Transfer Fabrication of Liquid Crystal Devices with Microgroove and Wall Structure on Plastic Substrate for Flexible In-plane Switching Liquid Crystal Displays

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Abstract In this paper, we propose the in-plane switching liquid crystal device with a microgroove and wall structure, fabricated by a transfer method for printable manufacturing of large-area flexible liquid crystal displays. We confirmed that the liquid crystal devices have a higher transmittance than conventional devices, and that a reduction of the thickness of the residual polymer film is necessary to decrease the driving voltage. Similar to the technique used on glass substrates, fabrication of flexible liquid crystal devices using a plastic substrate is possible using silicone elastomer.

Keywords: Flexible liquid crystal display, transfer fabrication, in-plane switching, roll-to-roll.

1. Introduction

Recently, there has been significant focus on the development of flexible displays using thin, rollable plastic substrates¹⁻³⁾. These characteristics can dramatically improve the portability of large-area displays, for easier carriage into small spaces such as houses compared to conventional flat-panel large-area displays. However, there are still a number of limitations on the realization of flexible large-area displays. First, low-cost manufacturing is required for these to become commonly used devices. The printing technology known as the roll-to-roll process is expected to fulfill this requirement⁴⁻⁵⁾. Furthermore, the devices are required to have high reliability. Most current long-life electronic displays are of a liquid crystal (LC) type, since LC materials do not degrade chemically. There is some potential for established manufacturing technologies for liquid crystal displays (LCDs) to be applied to flexible displays, to provide a low-cost manufacturing process for high reliability devices.

The manufacturing methods available for flexible LCDs include high-temperature thermal treatments based on the formation of thin-film transistors (TFTs), LC alignment layer and photo-resist spacers. However,

thermal processes over the glass transition temperature (T_g) will damage the dimensional stability of a plastic substrate. We have previously reported the fabrication of visible-range transparent and thermally stable polyimide substrate, based on the coat-debond method, to overcome this problem^{6, 7)}. The drawback of this polyimide substrate is not suitable for low-cost and large-area LCDs because it is more expensive than other plastic materials. Ideally, an inexpensive plastic material, such as polyethylene terephthalate (PET) or triacetylcellulose (TAC), is required for low-cost and large-area flexible LCDs. The T_g values of these plastic materials are much smaller than that of polyimide, at around 100 °C. Therefore, fabrication without use of a high-temperature thermal process is required, presenting a critical challenge.

It has been reported that organic TFTs can be fabricated under conditions close to room temperature⁸⁾. The remaining problems are formation of LC alignment layer and spacer structure at low temperature less than T_g of inexpensive plastic materials. As the solution of this problems, the fabrication of flexible LC device having microgroove and wall structure has already reported for twist nematic (TN) mode⁹⁾. However, the TN mode is not suitable for sharing visual information with large audiences, due to the narrow viewing angle; therefore, in-plane switching (IPS) mode LC devices are required. The IPS mode has a wide viewing angle because LC molecules are only driven within the

Received March 30, 2018; Revised August 30, 2018; Accepted September 13, 2018

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azimuthal direction. Based on the requirements discussed, the novel manufacturing method for realization of flexible and printable IPS mode LCDs at low temperature is required.

2. Proposal of structural transfer method

Here, we propose the novel manufacturing method using transferred formation of microgroove and wall structure for flexible IPS-mode LC devices, as shown in Fig. 1. An ultraviolet (UV) curable monomer is coated on the plastic substrate; then, a mold with microgroove and wall structure is pressed to the plastic substrate and irradiated with UV light. The microgroove and wall structure is aligned the LC molecules¹⁰⁾⁻¹¹⁾ and sustain the thickness of the LC layer. Hence, formation of the alignment layer and spacer using a thermal process is unnecessary. The proposed technique is effective for fabrication of low-cost and large-area flexible LCDs, because the structural transfer process can be diverted to roll-to-roll manufacturing.

