Journal of Information Display, vol. 6, no. 1, 2005

Phase-Separated Pixel Isolation Method for Roll-to-Roll Processing in Flexible Liquid Crystal Displays

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Abstract

We propose new fabrication methods of a pixel-isolated liquid crystal (LC) structure for flexible display applications. In the LC structure fabricated through the proposed method, the patterned interpixel walls for sustaining the cell thickness are supported by the solidified polymer layer through anisotropic phase separation of LC/polymer composite, causing the alignment of the LC molecules to have very good mechanical stability against external pressure. In addition, we show that such pixel-isolating walls can be made by the stamping method which can be applied to fabricate large size plastic LCDs by roll-to-roll processing.

Keywords : plastic LCD, polymer-LC composite, stamping method, roll-to-roll processing

1. Introduction

In recent years, roll-up displays have drawn much attention as the next-generation information displays because of their excellent portability such as light weight, thin packaging, and flexibility. Among the various existing technologies, it is expected that a liquid crystal (LC) device using plastic film substrates will be realized in the near future [1-3]. With only current technologies obtained through development of glass substrates-based LC displays (LCDs), the plastic LCDs will show superior visibility with low power consumption. However, there are some major problems hindering plastic LCDs from being commercially available. First, it has unstable LC structures due to hydrodynamic properties of the LCs at bending and, second, the two plastic substrates tend to separate due to the flexibility of the substrates. Such problems are not observed in the conventional glass substrates-based LCDs since theses substrates can support the stable LC alignment condition from external bending or pressure.

To solve these problems, several types of polymer wall and/or networks as supporting structures have been proposed and demonstrated [4-8]. Most of these adopt the methods of the electric field-induced or the photo-induced phase separation using the polymer-LC composite to make polymer wall structures. However, the electric field-induced phase separation method requires high electric field to form a stable polymer wall [5, 6] and the conventional photo-induced phase separation method suffers from the residual monomers or polymers in the unexposed regions of the bulk which severely degrades the electro-optic (EO) properties of the LCDs, consequently resultings in the increase in the operating voltage [9]. The pixel-isolating wall structures can be made by conventional photolithography process, but weak adhesion properties between the wall structure and the flexible substrates still remain to be solved. Moreover, conventional fabrication methods are not appropriate to a cost-effective roll-to-roll process, which is essential for fabricating large area plastic LCDs. Thus, an alternative fabrication method should be developed for the plastic LCDs to be commercialized.

In this work, we propose a new method to enhance the mechanical stability of the plastic LCDs using a solidified polymer layer near the patterned wall structures. Such polymer layer is formed by anisotropic phase separation in the vertical direction of the cell [10-12], thus the complete phase separation from the polymer-LC composite can be achieved showing almost the same optical behavior as

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Manuscript received January 25, 2005; accepted for publication March 10, 2005.
This work was supported by Korea Research Foundation Grant No. KRF-2004-005-D00165.
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normal LC modes without the wall structures. In addition, this paper provides a stamping method for fabricating the pixel-isolating wall structures using durable elastomers such as poly(dimethylsiloxane) (PDMS), which is applied to the roll-to-roll processing for mass production of large size flexible LCDs.

2. Phase Separation Method for Enhancing the Mechanical Stability

Fig. 1 shows the proposed structure of the pixel-isolated LC structure where the wall structures are formed in the bottom substrate. One of ITO-deposited glass substrates was spin-coated with a polyimide and then rubbed to promote a planar alignment condition. On this substrate, the micro-wall structures were fabricated by normal photolithographic method using photo-resist of SU-8 as shown in Fig. 2. The patterned pixel size was 100 μm × 300 μm and the distance between the pixels was 20 μm. As a polymer/LC composite to be filled into the cell, a mixture of UV curable epoxy, NOA 65 (Norland Co.) for prepolymer and E7 (Merck) for nematic LC (NLC) was used. A solution of the NLC and prepolymer with the weight ratio of 95:5 was dropped on the substrate with the microstructures and covered by a bare ITO-deposited glass substrate. In our structure, the cell gap was uniformly and stably maintained by the height of the microstructure in the whole area of the cell as shown in Fig. 2 (b). We adjusted the cell gap to be 5.4 μm. However, it is difficult to stably sustain the cell gap at bending process with only these fabrication steps becuase the attachment between the micro-wall structures and the bare ITO substrate covered later is very poor. In addition, such wall structures are still weak to external mechanical shock.

