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Adhesive-Transfer Bonding Technique for Flexible Liquid Crystal Displays with High Mechanical Stability

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We report on an adhesive-transfer bonding technique for improving mechanical stability of a flexible liquid crystal display (LCD) with an elastomer substrate. Permanent adhesion between an elastomer substrate and a plastic substrate is generated through thermal cross-linking of a curing agent prepared on the elastomer substrate by precise stamping. Our flexible LCD assembled using the adhesive-transfer bonding technique is found to show excellent mechanical stability in a highly bent environment.

Keywords: bonding technique; cross-linking; flexible LCD; mechanical stability; PDMS

INTRODUCTION

Flexible displays [1] have attracted great attention due to many advantages such as lightweight, durability, and portability. Several types of flexible displays using liquid crystals [2,3] (LCs), organic light emitting materials [4], or e-ink materials [5] have been developed so far. Among them, the LC-based flexible displays are most promising since relevant technologies have been well established. For flexible LCDs, typical glass substrates are commonly replaced by plastic substrates. However, flexible LCDs based on plastic substrates suffer from bonding problems such as detachment of two plastic substrates and cell gap variations against external forces. Therefore, a reliable

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method of bonding two substrates is one of the critical technologies in flexible LCDs so as to achieve mechanical stability against deformations.

Recently, a flexible LCD configuration with an elastomer substrate has been demonstrated [6]. This configuration was found to provide excellent bending properties compared to other flexible LCDs with two plastic substrates but it showed often relatively weak adhesion between the elastomer substrate and the alignment layer.

In this work, we develop a new bonding technique for fabricating a flexible LCD with an elastomer substrate and a plastic substrate through thermal cross-linking of a curing agent prepared on the elastomer substrate by stamping. This adhesive-transfer bonding technique provides nearly permanent adhesion of the elastomer substrate to the plastic substrate. In our flexible LC cell using adhesive-transfer bonding, the electro-optic (EO) properties are found to be well preserved in a highly bent environment.

EXPERIMENTS

The schematic diagram of the adhesive-transfer bonding technique for the elastomer substrate using a curing-agent is shown in Figure 1. The top substrate was fabricated using an elastomeric material of poly-(dimethylsiloxane) (PDMS) (Sylgard 184, Dow Corning) by a replica molding technique [7]. Using a photosensitive resin (SU-8) on a silicon wafer, we prepared the master with microstructures that were used as column spacers to maintain the uniform cell gap. The PDMS material was spin coated onto the master at the spinning rate of 500 rpm for 60 s (giving the film thickness of $d = 300 \mu\text{m}$), and subsequently cured at 120°C for 1 h. The cured PDMS was then peeled off from the master as shown in Figure 1(a). The physical dimensions of the width, the height, and the interval between column spacers were $w = 200 \mu\text{m}$, $h = 6 \mu\text{m}$, and $i = 200 \mu\text{m}$, respectively. Note that the PDMS material is optically isotropic and transparent, flexible, durable, and capable of aligning the LC vertically. The assembling processes of a flexible LCD through adhesive-transfer bonding are shown in Figure 1(b). A curing agent of PDMS (Sylgard 184B) was transferred onto the bonding sites of the top substrate by stamping. For the vertical alignment of the LC, JALS 684 (Japan Synthetic Rubber Co.) was coated on the bottom substrate of polyethersulfone (PES). The top substrate was assembled with the bottom substrate having a homeotropic alignment layer and in-plane electrodes with the width of $20 \mu\text{m}$ and the interval of $50 \mu\text{m}$. Bonding of the two substrates was subsequently generated

