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Achieving a robust homogenously aligned liquid crystal layer with reactive mesogen for in-plane switching liquid crystal displays

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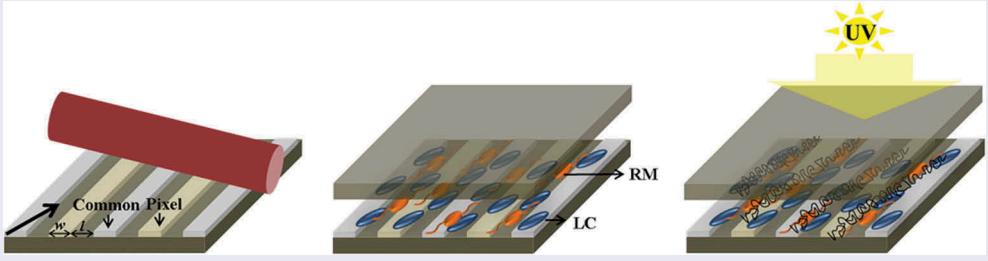
ABSTRACT

Uniformly aligned liquid crystals (LCs) are of crucial importance in a practical application, such as displays, phase modulators and virtual reality devices. Although an alignment layer using polyimide-type polymers can almost perfectly align the LCs, polymer-stabilisation at the surface using pre-mixed monomers has been attempted to reduce the fabrication process, i.e. eliminating the alignment layer, thereby reducing the fabrication cost. Here, we propose an approach to achieve a homogeneous alignment of LCs by controlling the molecular structure of reactive monomers mixed in LCs without using conventional polyimide alignment layer. The result shows an excellent initial dark state and acceptable electro-optic performance which implies that the polymer stabilisation at the surface successfully anchors the homogenous orientation of LCs. We believe that the proposed fabrication method can contribute to cost-effective fabrication process by eliminating an alignment layer with no fabrication step of a surface treatment.



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In-plane switching; alignment layer; homogeneous alignment; reactive mesogen

1. Introduction

Liquid crystals (LCs) are a fascinating state of matter owing to their long range orientational order in nematic phase. This long-range order gives rise to interesting features in its inherent characteristics, such as anisotropy in dielectric and optical properties. These anisotropic natures make it immensely useful for a display application if following conditions meet: a uniform LC director alignment and external stimuli which overcome surface anchoring energy of the LC director to reorient it. A mechanical treatment on the surface, like rubbing or brushing, can induce a uniform alignment [1], and also polymer-stabilisation method to induce LC alignment has been long reported [2,3]. One can easily switch the molecular orientation by applying an electric field for electro-optic devices, such as liquid crystal displays (LCDs), light modulators, lenses and virtual reality display devices. At present, LCDs dominate the flat panel display market owing to their high image quality and low product cost. Most of high-quality LCD modes, such as multi-domain vertical alignment [4,5], in-plane switching (IPS) [6,7] and fringe-field switching (FFS) [8–15], are subject to use polyimide (PI) type polymer for the alignment layer [16–18]. Recently, all high-resolution and high-performance LCDs adopt homogeneous alignment for IPS or FFS mode because of its superiority in transmittance, operating voltage, wide-viewing angle and touch suitability. To achieve the uniformly homogenous alignment, a substrate requires additional process for a preferred direction of LC director by either rubbing [19] or photo-alignment [20,21] techniques. These methods basically require additional fabrication processes on

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substrates such as a coating, baking, rubbing or UV exposure, curing and cleaning for long time and generating high cost. Recently, to simplify the complicated fabrication process, a homogeneous LC alignment is achieved with no PI type alignment layer [22,23] in such a way that LC layer, mixed with UV curable LC or photo-reactive mesogen (RM), is coated on a substrate by translational motion of a slit-coater to generate flow effect in LC and is spontaneously polymerised [24,25]. However, this approach seems not that efficient to get a uniform homogenous alignment although it seems successful in eliminating the PI type alignment layer.

In this article, we demonstrate a uniform homogenous alignment of LC with successfully achieving the elimination of an additional alignment layer, thereby reducing the cost of fabrication process. Furthermore, we also improve an initial dark state, i.e. the uniformity of the LC alignment by reducing the molecular length of RM. By this approach, the polymer morphology on the surface becomes much generous for the uniformity. We believe the results of our work will contribute to achieving cost-effective fabrication process while keeping a good initial dark state and acceptable electro-optic properties as compared with a conventional cell with an additional alignment layer.

2. Experimental conditions and principle of homogenous alignment without using PI

For the experiment of making IPS cells, transparent indium-tin-oxide (ITO) electrode is deposited with 400 nm on glass substrate and then ITO is patterned to have an electrode width (w) and gap (l) between two consecutive electrodes, 4 and 4 μm, respectively. Initially, a rubbing is performed on an electrode substrate and a top bare glass without alignment layer. Rubbing angle has been set to 20° with respect to the electrode direction. After rubbing, both the substrates had been assembled with rubbing direction oriented in an anti-parallel way. Uniform thickness of a cell (d) has been maintained by using 3.1-μm ball spacers. For the work, a LC mixture (Merck Advanced Technology, Korea) with physical properties (dielectric anisotropy $\Delta\varepsilon = 8.9$ at 1 kHz, birefringence $\Delta n = 0.1$ at 589.3 nm, 20°C) has been used as host material. Well-known reactive mesogenic monomer RM-257 (Merck Advanced Technology, Korea) has been used as stabilising agent. Another monomer, RM-ether (4,4′-acryloyl dihydroxy diphenyl) which has much less molecular weight with smaller size than that of RM-257 [26] was also tested for comparison (see Figure 1 for chemical structures of photo-reactive RM-257 and RM-ether). Both the RM-257 and RM-ether have been mixed with the host LC mixture at 0.4 wt%, separately. The mixtures have been filled at temperature 2°C above the clearing temperature of the mixture. The filled cells have been checked under polarising optical microscope (POM) (NIKON Japan, ECLIPSE E600W POL), and once LC director followed the direction of rubbing so that a homogenous orientation of LC was observed, UV exposure (HAMAMATSU Japan, LC8 L9588) with 1.5 mW/cm^2 has been applied for 20 min for photo-polymerisation of the monomer. Field-emission scanning electron microscope (FE-SEM) (FEI Korea, Nova NanoSEM 450) has been used to study the surface morphology.