In our structure, such problems were eliminated by producing a uniformly solidified polymer layer onto the bare ITO substrate using a complete and an anisotropic phase separation of the prepolymer/NLC mixture through UV exposure as shown in Fig. 1. The UV exposure was executed onto the bare ITO substrate. The solidified polymer layer causes the patterned wall structures to firmly attach to the other substrate and enhances the mechanical strength of the pixel-isolated LC device. However, to avoid degradation of electro-optic properties of displays, it is essectial that the polymer layer is kept uniform. To obtain uniform polymer layer, some requirements in the fabrication conditions such as the relative surface wetting properties between the prepolymer and the LC molecules, UV intensity gradient, and the mixing ratio of the composite should be satisfied [10-12]. In our structure, the bottom substrate in Fig. 1 prefers LC molecules over the prepolymers as the LC molecules can be completely wet to the LC alignment layer whereas the prepolymers can only be partial wetted. In addition, a sufficient UV unintensity gradient is produced in the vertical direction of the sample since the UV light is predominantly absorbed by the LC molecules in the solution [10]. Consequently, NOA 65 molecules first undergo polymerization near the top substrate as shown in Fig. 1 and the LC molecules are expelled from the polymerized volume, forcing them to diffuse away from the UV source. In our experiment, the source of the UV light was a Xenon lamp of λ = 350 nm operated at 200 W of electrical power. To induce such complete phase separation, the molecular fraction of the prepolymer should be limited. With the ratio of our prepolymer/LC composite, we could successfully isolate the LC molecules within the pixel surrounded by the micro-wall structures and the uniformly solidified polymer layer.

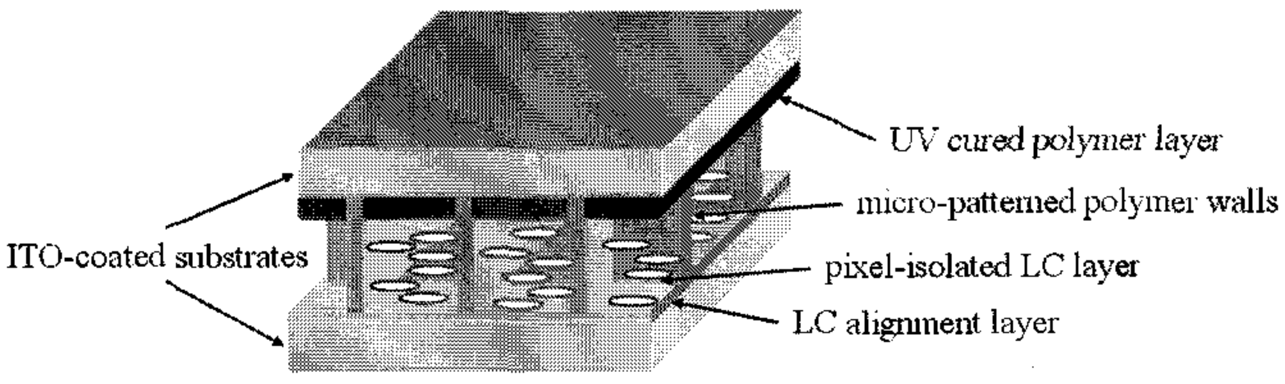
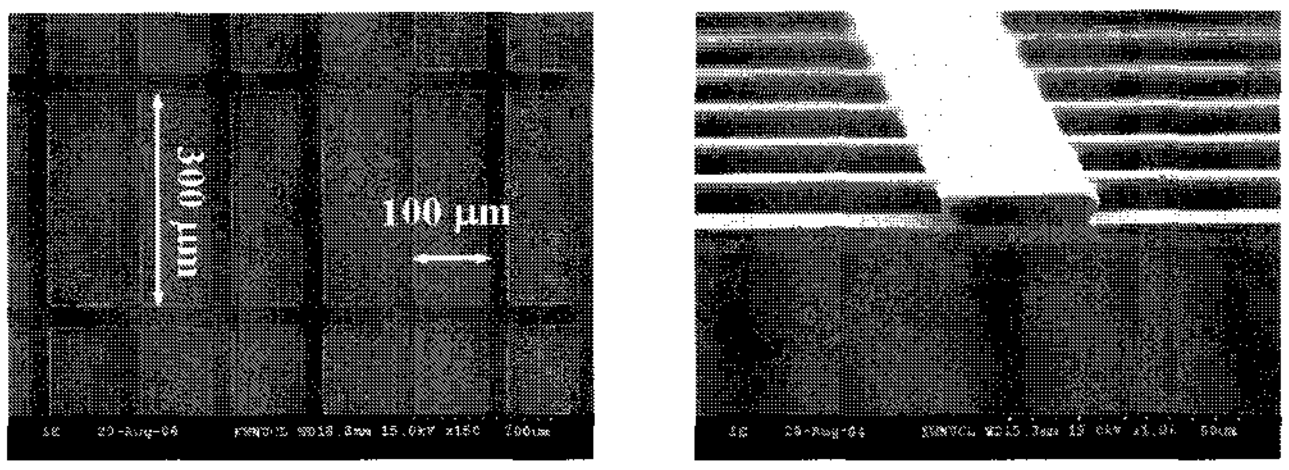


