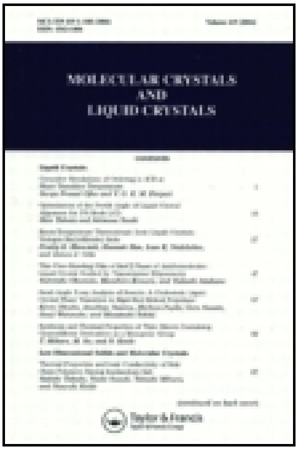

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Wide Viewing Liquid Crystal Displays with Bi-level Surface Microstructures Fabricated by an Imprinting Method

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Version of record first published: 05 Oct 2009

Mol. Cryst. Liq. Cryst., Vol. 507, pp. 245–252, 2009

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400903051432

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We report on a wide viewing liquid crystal display with bi-level microstructures fabricated at ambient temperature through an imprinting process which is simple and versatile. Hemispherical microstructures and rectangular microstructures, made of a photopolymer through a single-step imprinting process, produce multi-domains of the liquid crystal (LC) for enhancing the viewing property and provide spacers for maintaining the uniform cell gap, respectively. Our LC cell with embossed bi-level microstructures shows symmetric viewing properties in a wide range of polar angles, contrast ratio of 100:1, and the response time of 34 ms.

Keywords: bi-level microstructure; imprinting process; liquid crystal display; multi-domain; wide viewing

INTRODUCTION

Liquid crystal displays (LCDs) having light weight, slimness, and low power consumption are widely used in various application fields such as mobile appliances, notebook computers, high-definition television sets, and public information displays. Among several electro-optic (EO) properties including wide viewing characteristics, high contrast ratio, and fast response time, one of the most important issues in large size LCDs is to achieve wide viewing performances irrespective of both

This work was supported in part by Samsung Electronics Co. Ltd. and the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2006-005-J04104).

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the direction and the positions of a viewer. Beyond the twist nematic (TN) mode [7] possessing intrinsically narrow viewing characteristics, the in-plane switching (IPS) mode [1], the fringe field switching (FFS) mode [2], and the multi-domain vertical alignment (MVA) mode [3–6] have been developed to improve viewing angles. Compared to the IPS and FFS modes, the MVA mode is known to have such advantages that no rubbing process for the LC alignment, high contrast, and fast response. However, the realization of multi-domains of the LC in the VA mode involves inevitably additional processes of fabricating microprotrusions or patterned electrodes through complex photolithographic and wet-etching steps.

In this work, we present a wide viewing LCD with surface microstructures fabricated by an imprinting method [8–10] using a bi-level master at ambient temperature (25°C). A single-step imprinting method simultaneously produces microprotrusions and columnar spacers on the glass substrate for generating multi-domains of LC molecules in the field-on state and for maintaining the uniform cell gap of the LC cell. Our bi-level imprinting approach requires no repetitive wet-etching process, and thus it is simple and versatile for parallel replication of two-dimensional and three-dimensional structures on a micro/nano scales. Our LC cell shows the contrast ratio of 100:1, the response time of 34 ms, and symmetric viewing properties at more than $\pm 80^\circ$ of polar angles in the normally black mode.

EXPERIMENTAL

We first describe our bi-level imprinting process of simultaneously fabricating microprotrusions and columnar spacers on the bottom substrate as shown in Figure 1. Using a thermal reflow technique [11] with a photosensitive resin (AZ 1512), we prepared a bi-level mold where one of two microstructures is microprotrusions and the other is columnar spacers. The elastomeric material, poly(dimethylsiloxane) (PDMS) [8], was poured onto the mold and subsequently cured at 150°C for 1 hour. The cured PDMS was used as a bi-level master as shown in Figure 1(a). For fabricating bi-level microstructures on the bottom substrate, a photopolymer (NOA 65, Norland Ltd) was spin coated onto the glass substrate at the spinning rate of 8000 rpm for 100 sec, giving the film thickness of 4 μm. Using the bi-level PDMS master, the embossed bi-level microstructures of the NOA 65 photopolymer were produced and subsequently exposed to ultraviolet (UV) light ($\lambda = 365$ nm) at the intensity of 50 mW/cm^2 for 600 sec at ambient temperature (25°C). The embossed bi-level microstructures were then well maintained. Figure 1(b) shows the images observed with a

