

# Time-Sequential Ultraviolet Exposure to Alignment Layers Embedded With Reactive Mesogen for High-Speed In-Plane Switching Liquid Crystal Cell

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**Abstract**—We propose a time-sequential ultraviolet (UV) exposure process that can improve the surface anchoring energy of photopolyimide (PI) embedded with reactive mesogen (RM) in high-speed liquid crystal (LC) display devices. To increase the anchoring energy of the PI layer, a separated UV exposure process of polymerization for the embedded RM material and PI layer is required [1]–[8]. In this paper, we propose a novel single-frequency UV exposure method that can perform the separated polymerization of the UV alignment layer and the embedded RM material by optimizing the intensity of the exposure UV light. Using the proposed UV exposure method, we polymerize the RM material during the first 4 s, and then accomplish the polymerization of the UV alignment layer sequentially. To demonstrate the electro-optical performance, we measure the surface anchoring energy and the optical response time of in-plane switching LC cell. The measured results show that the surface anchoring energy and the optical response time are improved by more than 2.5 times and 28.2%, respectively, compared with the conventional UV exposure.

**Index Terms**—In-plane switching (IPS), liquid crystal, reactive mesogen (RM), response time, surface anchoring energy, ultraviolet (UV) exposure.

## I. INTRODUCTION

OVER the past 20 years, the technologies of liquid crystal displays (LCDs) have been rapidly developed toward high display quality, such as wide viewing angles, small color shifts, and high contrast ratios [9]–[13]. Despite the development of LC technologies, studies of the advanced technologies of LCD devices are still needed to maintain

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competition superiority compared with other display devices, e.g., organic light emitting diode displays.

The major optical disadvantage of LCDs is slow response time despite the development of various LC modes, e.g., in-plane switching (IPS) [9], [14], [15], vertical alignment [10], [16], [17], and fringe-field switching [18], [19]. The slow speed property can induce motion blur, color breakup, and crosstalk in applications for virtual 3-D images.

In general, the optical response time of LCDs is defined as the sum of the rising time ( $\tau_{\text{ON}}$ ) and falling time ( $\tau_{\text{OFF}}$ ). However, such as current display devices, the falling time is more important than the rising time, because the falling time of LC response is only dependent on LC material properties. On the contrary, the rising time can be simply enhanced by increasing the applied voltage. The response time of the IPS LC mode, which is widely used in display applications because of wide viewing angles, can be calculated using [20]

$$\tau_{\text{ON}} = \frac{\gamma}{|\varepsilon_0 \Delta \varepsilon| E^2 - \frac{2W}{d}} \quad (1-a)$$

$$\tau_{\text{OFF}} = \frac{\gamma d}{\left(\frac{Wd}{K_{22}} + 2\right) W} \approx \frac{\gamma d}{2W} \quad (1-b)$$

where  $\gamma$  is the rotational viscosity,  $K_{22}$  represents the twist elastic constant,  $\varepsilon_0 \Delta \varepsilon E^2$  is the electric field energy density,  $\Delta \varepsilon$  is the LC dielectric anisotropy,  $d$  is the cell gap of the LC layer, and  $W$  is the surface anchoring energy.

As shown in (1), a high surface anchoring energy, low cell gap, and small viscosity of the LC material lead to a fast response time. To achieve high surface anchoring energy of LC cells, several important alignment processes have been studied [1]–[4]. For high surface anchoring energy, reactive mesogens (RMs), which are polymerizable LCs, are used in typical photopolyimide (PI) layers. The RMs mixed with a photoinitiator can provide a rigid polymer network by interconnecting the molecules with the PI material under ultraviolet (UV) exposure. Consequently, the crosslinked polymer chains between the PI and the RMs can effectively improve the surface anchoring power of typical PI layers. However, the recent alignment technology of LCD devices has rapidly changed to the UV exposure method, which is a representative of the noncontact type, instead of the mechanical rubbing

process, because of the simple process, good uniformity, and, especially, excellent contrast ratios.