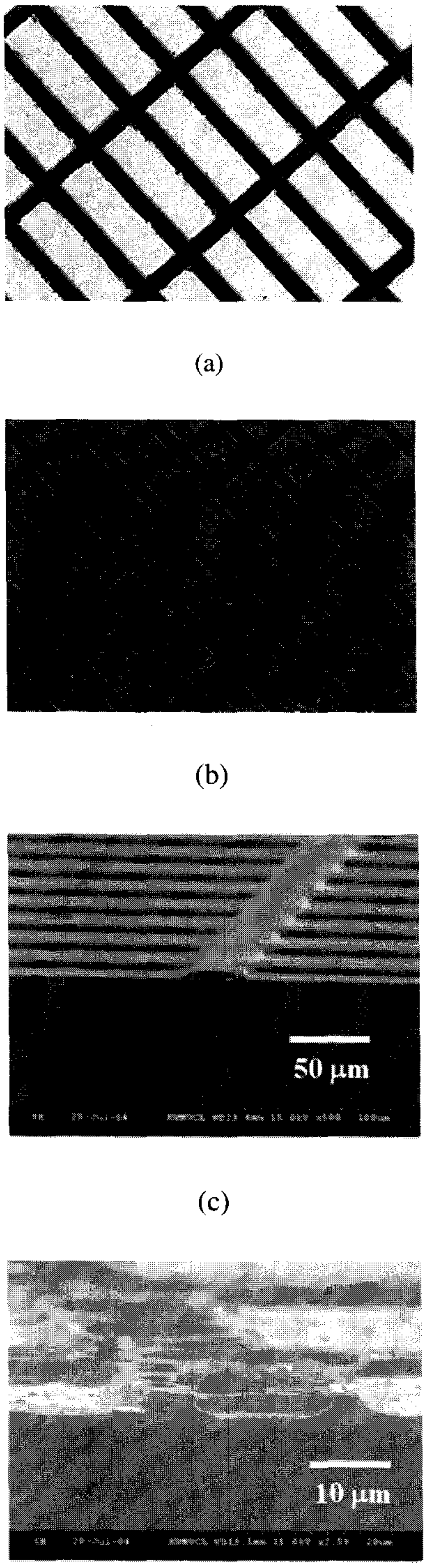
Fig. 1. The schematic diagram of the pixel-isolated LC device. After UV exposure, the wall structures are supported by the phase separated polymer layer.



(a) (b)

Fig. 2. The SEM images of the patterned microstructures taken by (a) top view and (b) side view.

Figs. 3 (a) and (b) show the polarizing microscopic textures of our pixel-isolated LC device at room tem-



(a)

(b)

(c)

(d)

Fig. 3. The microscopic and SEM images : The alignment textures of the sample were taken under polarizing microscope (a) in the absence of an applied voltage and (b) in the presence of an applied voltage. After separation of the substrates, the SEM images were taken (c) in the bottom substrate and (d) in the top substrate shown in Fig. 1.

perature after UV exposure in the absence of an applied voltage and also in the presence of an applied voltage of 7 V, respectively. It is clear that the LC is confined to the pixels and surrounded by the patterned microstructures. As the applied voltage was increased, we observed that the brightness within each pixel uniformly varied showing that the polymer layer was solidified only onto the top substrate with good uniformity. The internal structure of our device can be clearly verified by the SEM images of Figs. 3 (c) and (d). After opening the cell and completely removing the LCs with solvents, the SEM images were taken in the bottom substrate and the top substrate as shown in Figs. 3 (c) and (d), respectively. The SEM image of the bottom substrate shows almost the same image as in Fig. 2 (b) without any polymerized texture, whereas the surface image of the top substrate clearly shows the UV cured thin polymer layer, uniformly formed within the pixel area. The thickness of the solidified polymer layer became relatively thick near the micro-patterned wall structure, to allow the pixel-isolating walls of our structure to become tightly attached to the opposite substrate.

