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Pixel-encapsulated flexible displays with a multifunctional elastomer substrate for self-aligning liquid crystals

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We report on a pixel-encapsulated flexible liquid crystal display (LCD) based on an elastomer substrate of self-aligning LC molecules. The elastomer substrate, fabricated by a replica molding technique, has pixel-encapsulating walls that serve as spacers and allow for mechanical stability and reproducibility against bending deformations. Our pixel-encapsulated LCD provides great flexibility, durability, and excellent electro-optic performances in a highly bent environment.
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Recently, flexible displays have attracted great attention due to many advantages such as lighter weight, better durability, and higher portability than existing displays. They have potential to open up future application areas of wearable computers, smart cards, and display systems in small packages for more freedoms in design. Several types of flexible displays using liquid crystals (LCs),[1–5] organic light emitting materials,[6,7] or electrophoretic materials[8] as active layers have been developed so far. Among them, the LC-based flexible displays are most promising since the relevant technologies have been quite well established in recent years. As for an example, a variety of approaches to mechanical stability of the LC layer through the formation of polymer walls or polymer networks[4,5,9,10] have been reported for flexible applications. However, they suffer from inevitable drawbacks that are not desirable for large size panel and mass production. For instance, the high image quality and uniformity in the electro-optic (EO) performances are not guaranteed due to anisotropic phase separation and nonuniform distribution of residual polymer.[9,10] Although alternative technologies have been suggested, most of them are complex and expensive to be employed for manufacturing commercial flexible displays. Therefore, a new technology having potential for less processes and cost reduction in fabrication is to be developed.

In this work, we report on a pixel-encapsulated (PE) flexible LCD with a multifunctional elastomer substrate in the vertically aligned configuration. The elastomer substrate, fabricated by a replica molding technique,[12–14] provides the vertical alignment (VA) for the LC molecules without any surface treatment, pixel-encapsulating walls to maintain the uniform cell gap as spacers as well as to prevent the LC flow in the bent state, and mechanical stability. From the fundamental viewpoint, the precise control of surface interactions between the elastomer substrate and the LC molecules allows for well-defined wall structures and the self-aligning capability. In principle, flexible LCDs require to replace conventional glass substrates by either plastic or other bendable substrates. Considering that typical plastic substrates have limited flexibility and durability, difficulty in processing, and the necessity of the surface treatment for the LC alignment, the multifunctional elastomer substrates may be a better class of promising candidates. It is found that our PE flexible LCD preserves well the EO performances in a highly bent environment.

We describe the fabrication process of a multifunctional elastomer substrate shown in Fig. 1. The elastomer substrate, used as a top substrate for our PE flexible LCD, was fabricated by a replica molding technique which can easily duplicate the information, such as the geometrical shape and morphology, stored in a master. The two-dimensional and three-dimensional structures fabricated through a single step process[12] were shown in Fig. 1. Using a photosensitive resin (SU-8) (Ref. 11) on a silicon wafer, we prepared the master with flexible microstructures that were used as pixel-encapsulating walls to maintain the uniform thickness of the LC layer and to prevent the LC flow against bend deformations. The elastomeric material, poly(dimethylsiloxane) (PDMS) (GE silicones),[12–15] was spin coated onto the master at the spinning rate of 1000 rpm for 120 s (giving the film thickness of $h=40\ \mu$m), and subsequently cured at 130 °C for 1 h. The cured PDMS was then peeled off from the master as shown in Fig. 1(a). Note that the PDMS material is homogeneous, optically isotropic and transparent, flexible, durable, and capable of aligning the LC vertically. An image

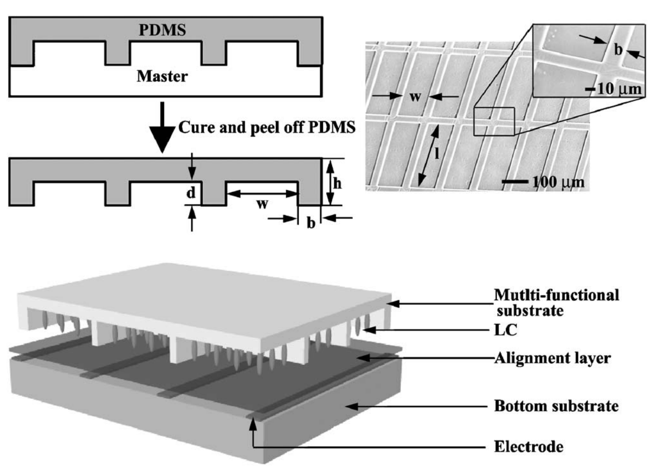

FIG. 1. A schematic process of fabricating a pixel-encapsulated flexible LCD having a multifunctional elastomer substrate: (a) an elastomer substrate fabricated by a replica molding technique, (b) the SEM image of the PDMS elastomer substrate duplicated from the master, and (c) the flexible LC cell with a multifunctional elastomer substrate used as the top substrate.

