Band-Separated UV Exposure on a Photosensitive Polyimide Layer With Embedded Reactive Mesogen for a High-Speed Liquid Crystal Display Device

Byung-June Mun, Joun Ho Lee, Byeong Koo Kim, Hyun Chul Choi, Bongsoon Kang, Ki Hoon Song, Seung Hee Lee, and Gi-Dong Lee

***Abstract*— In general, surface anchoring energy is one of the most important parameters that strongly affect electrooptical performance, especially the optical response time of liquid crystal (LC) displays. In this paper, we proposed a photoalignment method for strong surface anchoring energy by applying double ultraviolet (UV) exposure with a separated bandwidth to a photosensitive polyimide layer with embedded reactive mesogens (RMs) that can increase the anchoring energy during polymerization. We first polymerized the embedded RM molecules using long wavelength UV rays (over 340 nm), and then achieved the ordered photosensitive alignment layer using short UV rays (between 254 and 340 nm). We compared the measured surface anchoring energy and the optical response time by the proposed method with the conventional UV exposure using the in-plane switching LC mode for verification. As a result, we confirmed that the anchoring energy increased two times and the optical response time improved by 22% compared with the conventional pure UV exposure method.**

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

I. Introduction

OVER time, the displaying image quality of liquid crystal displays (LCDs) has been developed by extensively studying a variety of LC modes, such as the twisted nematic (TN) mode [1], [2], the in-plane switching (IPS) mode [3]–[5], the fringe-field switching mode [6], [7], the patterned vertical alignment mode [8]–[10], and the multidomain VA mode [11], [12]. Despite the superior optical modes, current technologies for LCD devices still need to improve the display performance, including brightness, resolution, viewing angles, and response time, in order to overcome the competition with an organic light-emitting diode (OLED) display. Fast response time is one of the most important factors, because slow response time of the LCD can induce motion blur and color breakup.

The major parameters that influence the response time include the cell gap of the device, the dielectric anisotropy, the viscosity, and the elastic constant of the LC material. Many studies have been performed to optimize high-speed LCDs so far [13]. However, current studies about the high-speed LC mode are focused on the surface anchoring energy of the alignment layer, because the anchoring power on the surface of the polyimide (PI) layer strongly affects the dynamic behavior of LC molecules on the substrates [14]–[16].

Recently, LC molecules have been embedded with ultraviolet (UV) curable reactive mesogens (RMs) to increase anchoring energy. RM polymers can provide a strong molecular interconnection with LCs. Therefore, embedding RMs within the LC layer can enhance the surface anchoring power [17], [18]. Lee *et al.* [19] and Kim *et al.* [20] proposed enhancing anchoring energy in a planer and vertical alignment layer by mixing the UV curable RMs with the alignment material. It was possible to make a strong bonding molecular structure between the LC molecules and the polymer chains during the UV exposure process so that the surface anchoring power of the alignment layer increased and the response time improved. On the contrary, other researchers have applied the method of mechanical rubbing of PI layers to reduce the uniformity of the cell, allowing for large-sized LCD applications. It is difficult to achieve a high optical contrast because of low ordering LC molecules on the PI surface. It is also hard to achieve a multidomain structure on the alignment layers.

To overcome the problems associated with the mechanical rubbing method, the current alignment technology is focused on noncontact alignment methods. One such method is photoalignment using UV exposure to result in the high ordered orientation of LC molecules on the surface of the photosensitive PI layer [21]–[23]. In terms of the UV exposure method, however, the anchoring power of the PI layer still needs to be strong in order to achieve a fast response time, which is a weak optical point compared with an OLED.

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In this paper, we propose a photoalignment method to enhance the surface anchoring energy of the photosensitive PI layer with embedded RMs using the separated bandwidth UV exposure method in the IPS mode. The proposed photoalignment method is divided into double UV exposure steps. The first step is the photopolymerization of the embedded RM molecules by exposing them to long wavelength UV rays over 340 nm, and the second step is to create the ordered photosensitive alignment layer by exposing the embedded RM molecules to short wavelength UV rays between 254 and 340 nm. We measured the surface anchoring energy of the fabricated samples using the torque balance method [24]. Finally, we measured the optical response time of the IPS LC cell depending on the anchoring energy and also verified the improved optical response time by comparing the method used in this paper with a conventional UV exposure method.