3. Stamping Method for Pixel Isolation in the Plastic LCDs

In this section, we will present a new stamping method for fabricating the pixel-isolating wall structures using elastomeric polymer, PDMS. Fig. 4 shows the schematic illustration of procedures for fabricating our plastic LC device with the microtransfer molding method. The first step shown in Fig. 4 (a) is intended to produce a master structure using the photo-resist SU-8 through the photolithographic method. In the microtransfer molding method, the master structure has an inverse structure to the Fig. 2 (b). The liquid PDMS was dropped on the master substrate and the excess liquid PDMS was removed as shown in Fig. 4 (b). The PDMS wall structure produced by the patterned master structure could be effectively transferred to the covered bare ITO substrate by heating under pressure as shown in Figs. 4 (b) and (c). In our experiment, the heating condition for transferring and solidifying the PDMS structure was 100 °C for 10 min. The bottom substrate with the PDMS wall structures was prepared by peeling away the master substrate. Since PDMS provides very low interfacial free energy and it is chemically inert, the master

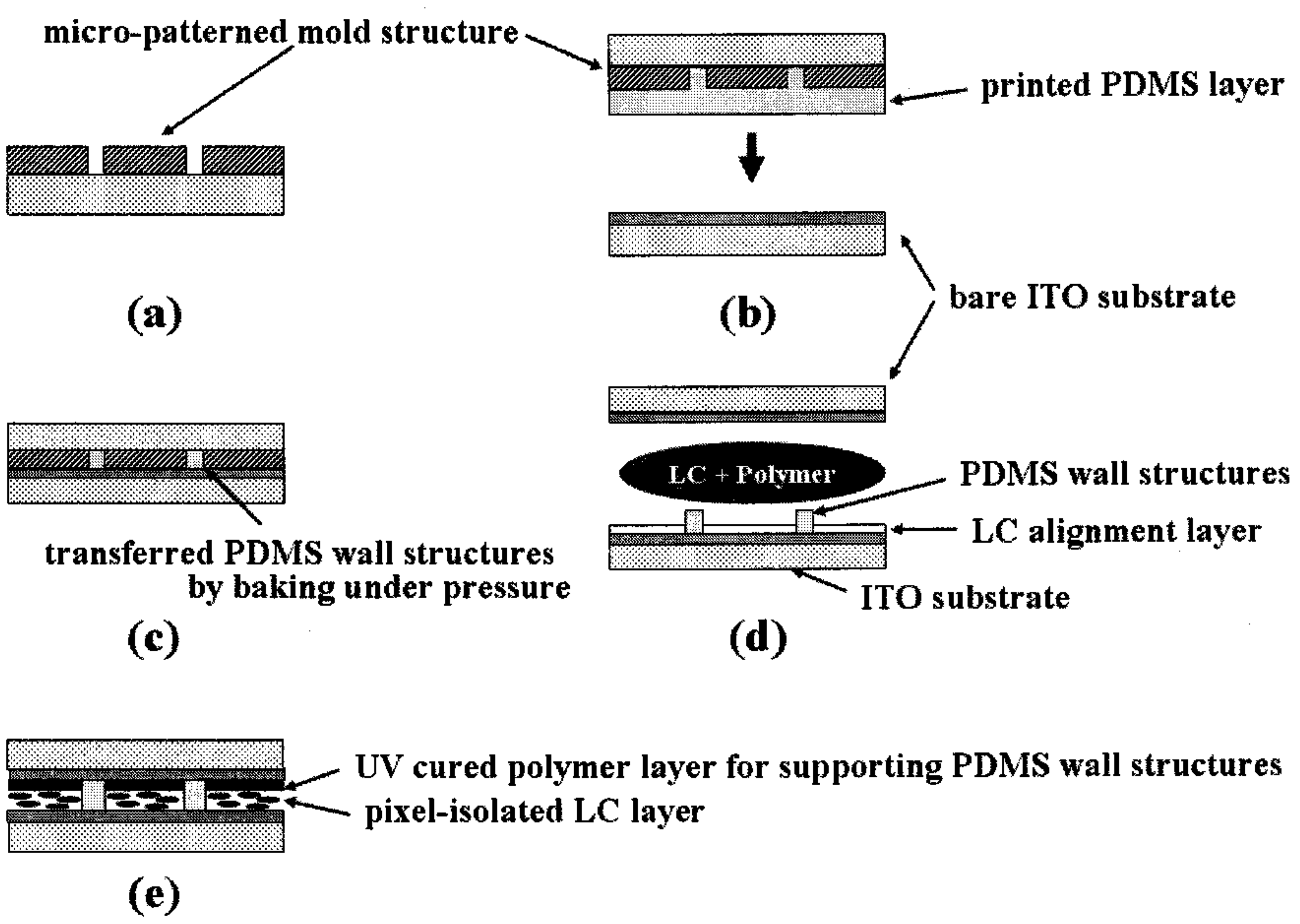
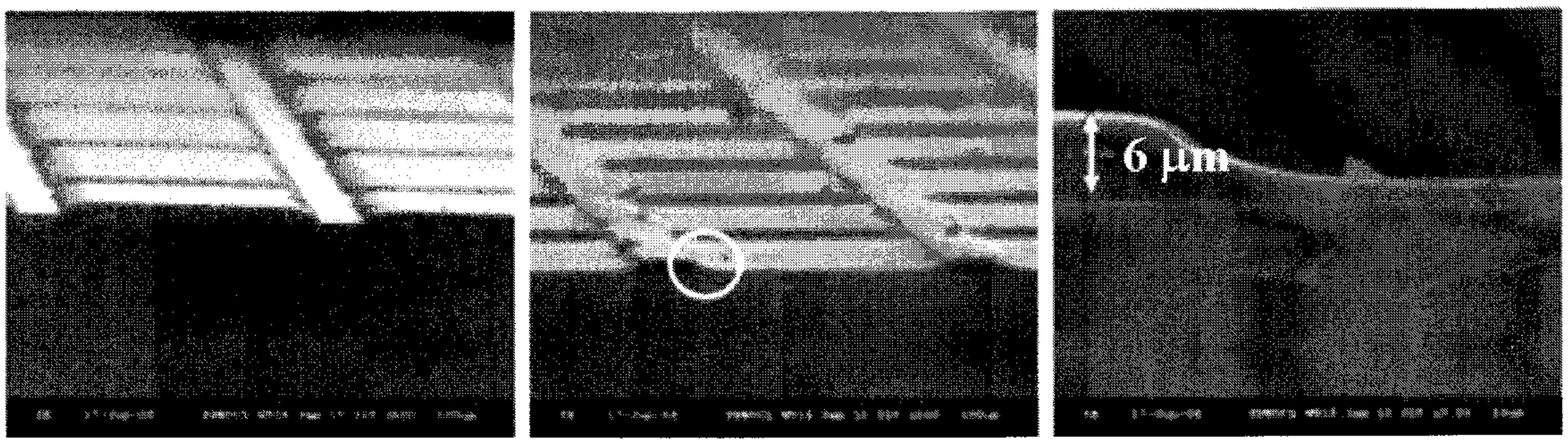


