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### Application to Mechanically Stable Flexible Liquid Crystal Displays Using Surface Induced Anisotropic Phase Separation

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## Application to Mechanically Stable Flexible Liquid Crystal Displays Using Surface Induced Anisotropic Phase Separation

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*We investigated the effect of surface wetting on the 2-dimensional anisotropic phase separation. The surface conditions were spatially modulated by laminating several types of alignment materials on the ITO substrate in a periodic square pattern using micro-contact printing methods. 2-dimensional phase separation was obtained without/with UV irradiation and the relative wettability of LC and polymer on alignment layer and ITO surface determined the diffusion direction of each material during phase separation. Furthermore the polymerized wall structures are different for different LC monomer mixing ratio. This technology can be applied to flexible liquid displays.*

**Keywords:** flexible LCD; liquid crystal and polymer composite; phase separation; surface wetting property

## INTRODUCTION

Liquid crystal (LC) devices with plastic substrates have drawn much attention for the applications such as mobile phone, PDA, smart card, e-paper and head-mount displays because of their light-weight, thin

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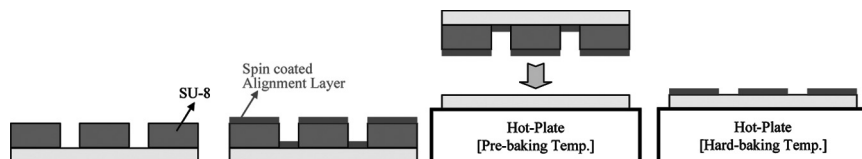
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packaging and flexibility [1–3]. The flexibility of substrates in plastic LC devices requires a stabilization of liquid crystal mode, mechanical stability and adhesion of two substrates. There have been wide studying to solve such problems by introducing the phase separation of polymer-LC mixture such as polymer dispersed liquid crystal, polymer network liquid crystal and pixel isolated liquid crystal mode (PILC) [4,5]. Among them pixel isolation structure using phase separation of polymer-LC mixture shows great possibility in performance such as novel electro-optic property, good mechanical stability and adhesion of two substrates.

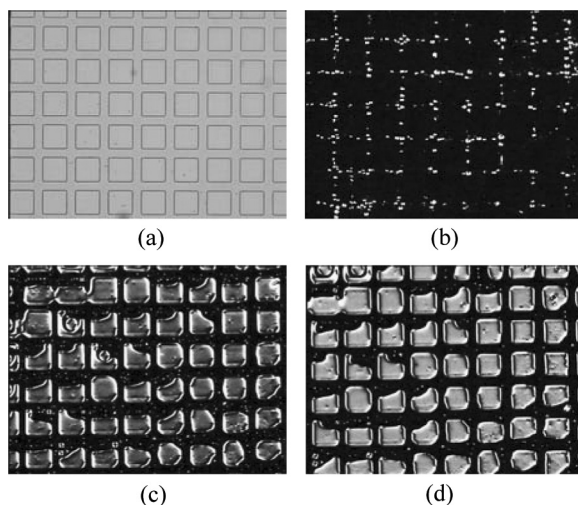
In previous work, we reported the fabrication of PILC mode using the method of UV irradiation through patterned photo-mask to form polymer wall structure. In this fabrication, the remained uncured monomers in an LC area were separated by successive weak UV exposure to form phase separated thin films on one side of substrate surface. Recently, the possibility of minimization of uncured monomers in an LC was reported by phase separation of polymer and liquid crystal mixture controlled by surface wetting properties [6]. By patterning the alignment layer periodically, the polymer rich- and LC rich-regions were also separated periodically. In this work we studied the phase separation morphology with different mixing ratio of liquid crystal and polymer.