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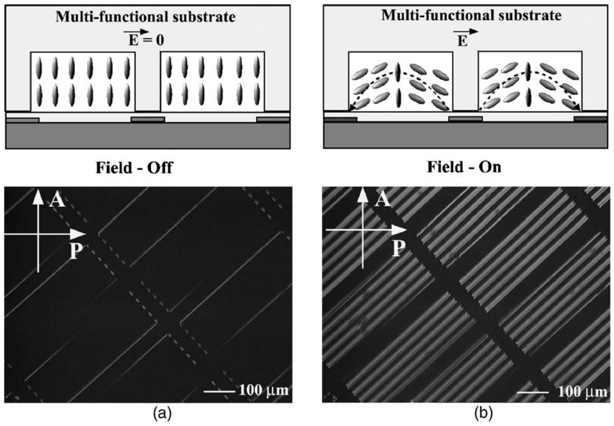

FIG. 2. The operation principle and microscopic textures of our pixel-encapsulated flexible LC cell with interdigital electrodes in the VA configuration: (a) under no applied voltage and (b) under the applied voltage of 8 V. The corresponding molecular orientations were depicted in (a) a dark state and (b) a bright state. The thick dashed arrow represents the electric field between two adjacent in-plane electrodes.

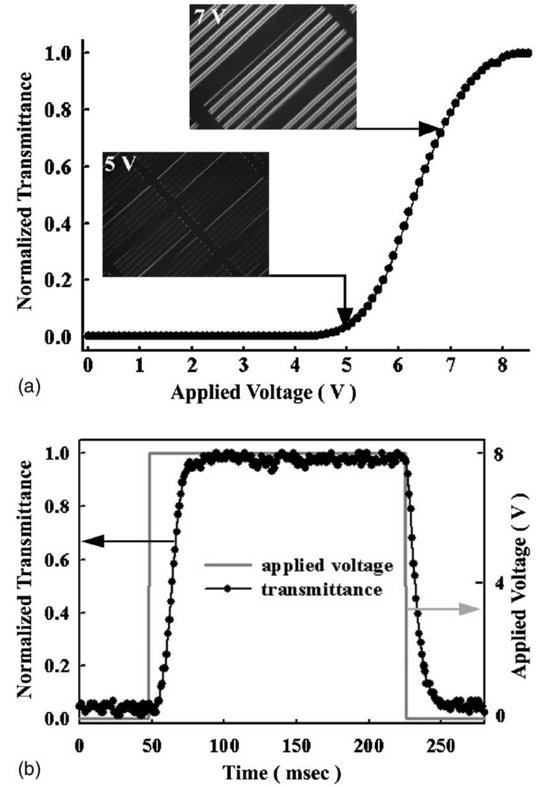

FIG. 3. The EO transmission and the response of our pixel-encapsulated flexible LC cell: (a) the normalized transmittance as a function of the applied voltage and (b) the rising and falling times, $\tau_{10-90}=16.3$ ms and $\tau_{90-10}=15.8$ ms, under the applied voltage of 8 V. The dark and gray lines represent the dynamic EO response and the applied voltage, respectively.

of a scanning electron microscope (SEM) of the multifunctional PDMS substrate was shown in Fig. 1(b). The physical dimensions of the width, the length, the height, and the interval of each pixel-encapsulating wall were $w=100$ μm, $l=300$ μm, $d=4.5$ μm, and $b=30$ μm, respectively. Our PE flexible LC cell, where one of the two substrates is a multifunctional substrate as a top substrate and the other is a polyethersulfone (PES) substrate as a bottom substrate, is schematically shown in Fig. 1(c). The aluminum layer of 1000 Å thick was prepared on the PES substrate by thermal evaporation and then patterned to produce interdigital electrodes with the width of 1 μm and the interval of 10 μm. The JALS 684 (Japan Synthetic Rubber Co.) was coated on the PES substrate for the VA alignment of the LC molecules. The LC material used in this study was ZLI 2293 (Merck) whose birefringence Δn and dielectric anisotropy $\Delta\epsilon$ are 0.1322 and 10, respectively. A square wave voltage at the frequency of 1 kHz was applied to the PE flexible LC cell to measure the EO transmission and the response times. The measurements were carried out at room temperature using a digitizing oscilloscope (TDS320, Tektronix) and a light source of a He–Ne laser with the wavelength of 632.8 nm.