Fig. 4. The schematic illustration of the fabrication procedures with stamping method: (a) Formation of the micro-patterned master structure, (b) printing of the PDMS layer onto the master structure, (c) transfer of the PDMS wall structure onto the ITO coated substrate by baking under pressure, (d) formation of a LC alignment layer onto the micro-structured substrate, then dropping or injection of polymer/LC composite. The LC cell was prepared by sandwiching the other ITO substrate, and (e) the cross section of the pixel-isolated LC device whose substrates were firmly attached to each other by the UV cured polymer layer.



(a) (b) (c)

Fig. 5. The SEM images of the substrates : (a) The master structure of SU-8, (b) the wall structures of PDMS at the bottom substrate of Fig. 4 which are pattern-transferred from the master structure of (a), and (c) the cross section image magnified in the circular region in (b).

substrate can be easily detached without degradation of the micro-structure on both substrates [13]. Then, a homogeneous alignment layer was spin-coated on the prepared bottom substrate shown in Fig. 4 (d), and rubbed to promote uniform LC alignment. Due to the interfacial property of PDMS, the alignment layer was formed only onto the ITO surface. After the mechanical rubbing process, the PDMS walls maintained the original micro-patterned structures because the PDMS walls were firmly attached to the ITO surface and PDMS was very elastic material. Subsequent procedures shown in Figs. 4 (d) and (e) are similar to the methods described previously. Also in these procedures, the attachment property between the wall structures and the top substrate was supported by the phase-separated polymer layer with the polymer/LC composite.

Fig. 5 (a) shows the SEM images of the master structure of SU-8 with the size of 100 μm × 300 μm for the pixel area. The pattern-transferred PDMS structures are