II. Optical Structure and Fabrication of the IPS LC Cell for Strong Surface Anchoring Energy on the Photosensitive PI Layer

We can easily prove that the optical response time defined as the summation of the rising time (τ_{ON}) and falling time (τ_{OFF}) is strongly dependent on the surface anchoring energy (W), if W has a finite value using the surface dynamic equation method for the Rapini–Papoular phenomenological model, as follows [14], [20]:

$$\tau_{ON} \approx \frac{\gamma}{|\varepsilon_0|\Delta\varepsilon|E^2 - 2W/d|} \tag{1-a}$$

$$\tau_{OFF} = \frac{\gamma d}{(Wd/K_{22} + 2)W} \approx \frac{\gamma d}{2W} \tag{1-b}$$

where γ 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, and d is the cell gap of the LC layer. From (1), we can confirm that τ_{ON} and τ_{OFF} of the LC cell are inversely proportional to the surface anchoring energy W so that the surface anchoring energy strongly influences the switching behavior of LC molecules. As a result, we can expect that the strong anchoring energy can make the high-speed LCD device.

To improve the surface anchoring power of the photoalignment layer, we embedded the RM polymers in the photosensitive PI materials. However, the photosensitive PI materials and the RM polymers were simultaneously polymerized using the conventional UV exposure method, because the bandgap of UV rays involved the absorption wavelength of UV rays for two polymers. For this reason, we separated the wavelength of UV rays for the photopolymerization and LC alignment process in order to avoid changing the chemical structure in the photosensitive PI layer with embedded RMs when exposing it to the UV rays.

Fig. 1 shows the modeled optical configuration of an IPS-LC cell used for calculations and experiments. In the case of the electrode structure of the IPS-LC cell, the width of the indium–tin-oxide (ITO) electrode that consists of common and pixel ITO electrodes and the interval between the electrodes were set at 10 and 30 μm, respectively, on the bottom substrate. The top substrate had no electrode layer. The cell thickness of the LC layer of the two samples is set to 3.2 μm.

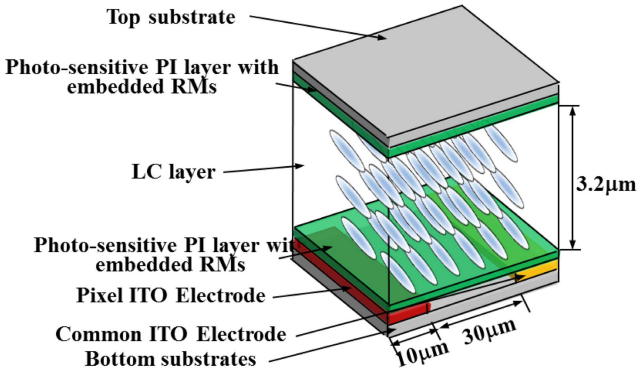

Fig. 1. IPS LC cell structure used for the calculations and experiments.

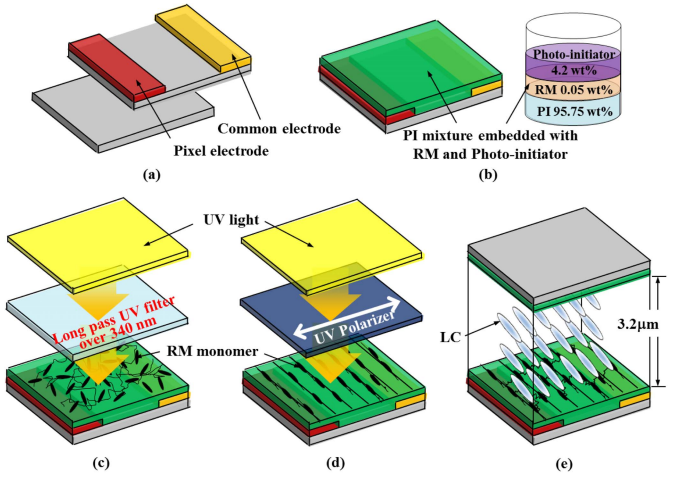

Fig. 2. Fabrication process of the double UV exposure method with a separated bandwidth to achieve strong anchoring energy of the photoalignment layer: (a) the preperation of substrates, (b) the spin-coating process, (c) the high band UV exposure for the polymerization, (d) the low band UV exposure for the LC alignment and (e) the injectoin of LC materials.

Fig. 2 shows schematics of the fabrication process to achieve the strong anchoring energy of the LC cell by applying the double UV exposure method with a separated bandwidth. We first prepared the top and bottom substrates, as shown for the sample structure in Fig. 2(a). Before performing the spin-coating process, the RM257 (Merck, Germany) and a photoinitiator (Ciba, Darocur TPO) were mixed in a ratio of 0.05:4.2 wt% in the photosensitive PI materials (RN-1322; Nissan Chemical Co., Japan), which is a photodecomposition type at a 254-nm wavelength. We then stirred the mixture at 80 °C for 1 h. In the case of the photoinitiators that help the efficient curing of RM monomers, the dominant absorption wavelength of UV light was set to be over 360 nm to avoid the chemical reaction between the RM polymers and the photosensitive PI layer. Next, the mixture was spin-coated on two prepared substrates at the rate of 1100 r/min for 15 s and then at 4000 r/min for 45 s. Next, it was prebaked at 80 °C for 5 min, followed by hard baking at 230 °C for 20 min for the polyimidization to occur [Fig. 2(b)]. To enhance the chemical