Figure 2 shows the operation principle of our PE flexible LCD together with microscopic textures in the dark and bright states observed with a polarizing optical microscope (Optiphot2-pol, Nikon) under crossed polarizers. This is similar to the VA in-plane switching mode using a positive LC material.[16,17] The optic axes of the crossed polarizers were placed at an angle of 45° with respect to the direction of interdigital electrodes. As shown in Fig. 2(a), in the absence of an applied voltage, an excellent dark state was obtained under no applied voltage, indicating that the LC molecules were vertically aligned. This confirms that the PDMS elastomer substrate in Fig. 1(b) is indeed capable of aligning the LC molecules vertically irrespective of the presence of the pixel-encapsulating microstructures. Under the applied voltage of 8 V, the LC molecules were reoriented along the in-plane electric field, denoted by a thick dashed arrow in the upper diagram of Fig. 2(b), the light was transmitted through the PE flexible LC cell due to the phase retardation through the LC layer. The LC molecules undergo mostly bend distortions whose directions are symmetric to each other with respect to the midplane between two adjacent electrodes. This means that self-compensated two domains in the LC alignment was formed between two adjacent electrodes so that the viewing angle characteristics would be spontaneously enhanced.[18,19]

Figure 3 shows the normalized EO transmission and the response times of our PE flexible LC cell. As shown in Fig. 3(a), the EO transmission starts to appear at the threshold voltage of about 5 V and becomes to saturate above 8 V, giving analog gray scales. The contrast ratio between the dark state at 5 V and the bright state at 7 V was about 150:1, which is sufficient for many applications. The dynamic EO response times were shown in Fig. 3(b). The rising and falling times were found to be $\tau_{on}=16.3$ ms and $\tau_{off}=15.8$ ms, respectively. Note that the EO response of our PE flexible LC cell is much faster than that of other flexible display fabricated with the LC/polymer mixture.[10]

We now examine the EO stability of our PE flexible LC cell against external bend deformations. The test of the mechanical stability and the EO reproducibility of the flexible LC cell was carried out with a homemade equipment shown in Fig. 4(a) where the geometrical curvature was expressed as R on a translation stage. For the bend deformation of $R=6$ mm, microscopic textures of our flexible LC cell under no voltage and the voltage of 7 V were shown in Figs. 4(b) and 4(c), respectively. It is clear that no change in the microscopic textures was observed in the highly bent state. Since the PDMS elastomer substrate has a regular array of pixel-encapsulating walls, the LC flow was restricted and the EO characteristics were well preserved. Another interesting point is that our PE flexible LC cell was fully recovered from the

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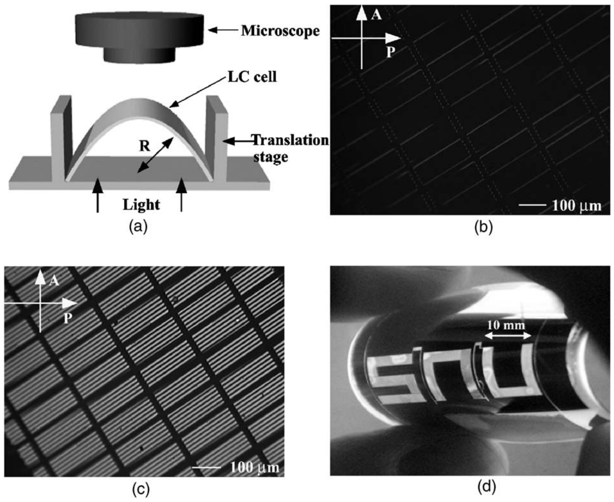