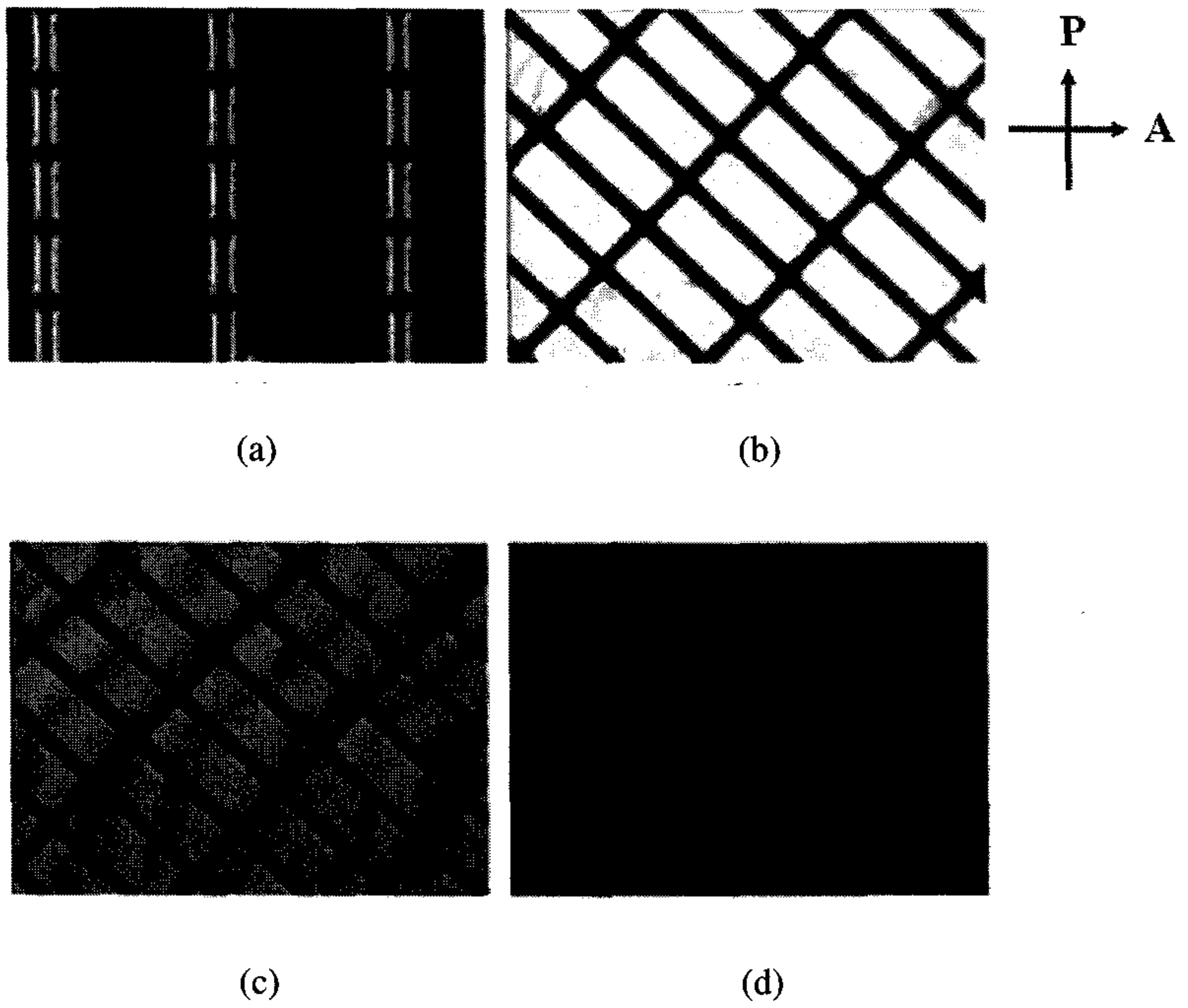


Fig. 6. The microscopic textures under the polarizing microscope: (a) was taken when the rubbing direction of the sample was parallel to one of the polarizers. (b), (c), and (d) were taken when the rubbing direction of the sample was rotated by 45° with respect to the polarizer in the presence of applied voltages by0 V,3 V, and 6 V, respectively.