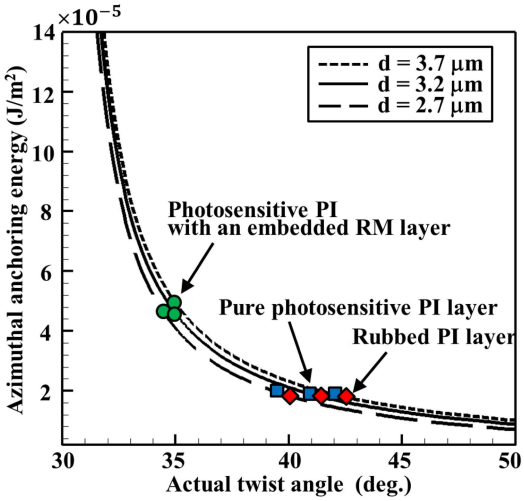

Fig. 3. Comparison of the measured surface anchoring energy for three PI samples: the PI layer achieved using the mechanical rubbing process, the pure photosensitive polymer materials, and the proposed photosensitive polymer with embedded RMs.

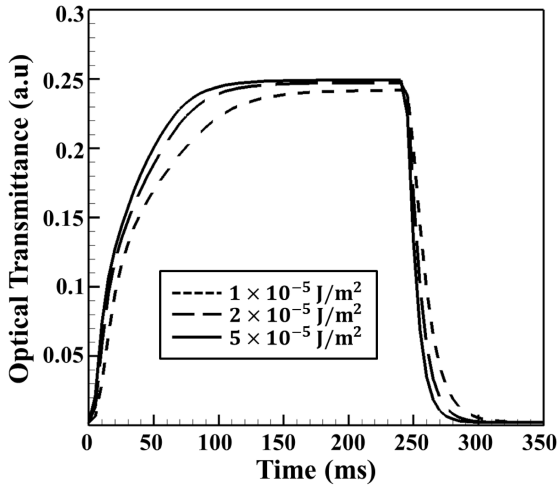

Fig. 4. Calculated optical response time of the IPS LC mode as a function of the surface anchoring energy density: 1×10^{-5} J/m^2 (12.9 V), 2×10^{-5} J/m^2 (15 V), and 5×10^{-5} J/m^2 (16.5 V).

interaction between RM monomers and the photoinitiators of the mixture, we performed long wavelength UV exposure over 340 nm for 80 s at 15 mW/cm^2 using the long pass UV filter [Fig. 2(c)] and then aligned the LC directors on the photosensitive PI layer by exposing the short linear polarized UV rays after eliminating the UV filter [Fig. 2(d)]. Using the double bandwidth UV exposure method in the fabrication process, we achieved strong anchoring energy and good LC ordering on the photoalignment layer without destroying the chemical bonding structure. Subsequently, two substrates were assembled with a cell gap of 3.2 μm. Finally, the LC material of MLC-7037 (Merck) ($\Delta\varepsilon = 5$, $\Delta n = 0.1144$, $K_{11} = 12.3$ pN, $K_{22} = 6$ pN, and $K_{33} = 13.25$ pN) was injected into the cell layer [Fig. 2(e)].

III. Results and Discussion

Fig. 3 shows the comparison of the measured surface anchoring energy of three PI layers: 1) a PI layer by mechanical rubbing process; 2) a pure photosensitive polymer layer; and 3) the proposed photosensitive polymer layer with embedded RMs. The anchoring strength (A) was measured in the TN LC cell using the torque balance method, as in the following [24]:

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

where ϕ_r is the angle between two alignment angles, ϕ_t is the actual twist angle related to ϕ_r and $\Delta\phi$, and p is the pitch of the LC.

In the experiments, the value of the alignment angle ϕ_r and pitch p was set to 30° and 12 μm, respectively. The three curves in Fig. 3 represent the relation between the surface anchoring strength and the actual angle ϕ_r if the cell gap is 2.7, 3.2, and 3.7 μm. We can see that the deviation angle $2\Delta\phi$ for the basic PI layer (JSR, AL1630K) and the pure photosensitive PI layer stayed between 42.5° and 39.5°, respectively, so that the average value of the azimuthal anchoring energy was calculated as 1.789×10^{-5} J/m^2 on the rubbed PI layer and 1.887×10^{-5} J/m^2 on the pure photosensitive PI layer. However, after mixing the RMs and photoinitiators in the photosensitive PI layer, the azimuthal anchoring energy was calculated to the average value of 4.581×10^{-5} J/m^2 at the twisted angle of 5°. This was about 2.5 times higher than for the other two samples, because the photopolymerized RMs in the photoalignment layer induced a strong interconnection with the LC molecules.

