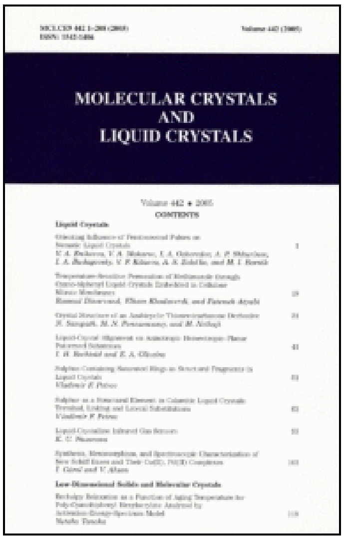

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Fabrication of Single Substrate Flexible Twisted Nematic LC Cell Using a Photo-Polymer Cover Film

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A single substrate flexible display was fabricated by laminating a thin cover film of UV curable photo-polymer on the plastic bottom substrate. The micro-walls of photoresist on the bottom substrate are tightly bound with the cover film to provide the solid mechanical support for preserving the molecular alignment of liquid crystals (LCs). The ability of aligning LCs is induced by rubbed alignment layer on the bottom substrate and micro-grooves formed on the photo-polymer film. We demonstrated a twisted nematic LC mode on the plastic substrate with in-plane switching electrode. The fabrication process and electro-optical characteristic of the device are described.

Keywords: flexible display; lamination; photo-polymer; single substrate LCD; twisted nematic LC mode

INTRODUCTION

For the upcoming ubiquitous environment, the flexible display is one of the most attractive devices due to several advantages such as

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flexibility, durability and portability [1]. The application range of flexible display is very wide from the mobile applications such as cellular phone and personal digital assistant to the new-concept devices like electronic-paper and electronic book. Among the competing technologies for fabricating the flexible display, the liquid crystal displays (LCDs) with plastic substrate are focused due to their various merits, for example, full-color realization, well-established fabrication, higher contrast ratio and good electro-optical characteristics [2–4]. One of the advantages of plastic LCD is that the cost effective roll-to-roll process can be adopted during fabrication. In order to achieve such merit, we should eliminate the one substrate for continuous printing process. Several researches on the plastic LCD with a single substrate are carried out so far [5–7]. However, the cumbersome fabrication and the weak mechanical stability of the device due to the lack of supporting structure for stable LC alignment or weak bonding of the cover layer should be solved to exhibit the fine performances for the practical applications.

In this work, we proposed a simple fabrication method of flexible liquid crystal (LC) cell with enhanced mechanical stability by laminating the photo-polymer cover film which has a high elongation property and strong adhesion ability, simultaneously. The photo-polymer cover film with the micro-groove structure has the ability of aligning LC molecules and tightly attached to the micro-wall structure of bottom plastic substrate. The tight bonding between the cover film and the bottom walls can be obtained by simply irradiating the UV since the photo-polymer has the adhesive property by itself. We demonstrated the conventional twisted nematic (TN) LC structure [8] to show the ability of LC alignment at the cover film. The proposed method can realize the plastic LCD with high mechanical stability and is applicable to the roll-to-roll process.

EXPERIMENTAL

Figure 1 shows the fabrication process of the UV curable photo-polymer cover film with the micro-grooves on the elastomeric supporting layer. In the first steps of fabrication, we spin-coated a poly-dimethysiloxane (PDMS) from GE silicon uniformly on the flat rigid glass substrate. The PDMS was used as the supporting layer due to its good elastic property, fine mechanical and chemical stability proved by the wide usages in the soft-lithography, which is necessary for lamination process. However, the photo-polymer can not be simply coated on the PDMS layer due to the high hydrophobicity of the PDMS. After having the O_2 plasma treatment for inducing a hydrophilic property to the PDMS