FIG. 4. Microscopic textures of our pixel-encapsulated flexible LC cell and a prototype of the flexible LCD panel with a logo of "SNU" under bend deformations: (a) a homemade equipment to measure the mechanical stability under the geometrical curvature of R, (b) a microscopic texture under no voltage for $R=6$ mm, (c) a microscopic texture under the voltage of 7 V for $R=6$ mm, and (d) a prototype flexible LCD panel of the size of 3×1.5 cm^2 in a direct driving scheme.

highly bent state without any damage because of the elasticity of the PDMS elastomer substrate, i.e., the completely reversible process of expansion and contraction. As a prototype, we fabricated a PE flexible LCD panel with a logo of "SNU" and presented the EO performances measured in a direct driving scheme in a bent environment. As shown in Fig. 4(d), the logo of SNU is well maintained even in the highly bent environment. It should be noted that a certain amount of the nonuniformity seen in the panel originates from a drop filling method used and can be removed by a more elaborate filling technique.

In summary, we presented a pixel-encapsulated flexible LCD with a multifunctional elastomer substrate fabricated by a replica molding technique which is rather simple and cost effective. It should be emphasized that the surface interactions of the PDMS elastomer substrate are well preserved and thus the LC EO effect is fully recovered from even a highly bent state. Our flexible LCD provides great stability and reproducibility, durability, and excellent EO performances under mechanical deformations. 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. The flexible LCD technology presented here would open up an opportunity of developing next-generation display systems.

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[1]J. P. A. Vogels, S. I. Klink, R. Penterman, H. D. Koning, and E. E. A. Huitema, SID Int. Symp. Digest Tech. Papers **35**, 767 (2004).
[2]D.-W. Kim, C.-J. Yu, Y.-W. Lim, J.-H. Na, and S.-D. Lee, Appl. Phys. Lett. **87**, 051917 (2005).
[3]I. Shiyanovskaya, A. Khan, S. Green, G. Magyar, and J. W. Doane, SID Int. Symp. Digest Tech. Papers **36**, 1556 (2005).
[4]H. Sato, H. Fujikake, Y. Iino, M. Kawakita, and H. Kikuchi, Jpn. J. Appl. Phys., Part 1 **41**, 5302 (2002).
[5]H. Sato, H. Fujikake, H. Kikuchi, and T. Kurita, Jpn. J. Appl. Phys., Part 2 **42**, L476 (2003).
[6]Y. Li, L.-W. Tan, X.-T. Hao, K. S. Ong, F. Zhu, and L.-S. Hung, Appl. Phys. Lett. **86**, 153508 (2005).
[7]A. N. Krasnov, Appl. Phys. Lett. **80**, 3853 (2002).
[8]A. Henzen, N. Ailenei, F. V. Reeth, G. Vansichem, R. W. Zehner, and K. Amundson, SID Int. Symp. Digest Tech. Papers **35**, 1070 (2004).
[9]V. Vorflusev and Satyendra Kumar, Science **283**, 1903 (1999).
[10]R. Penterman, S. I. Klink, H. delKoning, G. Nisato, and D. J. Broer, Nature (London) **417**, 55 (2002).
[11]J. C. Galas, B. Belier, A. Aassime, J. Palomo, D. Bouville, and J. Aubert, J. Visual Commun. Image Represent **22**, 1160 (2004).
[12]Y. Xia and G. M. Whitesides, Angew. Chem., Int. Ed. **37**, 550 (1998).
[13]C. M. Knobler, Nature (London) **369**, 15 (1994).
[14]M. Geissler and Y. Xia, Adv. Mater. (Weinheim, Ger.) **16**, 1249 (2004).
[15]W. M. Choi and O. O. Park, Microelectron. Eng. **70**, 131 (2003).
[16]S. H. Lee, H. Y. Kim, T. K. Jung, I. C. Park, Y. H. Lee, B. G. Rho, J. S. Park, and H. S. Park, *Proceedings of The Fourth International Display Workshop* (Society for Information Display, Nagoya, Japan, 1997), p. 97.
[17]K. H. Kim, S. B. Park, J.-U. Shim, J. Chen, and J. H. Souk, *Proceedings of The Fourth International Display Workshop* (Society for Information Display, Nagoya, Japan, 1997), p. 175.
[18]W. Liu, J. Kelly, and J. Chen, Jpn. J. Appl. Phys., Part 1 **38**, 2779 (1999).
[19]S. H. Hong, Y. H. Jeong, H. Y. Kim, H. M. Cho, W. G. Lee, and S. H. Lee, J. Appl. Phys. **87**, 8259 (2000).

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