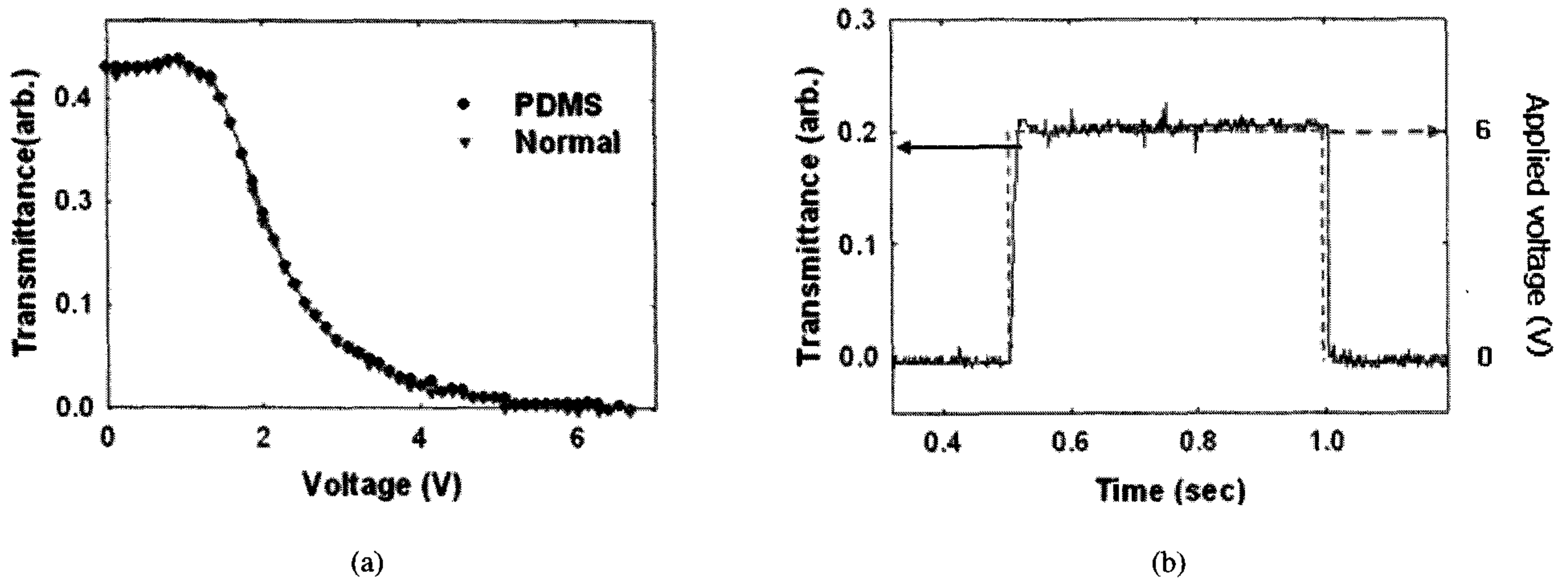


Fig. 7. The electro-optic (EO) properties of the plastic LCD: (a) The transmittance of the plastic LC device as a function of an applied voltage. For comparison, the EO property of a normal LC device was added. (b) The dynamic behavior of the plastic LC device in the presence of the unipolar square pulse with 6 V.

shown in Fig. 5 (b). Using our microtransfer method presented in this paper, we could successfully and repeatedly fabricate the micro-patterned wall structures which is almost the same with the result obtained by the conventional photolithographic method as shown in Fig. 2 (b). Fig. 5 (c) is the cross-section image near the PDMS wall structure magnified in the circular region as shown in Fig. 5 (b). The SEM image shows that the height of the wall structure in our cell was 6 μm.

The microscopic textures of our cell under the polarizing microscope are shown in Fig. 6. Fig. 6 (a) was taken when the rubbing direction of the bottom surface of the sample was parallel to one of the polarizers and Figs. 6 (b), (c), and (d) were taken when the rubbing direction was