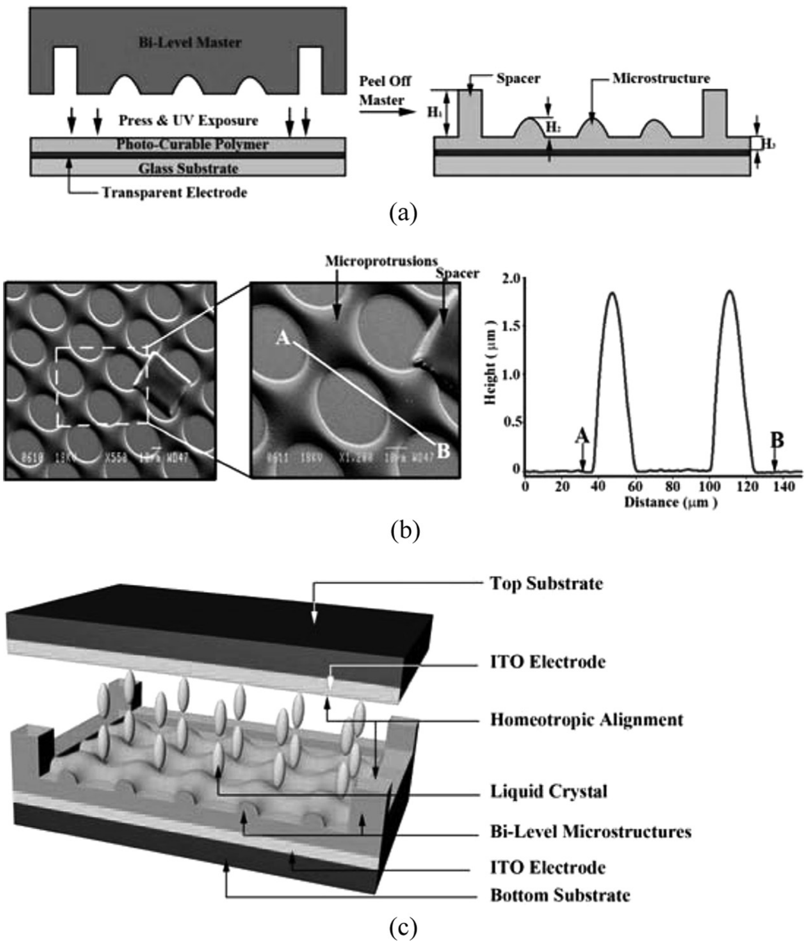


FIGURE 1 Fabrication process of a wide viewing LC cell having bi-level microstructures: (a) an imprinting process using a bi-level master on the bottom substrate, (b) the SEM image of the bottom substrate shown together with an enlarged image as well as the line profile of the microprotrusion from position A to position B, and (c) the schematic diagram of our LC cell with microprotrusions and spacers.

scanning electron microscope (SEM) and the profiles of microprotrusions measured with a surface profiler (AlphaStep 500, KLA Tencor Co.). From the results in Figure 1(b), the height of the columnar spacer, the maximum height of the microprotrusion, and the thickness of the residual photopolymer were obtained as $H_1 = 4\,\mu\text{m}$, $H_2 = 2\,\mu\text{m}$, $H_3 = 2\,\mu\text{m}$, respectively. Our LC cell was composed of two glass substrates, only one of which has bi-level microstructures as shown in Figure 1(c). A homeotropic polyimide, JALS 684 (Japan Synethetic Rubber Co), was coated onto the two substrates for the vertical alignment of the LC molecules. The LC material used was MLC 6883 whose birefringence Δn and dielectric anisotropy $\Delta\varepsilon$ are 0.1086 and -3.4, respectively. A square wave voltage at the frequency of 1 kHz was applied to our LC cell to measure the EO transmission and the response times. The measurement were carried out at room temperature using a digitizing oscilloscope (Lecory, WaveRunner 6030) and a light source of a He-Ne laser with the wavelength of 632.8 nm.