To achieve high surface anchoring energy of LC cells, the most important process for the alignment layer is the separation of polymerization for the RM and PI materials, because the functional chemical roles of RM and PI are different. The separation method of the polymerization process for RM and PI has been studied in a previous paper using a double-exposure method with different UV bandwidths [8]. It was shown that the double-exposure method could effectively perform polymerization of two target materials separately. However, the method required two UV light sources with different bandwidths and two exposure processes.

In this paper, therefore, we propose a single-frequency UV exposure that can achieve separated polymerization for the UV alignment layer and embedded RM material by optimizing the intensity of the exposure UV light. This method sequentially divides the UV exposure time into polymerization and alignment processes for the RM and PI materials, respectively, by optimizing the UV intensity. In the experiments, we observed high surface anchoring power of the PI layer embedded with RM, and showed fast response time of the IPS LC mode compared with the conventional UV exposure methods.

## II. EXPERIMENTS

In general, to increase the anchoring force of the PI layer, more rigid polymer network structures in the PI layer are required. We can realize a rigid polymer network in the PI layer by applying the RM material to the alignment layer as pointed out in Section I. However, we also need to keep in mind that the PI layer and the embedded RM material have their respective functions in aligning the LC molecules in the PI material and providing a rigid polymer network in the RM material simultaneously. Therefore, we need to separate the polymerization process of two materials to prevent the deterioration of the alignment function of the PI material during the polymerization process of the RM material. Hence, we inspected the time duration of each polymerization process as a function of UV light intensity by observing the optical characteristics of the LC cells and the surface contact angle of the alignment layer.

Fig. 1 shows the fabrication process for improving the surface anchoring energy of the PI layer embedded with RM in an IPS LC cell by applying the time-sequential UV exposure method. First, we prepared top and bottom indium–tin–oxide substrates consisting of a common and a pixel electrode. To perform the optimization of the UV light condition for strong anchoring energy of the surface, we set an experimental reference condition for the mixture of the PI material and RM257 monomer (Merck, Germany) with photoinitiators (Ciba, Darocur 1173) to a ratio of 94.89:5.11 wt%. Here, the concentration of the RM polymers mixed with photoinitiator can affect the surface anchoring force, because the cross-link power of the RM in the polyimide layer is determined by the concentration of RM. Obviously, high concentration of the RM material will make strong anchoring power compared with the

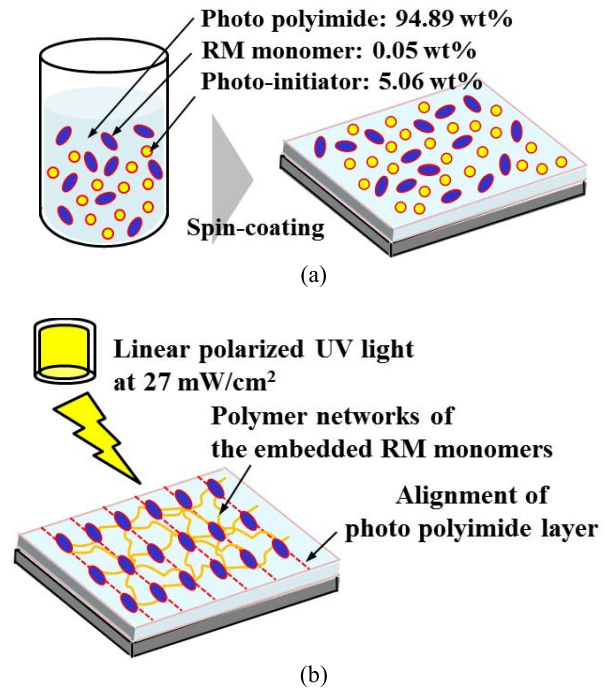


Fig. 1. Fabrication process of the high-speed IPS LC cell using single-frequency UV exposure of the PI layer embedded with RM. (a) Spin-coated mixture of the PI material and RM. (b) UV exposure of the PI layer.