In this paper, we evaluated the electrooptical characteristics of IPS-mode LC devices with microgroove and wall structure fabricated using the structural transfer method. To clarify the adaptability of the proposed method to flexible LCDs, we investigated the LC alignment behavior on the substrate.

3. Formation and Evaluation of Microgroove and Wall Structure

To establish the proposed method, we transferred microgroove and wall structure onto a glass substrate. The fabrication procedure for the microgroove and wall structure is shown in Fig. 2. First, we coated a UV curable monomer material (NOA 63; Norland Ltd.) diluted by toluene (mass ratio 1:1) onto a glass substrate with comb-shaped transparent electrodes (electrode width: 10 μm , distance between electrodes: 10 μm), using a spin-coating method for 150 seconds at 5,000 rpm. Next, a silicone elastomer mold (polydimethylsiloxane (PDMS); DOW CORNING Corp.), with microgroove and wall structure was placed on the coated monomer; then, UV light with an intensity of 100 mW/cm^2 was irradiated onto the monomer for 3 min, while the mold was pressed (see Fig. 2 (b)). To confirm the formation of the transferred structure, confocal microscope images of the silicone elastomer mold surface and polymer (photo-polymerized monomer) film surface were taken, as shown in Fig. 3. The formation of a uniaxially aligned microgroove and cross-shaped wall structure on the polymer surface was

Fig.1 Proposed manufacturing method of IPS-mode LCDs.

Fig.2 Fabrication process of microgroove and wall structure.

Fig.3 Confocal laser microscope images of transferred polymer surface.

Table 1 Estimated dimensions of microgroove and wall structure from confocal laser microscope images.

	Wall		Microgroove	
	Mold	Polymer	Mold	Polymer
Depth	2.49	2.42	0.18	0.18
Width	9.65	9.56	1.96	1.96

[μm]

confirmed, and the estimated dimensions are summarized in Table 1; these are consistent with those of the silicone elastomer mold. It was hence confirmed that the fabrication of accurately transferred microgroove and wall structure without air bubbles or contamination in the interface between the mold and monomer.

4. Voltage-transmittance characteristics

Fig. 4 shows the fabrication procedure for IPS-mode

Fig.4 Fabrication process of LC devices with microgroove and wall structure.

Fig.5 Crossed-Nicols polarizing microscope images of LC device with microgroove and wall structure.

Fig.6 Voltage-transmittance characteristics of IPS mode LC devices.

LC devices with a microgroove and wall structure. We constructed the cell-type structure using two substrates with a microgroove and wall structure, as discussed in Section 3; then, we injected nematic-phase LC (TD-5043XX; JNC) into the cell, utilizing capillary action. Figure 5 shows crossed-Nicols polarizing microscope images of the fabricated LC cells. Although light leakage due to the alignment defect of the LC at the wall structure interface was observed, other regions exhibited a uniform dark state. When the microgroove direction and polarization direction are inconsistent, bright state was observed. It was hence confirmed that the LC molecules aligned along the microgroove direction.

To investigate the electro-optical characteristics of this cell structure, the voltage-transmittance curves of the structurally transferred LC devices were measured, as shown in Fig. 6; the characteristics of conventional IPS-mode LC devices with polyimide alignment layer and spacer structure of 4 μm diameter glass beads is also shown for comparison. The driving voltage of the proposed LC device was higher than that of the conventional LC device. To discuss the mechanism of

Fig.7 Cross-sectional image of the interface between the microgroove and the glass substrate.

(a) Conventional type

(b) Proposed device

Fig.8 Microscope images and schematic of in-plane switching (IPS)-mode LC devices in the voltage ON state.

high driving voltage, the cross-sectional structure of the proposed LC device was investigated, as shown in Fig. 7. The estimated step height between the glass substrate and microgroove was 2.88 μm , and this can be attributed to the residual polymer layer on the substrate. The effective electrical field to the LC molecules is reduced by the presence of this residual polymer film; therefore, it is necessary to reduce the thickness of the residual polymer layer to decrease the driving voltage.