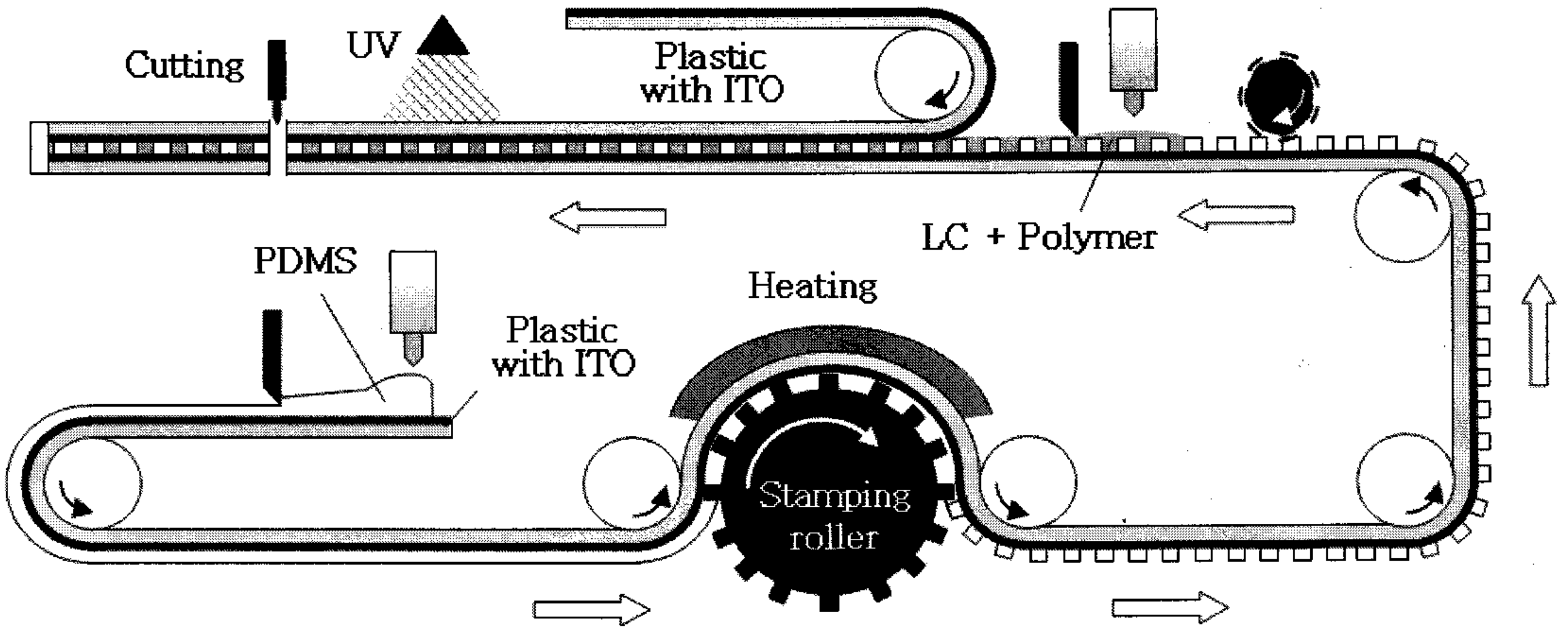


Fig. 8. The schematic diagram showing the continuous roll-to-roll process for fabricating the plastic LCDs with the methods presented here.

rotated by 45° with respect to the polarizer in the presence of applied voltages of 0 V, 3 V, and 6 V, respectively. The slight light leakage in Fig. 6 (a) implies that the PDMS wall surface has weak LC anchoring. However, the overall transmittance behavior in the pixel area was not observed in the whole range of applied voltages, as shown in Figs. 6 (b), (c), and (d).

Fig. 7 shows the EO properties of our plastic LC device. The transmittance of our cell as a function of the applied voltage between 0 V and 7 V showed the same behavior with that of normal LC sample. Thus, the proposed pixel-isolation method is easily applied to various types of plastic LC devices without having to modify the EO properties of the normal LC devices. The contrast ratio and the response time were about 100 : 1 and 27 ms, respectively, which are comparable to those of normal samples.

Fig. 8 shows the schematic diagram showing the continuous roll-to-roll process for fabricating plastic LCDs with the proposed methods in this paper. With the stamping roller, the micro-wall structures can be easily produced. In our demonstration, PDMS was used for the pixel-isolating wall structures. Further, PDMS can also be used for the master structures. After dropping polymer/LC composite onto the bottom substrate and assembling the top and bottom flexible substrates, the tight adhesion of two substrates can be achieved by the solidified polymer layer generated onto the top substrate by UV exposure.

4. Conclusion

We successfully fabricated plastic LCDs with the stamped polymer wall structure and the phase-separated polymer layer. The stable LC structure could be achieved by isolating LC molecules into the pixel surrounded by the micro-patterned PDMS wall structures. Using the interfacial properties of PDMS, such pixel-isolating wall structures could be fabricated onto one of the substrates easily and repeatedly with the same master substrate. The binding problem between two substrates in the conventional method was solved by the solidified polymer layer which can be uniformly produced using anisotropic phase separation from polymer/LC composite. Experimental results showed that our device had almost the same EO properties with those of normal LC modes without micro-wall structures. It is expected that our proposed methods can be applied for fabricating large size plastic LCDs with good mechanical stability as well as superior visibility through the cost-effective roll-to-roll processing.

References

[1] F. Matsumoto, T. Nagata, T. Miyabori, H. Tanaka, and S. Tsushima, in *SID '93 Digest* (1993), p. 965.

[2] J. L. West, M. Rouberol, J. J. Francl, J. W. Doane, and M. Pfeiffer, in *Proc. Asia Disp.* (1995), p. 55.

[3] R. Buerkle, R. Klette, E. Lueder, R. Bunz, and T. Kallfass, in *SID '97 Digest* (1997), p. 109.

[4] V. Vorflusev and S. Kumar, *Science,* **283**, 1903 (1999).

[5] Y. Kim, J. Francl, B. Taheri, and J. L. West, *Appl. Phys. Lett.,* **72**, 2253 (1998).

[6] J. L. Westm G. R. Novotny, M. R. Fisch, and D. Heinman, *J. Inform. Display,* **2**, 15 (2001).

[7] H. Sato, H. Fujikake, Y. Iino, M. Kawakita, and H. Kikuchi, *Jpn. J. Appl. Phys.,* **41**, 5302 (2002).

[8] J.-W. Jung, C.-J. Yu, S.-D. Lee, and J.-H. Kim, in *SID '04 Digest* (2004), p. 606.

[9] H. S. Kitzerow, H. Molsen, and G. Heppke, *Appl. Phys. Lett.,* **60**, 3093 (1992).

[10] T. Qian, J.-H. Kim, S. Kumar, and P. L. Taylor, *Phys. Rev. E,* **61**, 4007 (2000).

[11] J.-W. Jung and J.-H. Kim, *J. Inform. Display,* **3**, 4 (2002).

[12] J.-W. Jung, S.-K. Park, S.-B. Kwon, and J.-H. Kim, *J. Appl. Phys.,* **43**, 4269 (2004).

[13] Y. Xia and G. M. Whitesides, *Angew. Chem. Int. Ed.,* **37**, 550 (1998).