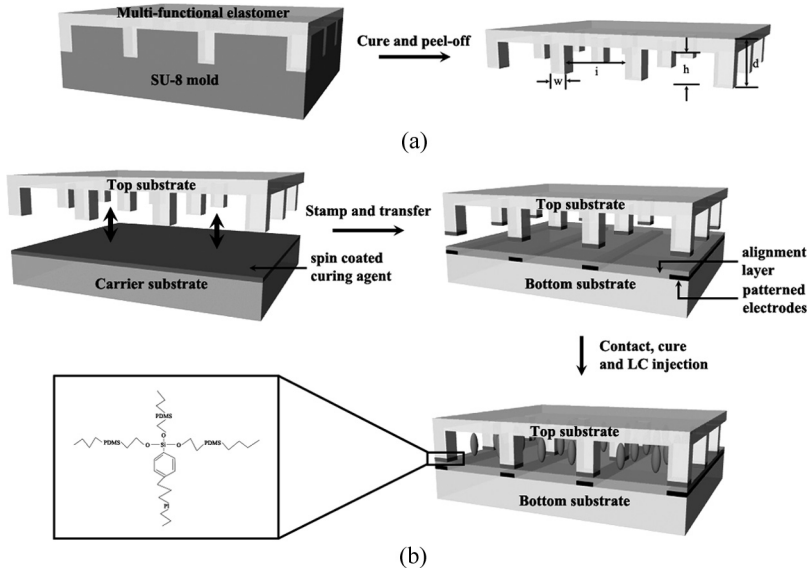


FIGURE 1 An adhesive-transfer bonding technique for the elastomer substrate using a curing agent; (a) a fabrication process of the top substrate by replica molding, (b) An assembling process of the flexible LC cell using the adhesive-transfer bonding technique: the bonding mechanism associated with thermal cross-linking of the polyimide and PDMS shown in the enlarged diagram.

by heating at 120°C for 30 min. A nematic LC, ZLI-2293 (Merck), having the birefringence $\Delta n = 0.1322$ and the dielectric anisotropy $\Delta\epsilon = 0.1322$, was filled into the cell by capillary action. Since the hydrophobicity of the PDMS surface tends to disturb LC injection, the UV/ozone treatments were carried out to make it hydrophilic [8]. The curing agent, produced nearly permanent adhesion between the PDMS substrate and the bottom substrate with a polyimide alignment layer [9]. By incorporation of terminated siloxane oligomers in the polyimide chain, polyimide and PDMS are cross-linked with each other as shown in Figure 1(b) in the enlarged diagram [10]. The PDMS substrate having a hydrophobic surface property is not strongly attached onto the plastic substrate without surface treatments such as O_2 plasma treatment [11,12]. Existing bonding techniques based on such surface treatments of the PDMS substrate have difficulty for the direct attachment to polyimide layers and may involve damages to the PDMS substrate. In contrast, adhesive-transfer bonding generated between

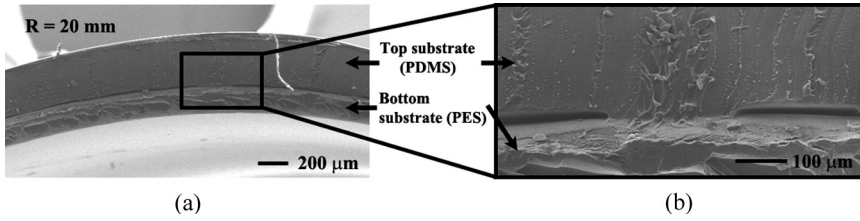


FIGURE 2 The SEM image of the bonding site for $R = 20$ mm; (a) $\times 100$ and (b) $\times 400$, the enlarged image of (a).

the polyimide and PDMS by thermal cross-linking is rather simple, cost effective, and of no damage to the PDMS substrate.

The cross-sectional image of the cell, taken with a scanning electron microscope (SEM) (XL30FEG, Philips Electron Co.), shows a site bonded tightly between the top and bottom substrates under the bending deformations as shown in Figure 2(a), where the curvature of radius was expressed as R . As clearly shown in Figure 2(b), the top and bottom substrates are tightly bonded and maintain the uniform cell gap in the bent state. The uniform cell gap of the flexible LCD guarantees the uniformity of the electro-optic (EO) performances in a highly bent environment. A polarizing optical microscope (Optiphot2-Pol, Nikon) was used for observing microscopic textures of our flexible LCD. 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. A light source of a He-Ne laser with the wavelength of 632.8 nm and a digital oscilloscope (WaveRunner 6030, LeCroy) were used for the EO measurements that were carried out at room temperature.