In contrast, the maximum transmittance of the proposed LC devices was higher than that of the conventional type. High transmittance in LCDs improves light utilization efficiency. However, minimum transmittance was also higher because of alignment defect. The calculated contrast ratio of conventional LC device was 57.1, which was 51.3 in proposed LC device. Figure 8 shows crossed-Nicols polarizing microscope images of the IPS-mode LC devices in the voltage ON state. Compared to the conventional device, the comb-shaped electrode region in the proposed device exhibits a bright state. This is caused by rotation of the LC molecules on the electrode due to the weak anchoring energy of the microgrooves¹²⁾, and/or to extension of the electrical field distribution due to the residual polymer film. To investigate the effect of these factors on the

Fig.9 Simulation result of LC direction and transmittance distribution under weak anchoring.

Fig.10 Simulation result of LC direction and transmittance distribution with polymer film.

Table 2 Simulation parameters for TD-5043XX.

Elastic constant of splay (K_{11})	8.42 pN
Elastic constant of twist (K_{22})	2.80 pN
Elastic constant of bend (K_{33})	11.66 pN
Value of dielectric anisotropy ($\Delta\epsilon$)	3.42
Value of refractive index anisotropy (Δn)	0.135

transmittance individually, we simulated the transmittance and LC alignment distribution based on elastic continuum theory, as shown in Figs. 9 and 10. Figure 9 shows the dependence of the transmittance on anchoring energy. In this simulation, strong and weak anchoring energies were set to be $1.0 \times 10^{-3} \text{ J/m}^2$ and $3.1 \times 10^{-6} \text{ J/m}^2$, respectively. $1.0 \times 10^{-3} \text{ J/m}^2$ is anchoring energy of general polyimide alignment layer. The value of the weak anchoring energy was adopted from calculated values based on Berreman's theory¹³⁾. Other physical parameters for the simulation are summarized in Table 2. Figure 9 (a) shows the direction distribution of the LC molecules on a comb-shaped electrode in the voltage ON state. The rotation behavior of LC molecules on electrodes can be observed through the elastic force arising from rotated LC molecules between electrodes. Compared to a strong anchoring energy, the transmittance increased under a weak anchoring energy, as shown in Fig. 9 (b). Here we evaluated response time for turn-on and turn-off processes of each devices, as shown in Table 3. Weak anchoring energy of microgroove caused longer turn-off time than that of

Table 3 Response time of conventional LC device and the proposed LC device.

	Conventional device	Proposed device
Turn-on	13.2	11.0
Turn-off	12.4	229
		[ms]

proposed LC device. Figure 10 shows the effect of the residual polymer film on the direction distribution and transmittance. In this simulation, we defined microgroove with width of $2 \mu\text{m}$ pitch and depth of $0.2 \mu\text{m}$ on $2.8 \mu\text{m}$ dielectric layer. Here, the anchoring energy was assumed to $3.1 \times 10^{-6} \text{ J/m}^2$, corresponding to weak anchoring effect. From Fig. 10 (a), it was demonstrated that LC molecules were rotated by extension of the electrical field due to the presence of the residual polymer film. As the result transmittance on electrode increased, as shown in Fig 10 (b). From these results, we clarified that the high transmittance of the IPS-mode LC device with the microgroove and wall structure is based on both the weak anchoring energy from the microgroove, and extension of the electrical field by the residual polymer film. Power consumption increases due to increasing of driving voltage, and it decreases due to increasing of maximum transmittance. Since power saving is important for portable and flexible LCDs, it will be necessary to optimize structural parameters for minimization power consumption.

