastomer and the bottom (PES) substrate using a micro-pipette. The LC droplets were distributed on the plastic substrate in the form of a two-dimensional array with the periodicity of about 5 mm by a micro-pipette.

The elastomer substrate was then placed onto the plastic substrate bearing the array of the LC droplets. Considering that the dimension of each pixel is 100 × 300 µm, each LC droplet covers a few hundred cavities of the elastomer to be filled with the LC molecules. Note that no macroscopic amount of the LC molecules remains on the ribs. The birefringence and the dielectric anisotropy of ZLI 2293 are ∆n = 0.1322 and ∆ε = 10, respectively. A small amount of the UV curable polymer, NOA 65 (Norland Ltd.), was used to attach the PDMS film to the plastic substrate along the rim of the LC cell. For a large-sized panel over 5 in., the O2 plasma surface treatment can be used to enhance the adhesion property. Figure 2(b) shows a cross-sectional view of the multi-functional elastomer substrate. The width, height, interval, and the thickness of this substrate are l = 300 µm, b = 30 µm, d = 4.5 µm, and h = 40 µm, respectively.

3 Results and discussion

The vertical alignment of the LC on the PDMS film without any surface treatment is shown in Fig. 3(a). In the initial state after the LC injection, the vertical alignment was developed and it was completed after 30 sec. We discuss the EO properties and mechanical stability of our highly bendable LC cell in the vertically aligned configuration. Figures 3(b) and 3(c) show the operation principle and microscopic textures of our flexible LC cell observed with a polarizing optical microscope (Nikon, Optiphoto2-pol) under crossed polarizers. As shown in Fig. 3(b), the LC with positive dielectric anisotropy was vertically aligned on the top and the bottom substrates, one of which has in-plane electrodes. The crossed polarizers were placed at an angle of 45° to the in-plane electrodes. In the voltage-off state, an excellent dark state was obtained in each pixel between the crossed polarizers because the LC molecules were vertically aligned. Note that vertical LC alignment was spontaneously
produced as shown in Fig 3(b). This is very important because the uniform alignment of the LC is usually difficult to obtain on a microstructured substrate. In the on-state (at about 8 V), the LC molecules are reoriented along the in-plane electric field, and thus the light is transmitted through the LC cell due to the phase retardation.

Figure 4 shows microscopic textures together with simulations for the LC director profiles between electrodes for various voltages. The simulations were performed using the electrode spacing of 10 µm, the electrode width of 10 µm, and the cell thickness of 4.5 µm. The LC director is symmetric with respect to the center of the active region. There are two opposite LC bending directions between the electrodes, which are evident from the simulations as shown in Fig. 4. This self-compensated two-domain LC alignment formed between electrodes produces enhanced viewing characteristics. 19

The normalized EO transmittance and the response time of highly bendable LC cell, measured by a He–Ne laser of the wavelength of 632.8 nm and a photodetector, are shown in Figs. 5(a) and 5(b), respectively. Light transmission begins to occur at about 5 V and is saturated at 8 V. A contrast ratio of about 150 : 1 and the analog gray-scale capability were obtained as shown in Fig. 5(a). Figure 5(b) shows that the dynamic EO response to the applied voltage is a square waveform at a frequency of 1 kHz. The rise and fall times were found to be \( \tau_{\text{on}} = 16.3 \text{ msec} \) and \( \tau_{\text{off}} = 15.8 \text{ msec} \). Let us theoretically estimate the response time using the typical values of the material parameters. In our case, the rise and fall times can be given as Ref. 20
where \( \gamma_1 \), \( \Delta \varepsilon \), and \( k_i \) are the rotational viscosity, the dielectric anisotropy, and the relevant elastic constant of the LC materials, respectively. The cell gap and the dielectric field are denoted by \( d \) and \( E \), respectively. From the literature values of \( \gamma_1 = 149 \text{ mPa-sec} \), \( k_i = 1.79 \times 10^{-12} \text{ N} \), and \( \Delta \varepsilon = 10 \), it was found from Eqs. (1) and (2) that \( \tau_{\text{on}} \approx 15 \text{ msec} \) and \( \tau_{\text{off}} \approx 17 \text{ msec} \) for \( E = 0.61 \text{ V/\mu m} \) and \( d = 4.5 \text{ \mu m} \). These results agree well with our experimental results. It should be noted that the EO response of our bendable LCD is much faster than that of other flexible display with the LC/polymer mixture.\(^{10} \)