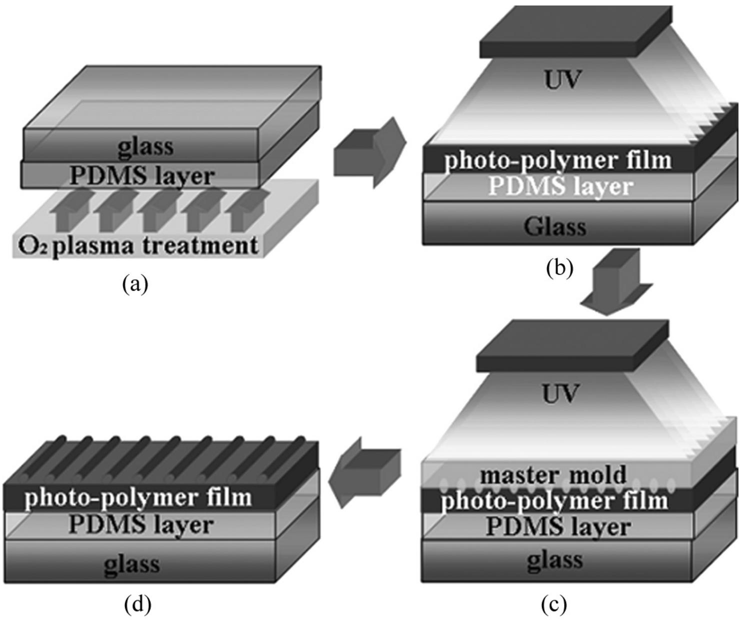

FIGURE 1 The schematic diagram for the fabrication of the UV curable photo-polymer cover film on the supporting layer. (a) O_2 plasma treatment on the spin-coated PDMS layer (b) Spin-coating and partial UV curing of photo-polymer film (c) Stamping of master mold on the photo-polymer film and UV curing (d) Resultant structure of photo-polymer with micro-grooves.

surface, a thin photo-polymer film can be formed uniformly as shown in Figure 1(a). In our experiments, NOA68 from Norland Products was used as the cover film due to its excellent flexibility and chemical durability. We irradiated the UV in a short time to reduce the liquidity of NOA68 film at the initial pre-polymerization step as described in Figure 1(b). The pre-designed master mold of PDMS which is prepared by conventional stamping method in the soft-lithography [9] was imprinted on this partially cured NOA68 film to form the micro-grooves on the cover film (Fig. 1(c)). The micro-groove structure of the master mold in this work has the pitch of 4 μm and the height of 1 μm. The master mold can be easily detached after stamping due to its low surface energy. After imprinting the micro-grooves to the cover film, UV was irradiated to stabilize the photo-polymer without exceeding the dosage for sustaining the pre-curing condition. Since the adhesion properties of the cover film are different at the upper interface (master mold-cover film) and the lower interface (cover film-supporting layer), the master mold can be removed easily without damaging the cover film (Fig. 1(d)).

Figure 2 shows the fabrication process of the single substrate LCD we proposed. In the bottom plastic substrate, a transparent electrode of indium-tin-oxide (ITO) was patterned by the photo-lithographic process to induce the in-plane electric field. The width and interval of the electrode are 10 μm and 30 μm, respectively. We spin-coated the homogeneous alignment layer (AL3046 from JSR) on the bottom substrate and rubbed to the direction which is parallel to the polymer walls for the LC anchoring. The periodic walls of photoresist were sequentially formed by the photo-lithography as the supporting structure of the device. The height (i.e., the cell gap of the device) and width of the micro-walls are 6 μm and 30 μm, respectively, and the distance between walls is 100 μm. Polycarbonate was used as the plastic substrate and the micro-walls were formed by the conventional photoresist (SU-8 from MicroChem. Co.). The photo-polymer film on the

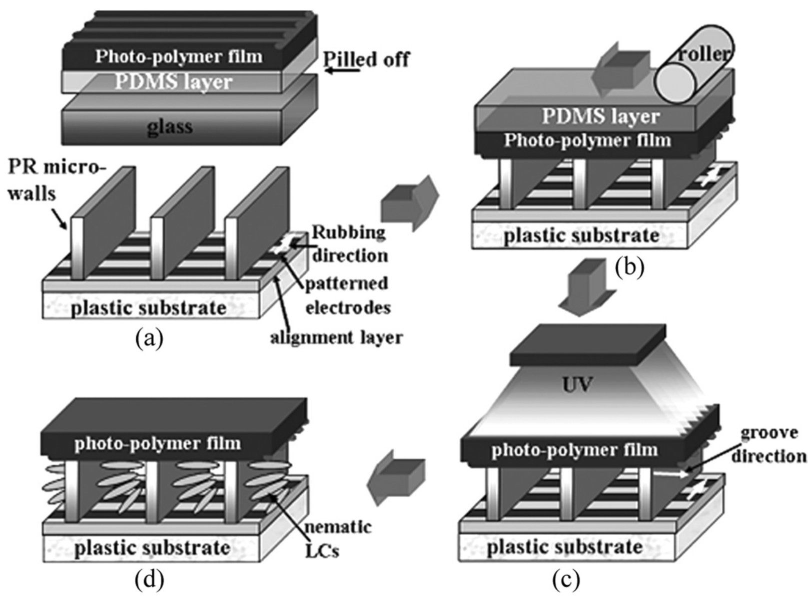

FIGURE 2 Fabrication of the proposed plastic LCD with a single substrate by laminating the cover film. (a) Preparation of the photo-polymer film and the bottom plastic substrate with polymer walls (b) Laminating process by soft roller (c) UV irradiation for solidification and tight bonding of cover film after removing the PDMS layer (d) LC injection and resultant single substrate flexible TN LC cell.