5. Fabrication of flexible LC device with microgroove and wall structure using plastic substrate

Figure 11 shows the transfer fabrication procedure for the flexible LC devices with a microgroove and wall structure on a plastic substrate. First, we coated a UV curable monomer material (NOA 63; Norland Ltd.) diluted by toluene (mass ratio 1:1) on the plastic substrate by spin coating for 150 seconds at 5, 000 rpm. Usually, the substrate is fixed at the center of the spin table using vacuum chuck; however, the soft plastic

Fig.11 Fabrication process of microgroove and wall structure on plastic substrate.

Fig.12 Surface images of fabricated polymer structure on the plastic substrate.

Table 4 Estimated dimensions of microgroove and wall structure from confocal laser microscope images of the plastic substrate.

	Wall		Microgroove	
	Mold	Polymer	Mold	Polymer
Depth	1.54	1.52	0.20	0.21
Width	8.37	8.25	1.92	1.94
[μm]				

substrate will be deformed by vacuum chuck. To overcome this problem, a glass plate was used to hold the flatness of plastic substrate and silicone elastomer was used as an adhesive buffer plate. Then, the mold with the microgroove and wall structure was placed on the coated monomer, and irradiated with UV light (365 nm wavelength) for 3 min. Here, UV intensity after passing through plastic substrate was adjusted 100 mW/m². Figure 12 shows confocal laser microscope images of the surface of the structurally transferred monomer after UV irradiation. It was confirmed that periodic microgroove and cross-shaped wall structure were formed on the polymer surface. However, structural distortion at microgroove was observed. We consider that this is caused by plastic substrate being soft and distorted. The dimensions of these structures were summarized in Table 4, and there was negligible difference in structural dimensions between the surfaces of the mold and the polymer. We have therefore succeeded in transferring the microgroove and wall structure onto the plastic substrate, as well as onto the glass substrate, as described in Section 3.

Figure 13 shows the fabrication procedure for the LC devices with the microgroove and wall structure using a plastic substrate. The LC cell structure was constructed using two structurally transferred plastic substrates, as shown in Fig.13 (a); then, we injected LCs (TD-5043XX, JNC) into the cells, utilizing capillarity action. Crossed-Nicols polarized microscope images of the fabricated LC device are shown in Fig. 14. When the direction along the microgrooves is matched to the transmission axis of

Fig.13 Fabrication process of LC device with plastic substrate.

Fig.14 Crossed-Nicols polarizing microscope images of LC device with microgroove and wall structure using plastic substrate. The described cross-like white dotted line represents a wall structure.

Fig.15 Side images of LC device using glass substrate and plastic substrate.

the polarizer, light leakage caused by the alignment defect of LCs was observed at the wall structure interface. Most regions on the microscope image exhibited a uniform dark state. With a 45 degree rotation of the crossed-Nicols polarizer, a bright state was obtained in all regions, except for at the wall structures. However, alignment defect was observed in bright region. Distortion of microgroove is considered as this cause. These results indicate that LC molecules were aligned parallel to the microgrooves. In addition, the flexible LC device using plastic substrate was thinner than LC device using glass substrate, as shown in Fig. 15. In this study, we have demonstrated that the transfer method for the microgroove and wall structure can also be applied to a flexible plastic substrate. Hence, we showed the possibility of realization of large-area flexible LCDs with improved portability.

6. Conclusions

In this study, we proposed a fabrication method using transferred formation of microgroove and wall structure for flexible IPS-mode LC devices. For demonstration of the proposed method, we fabricated an IPS-mode LC device with a microgroove and wall structure, which exhibited higher transmittance and driving voltage than conventional IPS-mode LC devices. We clarified that a reduction in the thickness of the residual polymer film was necessary to decrease the driving voltage based on LC elastic continuum theory. In addition, we succeeded in fabricating flexible LC devices with a microgroove and wall structure on a plastic substrate, and confirmed that the transfer technique for the microgroove and wall structure can be applied for fabrication of flexible LC devices using a plastic substrate.

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