We now examine the EO stability of our highly bendable LC cell against an external bending deformation. The physical size of our bendable LC cell is 2.5 × 5 cm in a rectangular shape. The test of the mechanical stability against bending was carried out with homemade equipment shown in Fig. 6(a). The width and the interval of the microstructures on the elastomer substrate, dividing the LC layer into small active regions, were 300 and 30 \( \mu \text{m} \), respectively. Our bendable LC cell undergoes a curvature radius of about 6 mm without delamination of the two substrates. As shown in Fig. 6(b), our bendable LC cell, observed with a polarizing microscope, shows essentially no change under no applied voltage and a voltage of 7 V in the bend state. In the off-voltage state, the LC alignment was maintained in the bent state as clearly shown in Fig. 6(b). Under an applied voltage of 7 V, the uniformity of the voltage-on state was well preserved. This tells us that our microstructures on the elastomer substrate indeed prevent the LC flow across the pixels. Another important point is that our bendable LC cell was fully recovered from the bent state without any damage because of the elastic nature of the PDMS elastomer substrate, i.e., the reversible process of the expansion and contraction.

Let us describe the bending effect of our PDMS substrate on the LC molecular alignment. Consider the difference of \( \Delta L = x - y \) between the outer (x) and the inner (y) substrates for a fixed cell thickness of 4.5 \( \mu \text{m} \) and a width (z) of 300 \( \mu \text{m} \) as shown in Fig. 7(a). For a given geometric curvature radius \( R \) of bending, \( \Delta L \) can be obtained by Ref. 5

\[
\Delta L (\text{nm}) = \frac{1350}{R},
\]

where the unit of \( R \) is in mm. In deriving Eq. (3), the thickness of the LC layer was assumed to be constant. In our case of \( R = 6 \text{ mm} \), \( \Delta L \) was estimated as about 225 nm. This corresponds to a 5% variation of the LC cell thickness, indicating that the EO characteristics are well maintained. It may be then concluded that our highly bendable LC cell with an elastomer substrate is sufficiently durable and flexible for practical applications.

As a prototype, we fabricated a highly bendable LCD panel with a logo of ‘snu’ and presented the EO performances measured in a direct driving scheme under bending as shown in Fig. 7. It is clear that from Fig. 7(c) the logo of “snu” was well preserved in the bent state. In this case, the radius of the geometrical curvature is about 10 mm. Note that some spots observed in Fig. 7(c) simply arise from the

\[
\tau_{\text{off}} = \frac{\gamma_1 d^2}{\pi^2 k_i},
\]

\[
\tau_{\text{on}} = \frac{\gamma_1 E^2}{\varepsilon_0 |\Delta \varepsilon| E^2 - \frac{\pi^2}{d^2} k_i},
\]

FIGURE 6 — Microscopic textures of our bendable LC cell with a multi-functional elastomer substrate under crossed polarizers during mechanical bending: (a) an equipment used for testing the mechanical stability of our bendable LC cell in terms of the geometric curvature \( R \), (b) microscopic textures in the bent state with \( R = 6 \text{ mm} \) under the no applied voltage and an applied voltage of 7 V.

FIGURE 7 — Mechanical stability of our bendable LC cell in a direct driving scheme: (a) the description of the bent state, (b) photograph of our bendable LC cell having a curvature radius of about 10 mm, and (c) photograph showing a logo of ‘snu’ in the bent state.
drop-filling method of the LC into the bendable LC cell, and they can be removed by a better filling technique.

4 Conclusion

We demonstrated a highly bendable LCD with a multi-functional elastomer substrate fabricated by the replica-molding technique which is rather simple and cost effective. Our bendable LCD shows good EO properties, great mechanical stability, and needs much simpler fabrication process than conventional flexible LCDs. It was found that the use of an elastomer material as one of the flexible substrates plays a critical role in the recovery from expansion and/or contraction generated in the flexible LCD. This means that our bendable LCD is expected to bring a new product category of information displays. The fabrication technology presented here will be viable to highly bendable LC devices.

Acknowledgment

This work was supported in part by the Ministry of Science and Technology of Korea through the 21st Century Frontier Research and Development Program at the Information Display Center and the SNU-SDI Display Innovation Program.

References


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