## EXPERIMENTAL

ITO-coated glass substrates were used in this experiments. The LC and polymer used were nematic MLC6610 (negative dielectric anisotropy) and photocurable NOA65 (Norland co.). The alignment material was JALS684 (vertical alignment). Alignment layer was spin coated on one of the glass substrates and patterned periodically on the other substrate by using micro-contact printing method. Figure 1 shows the schematic diagram of fabrication process. The size of square pattern is  $100\ \mu\text{m} \times 100\ \mu\text{m}$  with  $40\ \mu\text{m}$  spacing. Two glass substrates



**FIGURE 1** Schematic diagram of the fabrication process using micro-contact method.

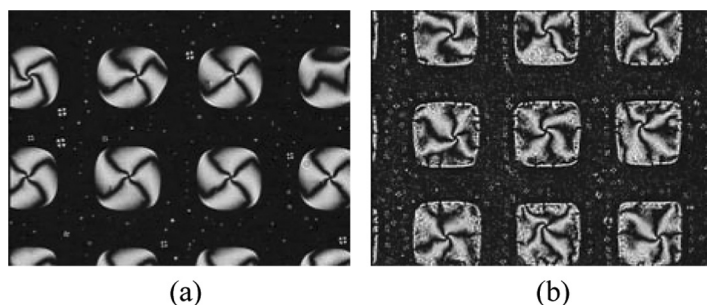


**FIGURE 2** Optical microscopic textures of lateral phase separation. (a) JALS684 pattern on ITO glass substrate, (b) after filling the LC and polymer mixture, (c) after 4 hour at 4 V applied and (d) after 1 day at 4 V applied.

were assembled and cell gap was maintained by  $4.7\mu\text{m}$  using glass spacers. LC and polymer mixture was introduced by capillary action at a temperature higher than the clearing point of LC and cooled down slowly to room temperature. After cooling, the samples were remains during several days to obtain phase separation of liquid crystal and polymer. Figure 2 shows the change of polarizing microscopic textures according to time. After that, the cells were exposed to UV light of  $\lambda = 350\text{ nm}$  to initiate polymerization. The source of UV light was a Mercury-Xenon lamp operated at 1000 W of electrical power and UV intensity was about  $100\text{ mW/cm}^2$ .

## RESULTS AND DISCUSSION

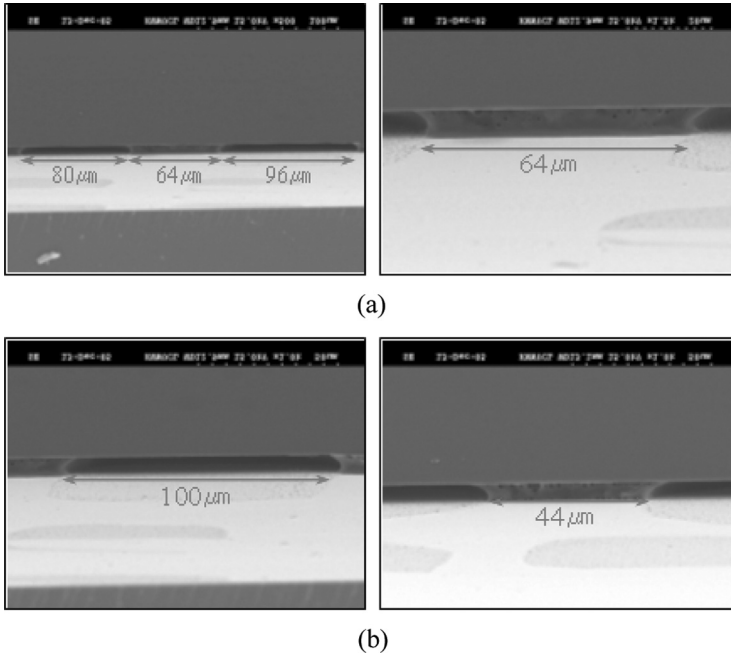
Figure 2 shows the evolution from just after filling the mixture with 60% LC concentration. We can see that the boundary between LC-rich and monomer rich region becomes more clear with time. Because we used LC with negative dielectric anisotropy and vertical alignment material, we applied electric field to observe clearly as shown in Figures 2(c) and (d). The homogenous textures originated from rubbing alignment layer. Figure 3 shows the polarizing microscopic images before and after UV irradiation on the mixture of monomer and LC with the mixing ratio of LC 50%. In this case, we did not