RESULTS AND DISCUSSION

Figure 3 shows the schematic director profiles together with microscopic textures of our flexible LCD, observed with a polarizing optical microscope under crossed polarizers, in the field-off and field-on states. One of two crossed polarizers was placed at an angle of 45° with respect to the direction of interdigital electrodes. As shown in Figure 3(a), in the absence of an applied voltage, the LC molecules were vertically aligned so that a dark state was obtained. A certain amount of the light leakage in the field-off state was observed since the LC molecules were aligned perpendicular to the surface of PDMS column spacers. Under the applied field of $1 \text{ V}/\mu\text{m}$, the LC molecules

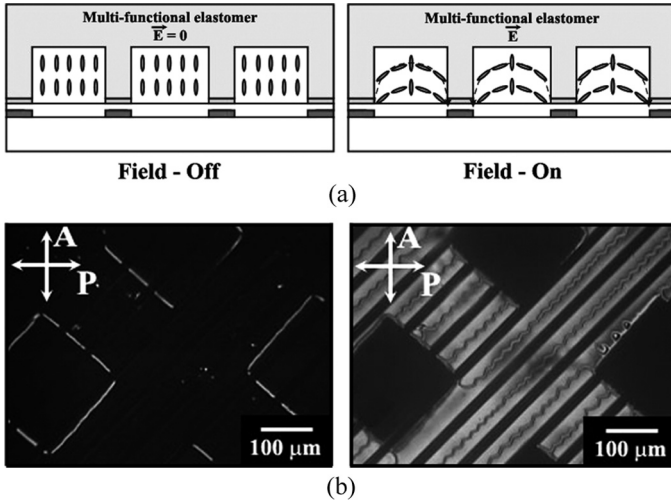


FIGURE 3 Schematic director profiles and microscopic textures of our flexible LC cell fabricated using our adhesive-transfer technique; (a) a dark state under no applied voltage, (b) a bright state at the applied voltage of $1 \text{ V}/\mu\text{m}$.

were reoriented along the in-plane electric field, denoted by a dashed arrow in the upper diagram of Figure 3(b), so that a bright state was obtained. The director profiles are symmetric with respect to the mid-plane between two adjacent electrodes. This implies that two self-compensated domains in the LC alignment were formed between two adjacent electrodes so that the viewing characteristics became spontaneously enhanced [13,14].

Figure 4 shows the normalized EO transmittance and the dynamic response of our flexible LC cell fabricated using the adhesive-transfer bonding technique. The EO transmission and the dynamic response in Figure 4 were measured under the bending curvature of $R = 20 \text{ mm}$. As shown in Figure 4(a), the EO transmittance appears at the threshold voltage of $0.3 \text{ V}/\mu\text{m}$, and becomes to saturate above $1 \text{ V}/\mu\text{m}$. The contrast ratio between the dark state at $0 \text{ V}/\mu\text{m}$ and the bright state at $1.5 \text{ V}/\mu\text{m}$ was about 50:1, which is relatively low due to the light leakage around the PDMS column spacers as shown in Figure 3(a). The rising and falling times, defined as the transition times between two states of 10% and 90% in the EO transmittance, were measured to be $\tau_r = 25 \text{ ms}$ and $\tau_f = 55 \text{ ms}$ as shown in Figure 4(b). Note that τ_f can be decreased with reducing the interval between electrodes and/or the cell gap.