low concentration of the RM. However, the concentration of the RM to the polyimide cannot be increased consecutively because very high concentration of the RM in the polyimide induces coloration of the mixture of the materials, which can deteriorate the optical property, due to RM's own material property. Therefore, we optimized the concentration of the RM material in the PI to 5.11 wt%. The wavelength of the UV light for the photodecomposition of the PI layer was 254 nm. Then, the mixture was spin-coated on two prepared substrates at a rate of 1100 rpm for 15 s and then 4000 rpm for 45 s, as shown in Fig. 1(a). After the spin coating, it was prebaked at 80 °C for 5 min, followed by hard baking at 230 °C for 20 min for polyimidization. To perform the polymerization process for the rigid polymer network and high-order parameter properties in the PI layer, we attempted to expose a linearly polarized UV light at the optimized UV intensity of 27 mW/cm<sup>2</sup>, as shown in Fig. 1(b). Finally, the two prepared substrates were assembled with a cell thickness of 3.5 μm and then the LC material (MLC-7037,  $\Delta\epsilon = 5$ ,  $\Delta n = 0.1144$ ,  $K_{11} = 12.3$  pN,  $K_{22} = 6$  pN, and  $K_{33} = 13.25$  pN, Merck) was injected into the cell layer in a twisted nematic (TN) mode.

## III. RESULTS AND DISCUSSION

Fig. 2(a) shows the measured optical transmittance of the TN LC cell as a function of the polymerization time of the PI layer for various exposure UV light intensities. In general, the RM material in the PI layer does not affect the alignment property of the PI layer, and hence, Fig. 2(a) may indicate the required polymerization time for the PI layer. During the UV exposure, we observed that the PI material is decomposed along the optical axis of the polarizer so that the transmittance

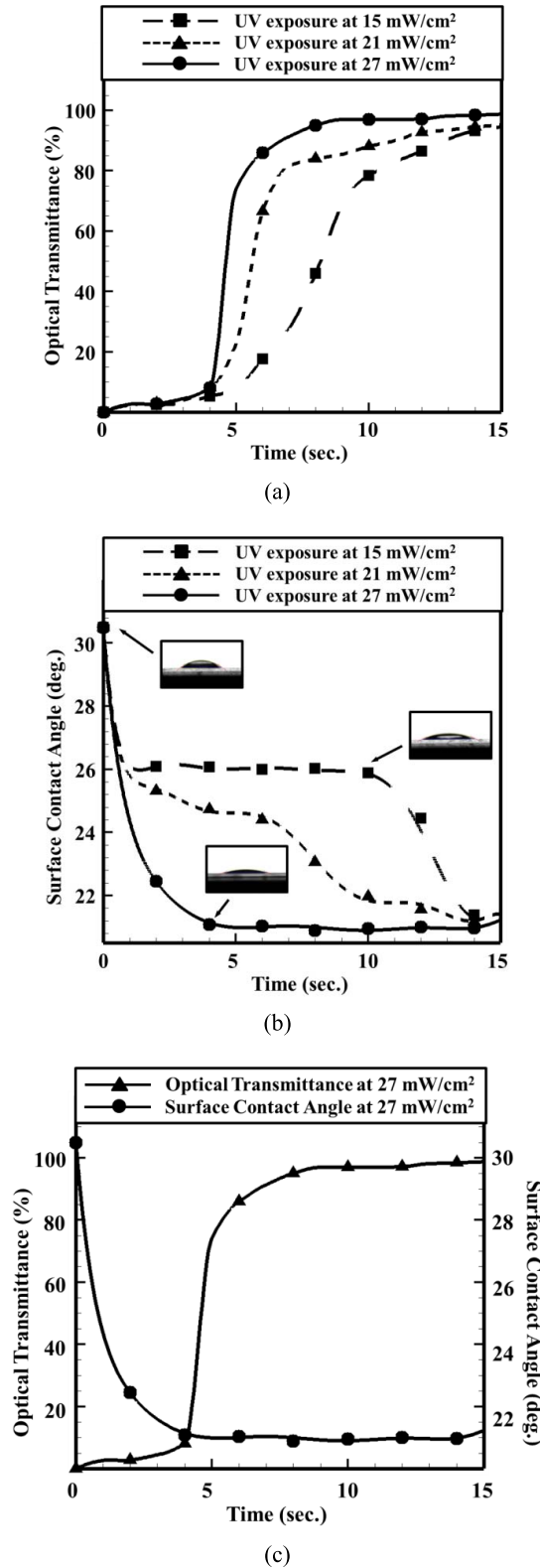


Fig. 2. (a) Measured optical transmittance and (b) measured surface contact angle versus polymerization time of the PI layer for various intensities of the exposure UV light. (c) Combined graph of the optical transmittance and surface contact angle at 27 mW/cm<sup>2</sup>.