To verify the dependence of the optical response time to change the surface anchoring energy, we investigated the optical response time of the IPS LC cell using calculations and an experiment. Fig. 4 shows the calculated response time of an IPS LC mode as a function of the surface anchoring energy density. Here, the calculation was performed using the commercial LC software TechWiz LCD (Sanayi System Co., Korea). As shown in Fig. 4, we can observe that the rising time and the falling time of an IPS LC mode are calculated as 84.154 and 28.719 ms at 1×10^{-5} J/m^2 under 12.9 V, and 68.077 and 21.559 ms at 2×10^{-5} J/m^2 under 15 V, respectively. On the contrary, the rising time and the falling time for the anchoring condition of 5×10^{-5} J/m^2 were significantly decreased to 60.898 and 17.711 ms, respectively, under applied 16.5 V. Consequently, the total response time at 5×10^{-5} J/m^2 anchoring energy is reduced by ~30% compared with that for the 1×10^{-5} J/m^2 anchoring condition. The results show that the optical response of the LC cell is sensitive to the variations of the surface anchoring energy (1).

Fig. 5 shows a comparison of the measured optical response time for the proposed photosensitive PI layer with two samples: 1) a PI layer achieved using the mechanical rubbing process and 2) a pure photosensitive PI layer in the IPS LC cell. We observed that the rising time and the falling time of the two samples with relatively weak anchoring

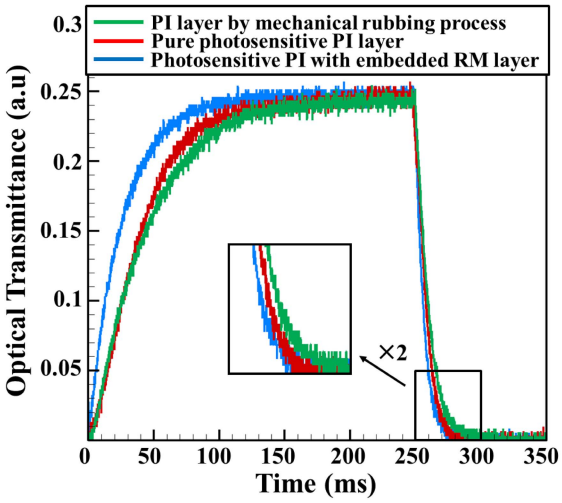

Fig. 5. Measured optical response time of the IPS LC mode for three PI samples: a PI layer achieved using the mechanical rubbing process (13 V), the pure photosensitive polymer materials (15 V), and the proposed photosensitive polymer with embedded RMs (16.5 V).

energy were measured as 69.34 and 17.14 ms at 13 V on the rubbed PI layer and 58.79 and 14.09 ms at 15 V on the pure photosensitive PI layer. The rising time in the proposed method was measured at 45.89 ms, and the falling time was measured at 10.71 ms under applied 16.5 V. Consequently, the total response time of the IPS LC cell was reduced by ∼22.3% compared with that of the pure photosensitive PI layer. Based on the results, we demonstrated the fast response time of the IPS LC mode on the photosensitive alignment layer due to the strong anchoring energy.

Finally, we successfully achieved strong anchoring energy in the photosensitive PI layer with embedded RM polymers and the photoinitiator using the band-separated UV exposure method and also confirmed the fast response time of the IPS LC cell.

IV. Conclusion

In summary, we increased the anchoring energy of the photosensitive PI layer using the double UV exposure method with separated bandwidth for the mixture of typical UV alignment material and the RMs. To demonstrate the enhanced surface anchoring power of the proposed band-separated UV exposure method, we compared the measured anchoring energy and the optical response time of three samples: 1) the rubbed PI layer; 2) the pure photosensitive PI layer; and 3) the proposed photosensitive polymer layer with embedded RMs in the IPS LC cell. As a result, we confirmed that the surface anchoring energy increased two times and the optical response time decreased by 22% using the proposed method compared with the pure UV exposure method and the mechanical alignment method. The measured results for the three PI layers were verified by calculating the optical response time in each case.

Obviously, the photoalignment method is one of the most important factors for high displaying performance of LCD devices. Therefore, we believe the proposed photoalignment method that can increase surface anchoring energy will help in improving the electrooptical performance of LCDs.

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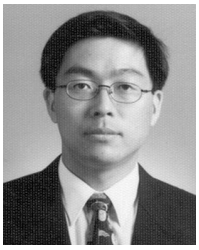

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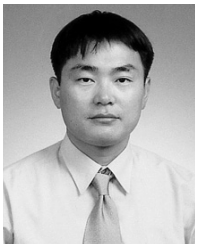

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