RESULTS AND DISCUSSION

Figure 2 shows microscopic textures of our LC cell with surface microstructures in a dark state, a gray state, and a bright state observed with a polarizing optical microscope (Optiphot2-pol, Nikon) under crossed polarizers at different voltages. Under no applied voltage, the LC molecules were aligned perpendicular to the substrate so that a dark state was obtained as shown in Figure 2(a). Above the Fredericks threshold voltage [12], axially symmetric LC structures were formed around imprinted microprotrusions as shown in Figures 2(b) and 2(c) because of the field distortions resulting from the difference in the effective voltage across the LC layer between the region 1 and region 2. The effective voltage can be written as [13]

$$V_{LC} = V_{appl}\left(1 + \frac{\varepsilon_{LC} h}{\varepsilon_{polymer} d_{LC}}\right)^{-1},$$

where V_{appl}, h, d, and ε represent the applied voltage, the thickness of the photopolymer, the thickness of the LC layer, and the dielectric constant,

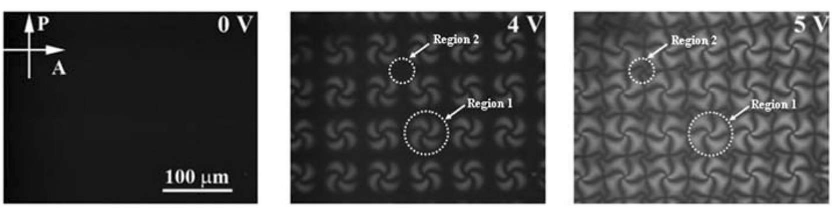
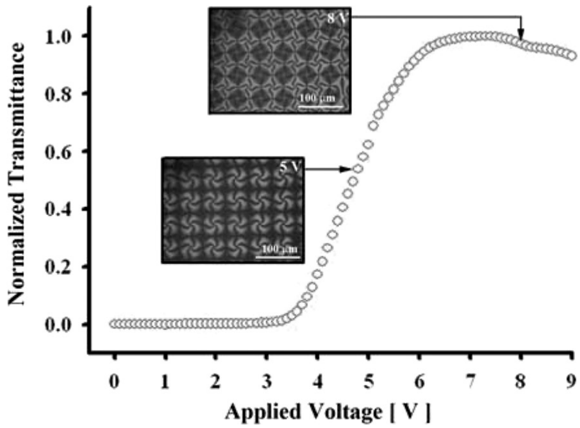


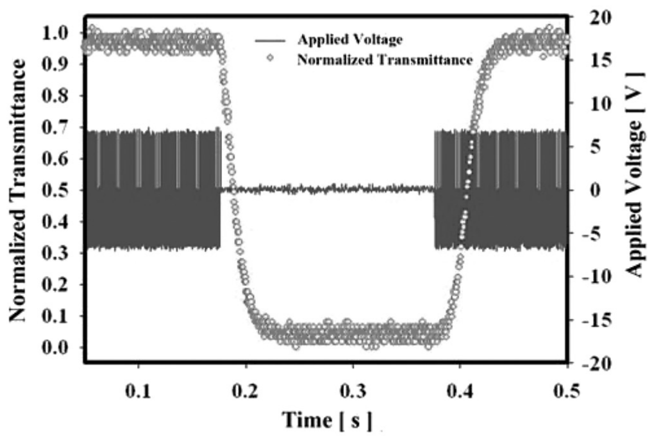
FIGURE 2 Microscopic textures of our LC cell with embossed microprotrusions and spacers: (a) a dark state under no applied voltage, (b) a gray state under the applied voltage of 4 V, and (c) the bright state under the applied voltage of 5 V.

respectively. Due to the difference in the effective voltage between region 1 and region 2, the LC molecules are reoriented at different voltages in the two regions as shown in Figures 2(b) and 2(c). It should be noted that four-domains with axial symmetry were spontaneously formed.

Figure 3 shows the normalized EO transmission and the response times of our LC cell with the embossed bi-level microstructures. As



(a)



(b)

FIGURE 3 The EO transmission and the dynamic response of our LC cell: (a) the normalized transmittance as a function of the applied voltage and (b) the rising and falling times, $\tau_r = 42$ ms and $\tau_f = 26$ ms, under the applied voltage of 6.5 V. The open circles and the solid line represent the normalized transmittance and the applied voltage, respectively. (See COLOR PLATE VI) shown in Figure 3(a), the EO transmission started to appear at the threshold voltage of about 3.5 V and became saturated above 7 V. The contrast ratio between the dark state at 0 V and the bright state at 6.5 V was about 100:1. The operating voltage is somewhat higher than that of a conventional VA cell due to the existence of the photopolymer layer. The dynamic EO response times were shown in Figure 3(b). The rising and falling times were measured to be $\tau_{on(10-90)} = 42$ ms and $\tau_{off(90-10)} = 26$ ms, respectively.