of the LC cell is increased because of the higher-ordered LC molecules. In Fig. 2(a), all the optical transmittances start to polymerize from around 4 s and then reach over 80% after 10 s. This means that the starting times of the polymerization

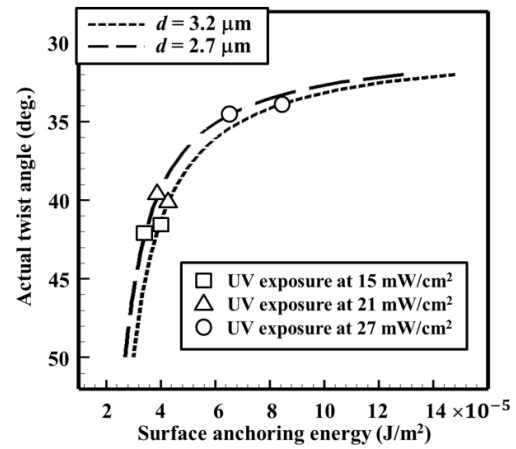


Fig. 3. Measured surface anchoring energy of the PI layer embedded with RM as a function of UV intensity.

in each condition are almost the same and the processes are nearly completed before 10 s. Hence, the required exposure time for PI material polymerization is between 4 and 10 s for all intensities of UV light exposure.

However, the embedded RM material of the PI layer shows a different polymerization time range for each UV intensity, as shown in Fig. 2(b). In general, the PI and RM materials show higher hydrophilic property by polymerization. At the UV light intensities of 15 and 21 mW/cm<sup>2</sup>, the surface contact angle decreased from an initial angle of 30° to 21° after 14 s UV exposure. However, at 27 mW/cm<sup>2</sup>, the contact angle decreased sharply to 21° in 4 s. Moreover, Fig. 2(c) shows the optical transmittance and the contact angle at 27 mW/cm<sup>2</sup>. The higher UV intensity can make a shorter time of the RM material network but not rigidity of the network in this experiment. Therefore, we can understand that the increase of the UV light intensity to higher than 27 mW/cm<sup>2</sup> was not needed. Therefore, a perfect separation of the polymerization process for the PI and RM materials can be achieved by controlling the UV intensity at 27 mW/cm<sup>2</sup>.

Fig. 3 shows the measured surface anchoring energy of the PI layer embedded with RM for various UV exposure intensities. The surface anchoring energy ( $A$ ) was determined by measuring the actual twist angle ( $\phi_t$ ) of a TN LC cell using the torque balance method as follows [21]:

$$A = \frac{2K_{22} \left( \phi_t - 2\pi \frac{d}{p} \right)}{d \sin(2\Delta\phi)}, \quad 2\Delta\phi = \phi_r - \phi_t \quad (2)$$

where  $\Delta\phi$  is the angle between two alignment angles  $\phi_t$  and  $\phi_r$ , and  $p$  is the LC pitch. In the experiments, the values of the alignment angle  $\phi_r$  and pitch  $p$  were set to 30° and 12 μm, respectively. The dashed and dotted lines in Fig. 3 represent the fit curves for the actual twist angle as a function of anchoring energy for 2.7 and 3.2 μm cell gaps, respectively. The measured actual angle  $\phi_t$  of the PI layer was rotated to 41.5° at 15 mW/cm<sup>2</sup> and 40° at 21 mW/cm<sup>2</sup>, and the corresponding surface anchoring energies were  $1.789 \times 10^{-5}$  J/m<sup>2</sup> and  $2.111 \times 10^{-5}$  J/m<sup>2</sup>, respectively. After UV exposure at 27 mW/cm<sup>2</sup>, however, the surface anchoring energy of the