PDMS layer prepared in the previous step was pilled off from the glass and then was laminated on the micro-walls by the roller (Fig. 2(b)). In this work, the direction of the micro-grooves sets to be perpendicular to the rubbing direction of the bottom substrate for TN LC mode. After detaching the PDMS layer from the photo-polymer cover film, UV is irradiated for fully cured structure as shown in Figure 2(c). In final, we injected commercial nematic LC of ZLI-3950 from Merck ($\Delta n = 0.137$, $\Delta\varepsilon = +6.4$) by capillary action. The resultant TN LC structure with a single substrate is illustrated in Figure 2(d). The thickness of cover film was measured as 30 μm by observing the cross-sectional image using scanning electric microscope.

RESULTS AND DISCUSSION

Figure 3(a) shows the polarizing microscopic texture of our single substrate sample in initial state. The LC molecules are twisted as 90° and rotate the incident linearly polarized light to exhibit a maximum transmittance under crossed-polarizers. Transparent electrodes of ITO are placed perpendicular to rubbing direction of the bottom substrate to apply an in-plane electric field for switching LCs. The direction of micro-grooves is perpendicular to the micro-walls as shown in the figure. On the PR micro-walls, there was no light leakage, which proves that there was no infiltration of LCs in those areas during LC injecting and the photo-polymer cover film was strongly attached to the micro-walls. The pitch and depth of the micro-groove structure are clearly observed in Figure 3(b) and

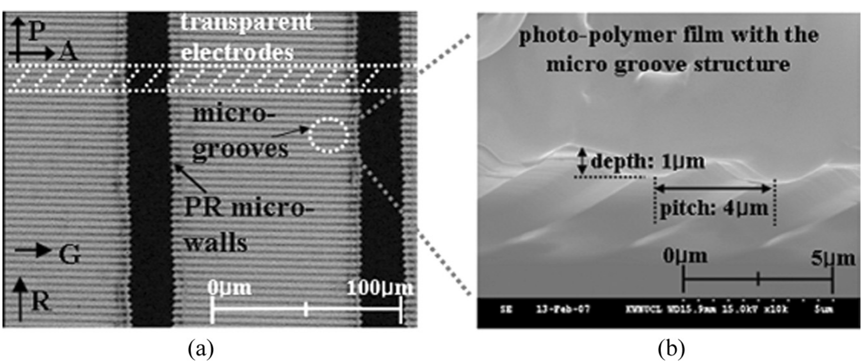

FIGURE 3 (a) The polarizing microscopic texture of proposed sample (b) Cross-sectional images of the photo-polymer cover film with micro-grooves using FESEM.

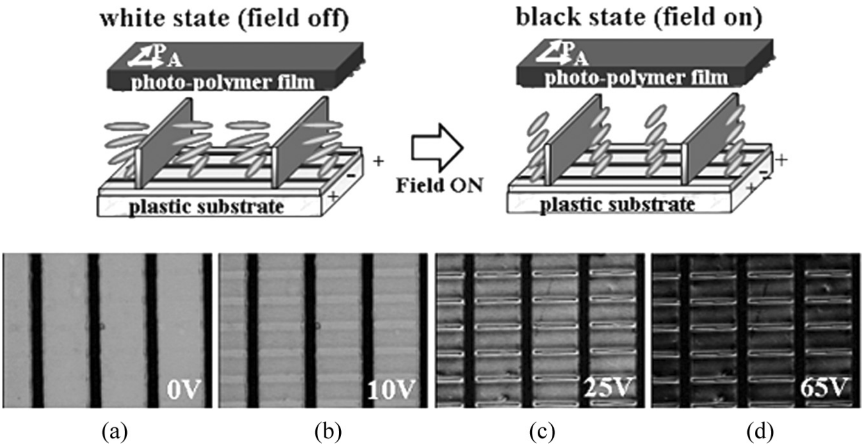

FIGURE 4 Schematic illustration of LC alignment during the driving and the microscopic images under crossed polarizers at applied voltages of (a) 0 V, (b) 10 V, (c) 25 V, and (d) 65 V.

measured as 4 μm and 1 μm, respectively. This is well matched to the specification of used master mold.