**FIGURE 3** Optical microscopic images (a) before and (b) after UV irradiation with the mixing ratio of 5:5.

rub the alignment layer and we can see disclinations in the LC rich area from Figure 3(a) unlike Figure 2. After curing monomers by UV irradiation, there remains solidified polymers in the LC rich region as shown in Figure 3(b). And the width of polymer wall is larger than the spacing of square pattern of alignment layer. We compared the structure of polymer walls for the two mixing ratio 5:5 and 6:4 by scanning electron microscopic images in Figure 4. The width of polymer wall of 5:5 mixing ratio is larger than that of 6:4 mixing ratio. There are two possible ways when there are two different mixing ratio. One is enlarging of wall width as shown in Figure 4. The other is increasing of LC concentration in LC rich region and polymer walls are almost coincide with square pattern. Let's consider the phase separation and its morphology briefly.

The binary mixture system of liquid crystal and polymer shows a phase diagram with upper critical solution temperature (UCST) [7]. Below isotropic mixing temperature, there occurs spontaneous phase separation and the characteristic length scale (droplet size) increases depending on temperature and time. Typically, the droplet size in polymer dispersed liquid crystal or spinodal decomposition is a few microns. But in this case of surface induced phase separation, the separation length scale is enlarged to a few hundred microns (the pattern size). This can be understood as follow. When the droplet size approaches the cell gap, the thickness of wetting layer of LC or monomers also increases nearly up to the cell gap [8,9]. Hence the system shows macroscopic scale of phase separation. The concentration current and equilibrium concentration of LC in LC rich is related to relative wetting difference of LC and polymer on ITO and alignment surface. We denote it simply as surface potential. The surface potential which represents the degree of difference of surface wetting is



**FIGURE 4** Cross sectional images of scanning electron microscopy for (a) LC: monomer = 5:5 mixing ratio and (b) 6:4.

given by

$$V = \begin{aligned} &h/2 \quad (\text{surface A}) \\ &-h/2 \quad (\text{surface B}) \end{aligned}$$

where  $h = \gamma_{LC\_align} - \gamma_{pol\_align} - (\gamma_{LC\_ITO} - \gamma_{pol\_ITO})$  is the relative difference of surface tension of LC and polymer on alignment layer and ITO. Here  $\gamma_{A,B}$  means surface tension of A on surface B. The amount and sign of  $h$  determine the LC rich area and concentration flow across the pattern boundary. The sign of  $h$  is negative, the alignment area becomes LC rich area and vice versa. Typically, below the isotropic mixing temperature, the LC concentration in LC rich region and in polymer rich region is function of temperature. If  $h$  is small, then patterned surface plays a role of determining of LC rich region (or polymer rich are). In this case, for the different mixing ratio of LC and polymer mixture, the area of LC rich region will be different. But if  $h$  is relatively large, the concentration flow across the pattern boundary is large enough to break the bulk equilibrium concentration in LC

rich region (also in polymer rich region). Therefore in this case, the separation boundary will almost coincide with pattern boundary. Our experimental results indicated small  $h$  value of surface potential. Hence in this case, the choice of suitable mixing ratio is important to obtain same boundary between pattern and phase separation.

Our method can be applied to fabrication of flexible LCDs. By irradiation of UV light, the solidified polymers acts as supporting structure of LC molecules when using plastic substrate. Moreover the two plastic substrates are tightly attached via polymer walls.

## CONCLUSIONS

We studied the anisotropic phase separation of liquid crystal and polymer composite on patterned alignment layers. Because of differences of surface wetting in each patterned region, as the temperature is slowly cooled down, the LC rich- and polymer rich-regions were separated. We studied the effect of mixing ratio and qualitatively analyzed the polymer wall morphology after UV irradiation. In our experimental case such as small surface potential parameter  $h$ , the choice of suitable mixing ratio was important in obtaining polymer wall boundary according to pattern boundary. These separation structures can provide the solution of some problems underlying in application of flexible liquid crystal display using plastic substrates. This technology also can be applied to optical devices such as optical gratings.

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