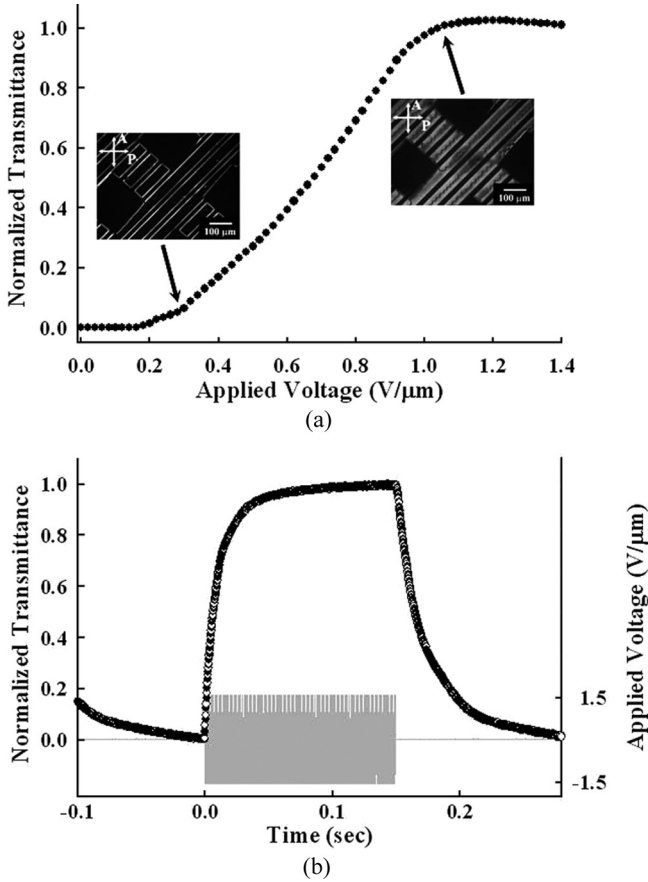


FIGURE 4 EO transmission and the dynamic response of our flexible LC cell; (a) the normalized EO transmittance as a function of the applied voltage and (b) the rising and falling times, $\tau_r = 25$ ms and $\tau_f = 55$ ms, between two states the applied field of $0 \text{ V}/\mu\text{m}$ and $1.5 \text{ V}/\mu\text{m}$.

We demonstrate a prototype flexible LCD of 3 cm wide and 1.5 cm long. As shown in Figure 5, the EO properties show essentially no change under $R = 20$ mm. This indicates that nearly permanent adhesion was produced between the top and bottom substrates through the adhesive-transfer bonding process. It is noted that our flexible LC cell was fully recovered from a highly bent state without any deterioration of the EO properties due to the strong adhesion and the elasticity of the PDMS elastomer substrate.

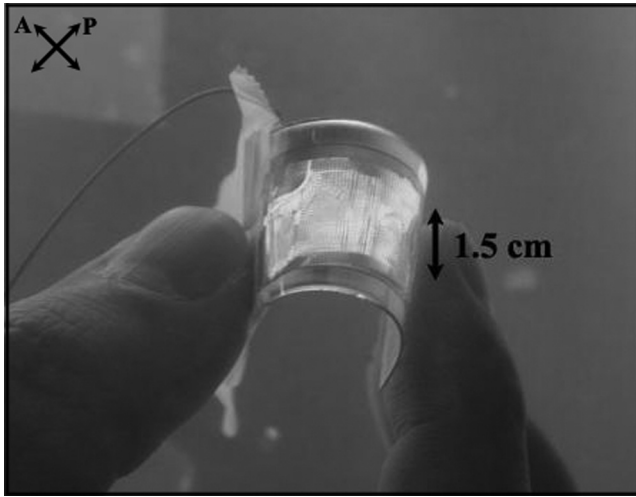


FIGURE 5 A prototype flexible LCD panel with the size of $3\text{ cm} \times 1.5\text{ cm}$ in a direct driving scheme.

CONCLUSIONS

We developed an adhesive-transfer bonding technique for producing strong adhesion in a flexible LCD through a simple stamping process. Permanent adhesion between two substrates in the flexible LCD was obtained by thermal cross-linking of the PDMS and polyimide. It should be emphasized that permanent adhesion of two substrates guarantees the uniformity of the cell gap and the mechanical stability in a highly bent environment. The bonding technique described here would have an impact on the design freedom of a variety of flexible LCDs.

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