The iso-contrast map of our LC cell is shown in Figure 4. Four-fold symmetry in the viewing property along the vertical and horizontal directions was obtained due to the optical compensation among four-domains as shown in Figure 2. In our case, the columnar microstructures used as spacers leads to relatively low contrast and thus they can be replaced by black matrices to reduce the light leakage around the spacers.

We fabricated a prototype of a wide viewing LC cell (3 cm × 1.5 cm) with a logo of "SNU" as shown in Figure 5. The prototype was operated in a direct driving scheme to show the logo of SNU. The image was found to be well reproducible. The white background in our prototype LC cell was obtained at the applied voltage of 9 V in the normally black

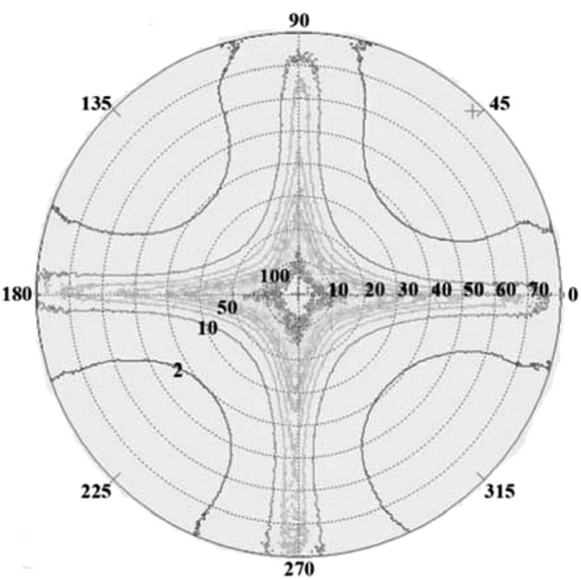


FIGURE 4 The iso-contrast map of our LC cell having surface microstructures. (See COLOR PLATE VII)

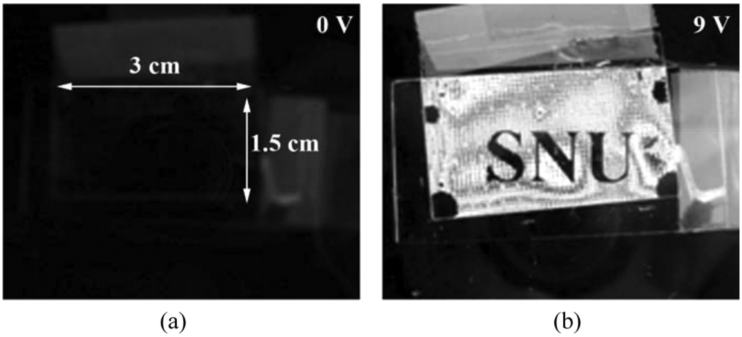


FIGURE 5 A prototype of a wide viewing LC cell of the size of 3 cm × 1.5 cm with a logo of "SNU" in a direct driving scheme: (a) the field-off state and (b) the field-on state.

mode. Note that the non-uniformity observed in certain areas in the prototype LC cell results from less embossed bi-level microstructures during the imprinting process. This may not limit the potential applicability of our bi-level imprinting method to the fabrication of surface microstructures for wide viewing LCDs.

CONCLUSION

We presented a wide viewing LCD with bi-level surface microstructures fabricated by a simple and versatile imprinting technique in comparison to a photolithography technique requiring repeated wet-etching processes. A bi-level imprinting method was developed to simultaneously fabricate microprotrusions for generating multi-domains of the LC molecules and spacers for maintaining the uniform cell gap. Four-fold symmetric multi-domains of the LC, spontaneously appeared due to the presence of the surface microstructures, were found to improve the viewing characteristics of the LCD. Our imprinting method has capability of constructing other LC-based EO devices on plastic substrates at low temperatures.

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