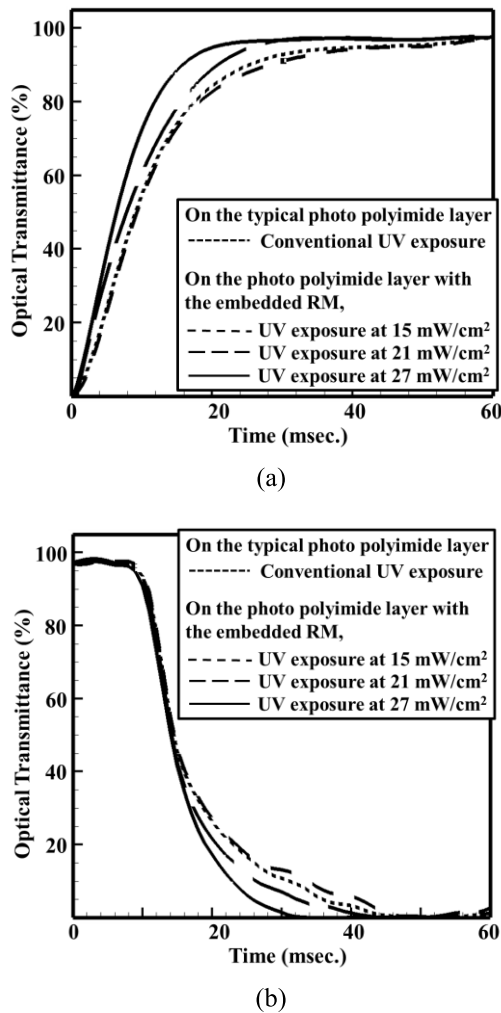


Fig. 4. Measured dependence of (a) rising time and (b) falling time of the IPS LC mode in the polymerization conditions.

cell increased to  $5.817 \times 10^{-5} \text{ J/m}^2$  as the measured twist angle  $\phi_t$  decreased to  $34^\circ$ . Therefore, the anchoring energy of the cell at the optimized UV intensity of  $27 \text{ mW/cm}^2$  could be improved by approximately three times, compared with the conventional UV exposure methods, thus giving rise to a fast response time of the LC cell.

Fig. 4(a) and (b) shows the measured rising and falling times of the IPS LC cell at various UV exposure intensities. The width of electrode and the distance between electrodes in the experiments were set to 10 and  $30 \mu\text{m}$ , respectively. In a reasonable measurement, we controlled an applied voltage so that the measured maximum optical transmittance was the same in each condition. The dotted line represents the measured rising and falling times of the LC cell in the PI layer by applying conventional UV exposure as a reference. The measured rising and falling times were 58.79 and 14.09 ms, respectively, at 15 V regardless of the UV intensity. With the embedding RM material in the PI layer, the rising and falling times of the LC cell at a low UV intensity of  $15 \text{ mW/cm}^2$  were 69.68 and 17.47 ms, respectively, at 15 V (short dashed line). Compared with typical PI layers, the response time of the LC cell for the PI layer embedded with RM at  $15 \text{ mW/cm}^2$  is slightly short because of the overlapped region of exposure

time in the polymerization process. At  $21 \text{ mW/cm}^2$ , the rising and falling times of the LC cell were 52.41 and 13.78 ms at 16 V, respectively. However, the measured rising and falling times of the LC cell at  $27 \text{ mW/cm}^2$ , respectively, decreased to 42.13 and 10.20 ms at 17 V. As the measured results show, the total optical response time of the IPS LC cell was improved by 28.2% compared with typical PI layers. Particularly, the falling time was obviously decreased by 27.61% because of the strong anchoring power. Finally, we obtain strong surface anchoring energy of the PI layer embedded with RM using the single-frequency UV exposure method and successfully achieve the high-speed IPS LC mode.

#### IV. CONCLUSION

In summary, we proposed a single-frequency UV exposure method for improving the surface anchoring energy of the PI layer embedded with an RM material. The proposed UV exposure could sequentially separate the polymerization process for the PI layer and embedded RM by optimizing the UV light intensity. In the experiments, we demonstrated that the surface anchoring energy is improved by approximately three times compared with conventional UV exposure of the PI layer embedded with RM. The total response time was improved by 28.2% compared with the conventional UV exposure methods, and, especially, the falling time was decreased by 27.61% because of the strong surface anchoring power. We believe that the proposed UV exposure method can help in improving the electrooptical properties of LCD devices and enhancing display performance compared with other display devices.

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