Figure 4 shows the schematic illustration of driving and the resultant microscopic images observed with a polarizing microscope under crossed polarizer by varying an applied voltage. A maximum bright state is achieved at no applied voltage due to the wave guiding effect of TN structure [8] as shown in Figure 4(a). As we increased the applied in-plane field, LC molecules are aligned parallel to the field due to the positive anisotropy of dielectric constant, and in final, homogeneously aligned LC structure can be obtained as depicted in the figure [11]. The microscopic textures of Figures 4(b)–(d) show the change of the transmittance in our sample at 10 V, 25 V, and 65 V, respectively. On the transparent electrode, the light leakages are inevitable since there are no in-plane fields. It can be reduced by adjusting the patterning size of electrodes. Note that small dark areas on the transparent electrodes are observed in the figure. It is believed that this comes from the homeotropic alignment of LCs induced by the vertical fringe field over applied voltage of 25 V and could help to increase the contrast ratio of the device with an appropriate design of electrode structure.

Electro-optical characteristics of our single substrate LCD are measured in Figure 5. The transmittance of an initial white state is gradually diminished as we increase the applied in-plain field and is saturated after applying 40 V as shown in Figure 5(a). The threshold

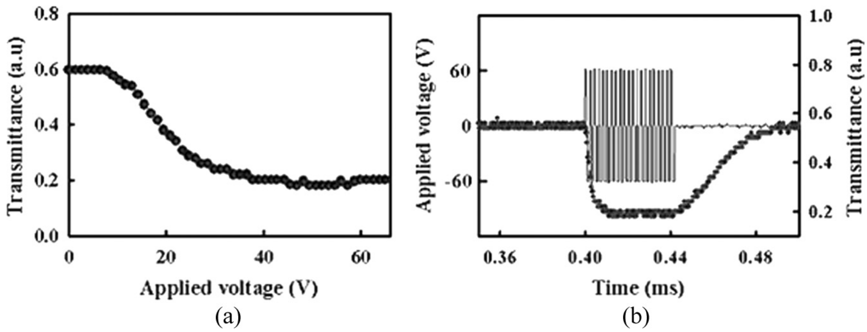

FIGURE 5 (a) Transmittance vs applied voltage curve and (b) the response time of proposed structure.

voltage and contrast ratio of our sample are measured about 6 V and 3:1, respectively. However, this small value of the contrast ratio and rather high driving voltage can be improved by optimizing the design parameters of in-plane switching electrode and using an appropriate black matrix. The response time of white to dark state and dark to white state are measured 8.3 ms and 32 ms, respectively.

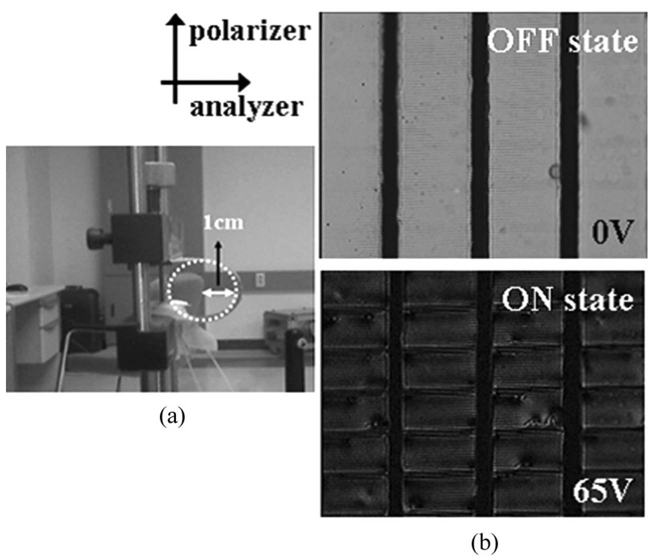

FIGURE 6 (a) Experimental setup for measuring the mechanical stability of the device (b) Microscopic images of the experimental sample under the bending conditions of $R = 1\,\text{cm}$.

Finally, we discuss the mechanical stability of our flexible single substrate LCD under a highly bent condition. The experimental setup for bending test is shown in Figure 6(a). The smaller radius of the curvature (R) represents the higher external bending condition. The experimental sample bears the distortion of $R = 1\,\text{cm}$ and the optical characteristics of the sample at this bending condition are almost similar to that of the unbent case. The microscopic textures at 0 V and 65 V in Figure 6(b) show the good extinction of the sample even under highly bent environment. Thus, it is verified that our fabrication technique of single substrate LCD can maintain the stable LC alignment under external distortions.

CONCLUSIONS

We have demonstrated a single substrate flexible TN LC cell by laminating the thin cover film of photo-polymer with micro-grooves on the micro-walls of the bottom plastic substrate. The electro-optic characteristics of proposed structure are stable under the high bending conditions. The fabricating method proposed in this work is very simple and applicable for the cost effective roll-to-roll process for the printable display. This single substrate plastic LCD is expected to play a critical role in the flexible display technology in ubiquitous environment.

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