Figure 2 shows schematic modelling how a homogenous alignment can be achieved without using conventional PI. Once the rubbing was performed on both substrates, both substrates were assembled together (see Figure 2(a)) and then both LC and RM are filled in the cells aligned along the rubbing direction (see Figure 2(b)). According to a previous report [27], the concentration of RM inside LC layer is anisotropic such that the RM diffuse into the interface between LC and surface, resulting in more RM concentration than that in the middle of LC layer. Once the homogenous alignment was achieved, UV was exposed to top

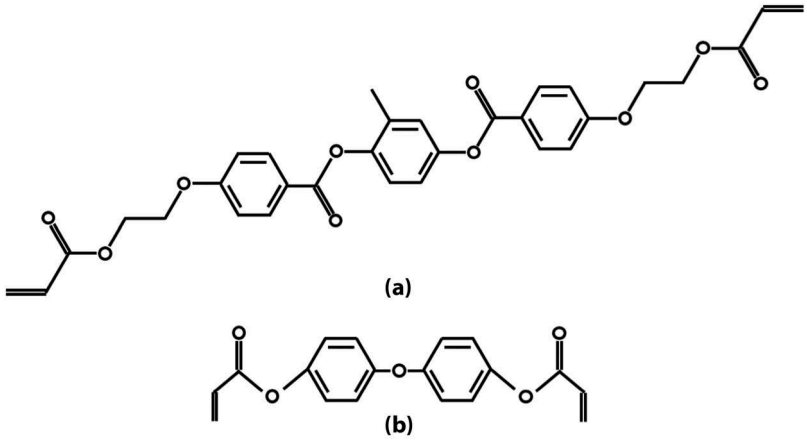

Figure 1. Chemical structures of photo-reactive RMs: (a) RM-257 and (b) RM-ether.

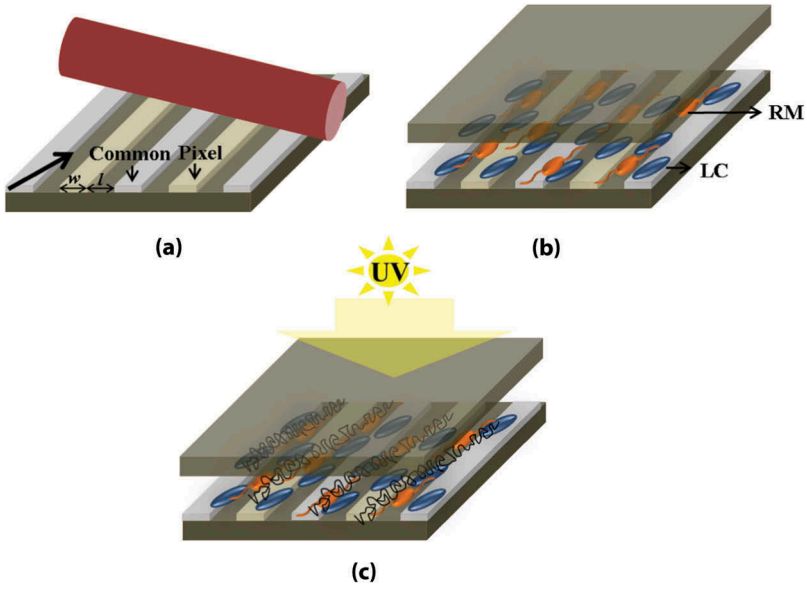

Figure 2. (colour online) Novel fabrication method to achieve a homogenous alignment of LC: (a) strong rubbing process is applied on the substrate, (b) the LC/RM mixture is homogeneously aligned, and (c) UV is exposed to the IPS cell to fix the LC molecules at both surfaces of the substrates.

substrate, resulting in polymerisation of the RM. Then, a stable homogenous alignment is achieved by a stable polymer network, as shown in Figure 2(c).

3. Results and discussion

In the homogeneously aligned LC molecules with its optic axis coincident with one of crossed polarisers, the normalised transmittance (T) is proportional to $\sin^2(2\alpha)\sin^2(\pi d\Delta n/\lambda)$ whereα is an angle between the optic axis of LC and the transmittance axis of a polariser, and λ is a wavelength of an incident light. Therefore, in order for the cells proposed by new approaches to achieve an excellent dark state, an angle α should be equal to 0°.

After photo-polymerisation of the monomer, the cells have been carefully observed under POM. Firstly, we compare the POM images for three cases: the conventional cell with PI alignment layer, the proposed cell with RM-257 and the proposed cell with RM-ether as shown from left to right in Figure 3(a). One can recognise that the cell with RM-257 has uniaxial alignment of LC, but there is unacceptable amount of light leakage (circles with dotted line in the middle in Figure 3(a)) under crossed polarisers at $\alpha = 0°$. To compare the dark states quantitatively, we capture the dark state images and do image processing that acquires the spatially averaged brightness value in 8-bit grey scale, and the results are 1.43, 2.55 and 1.72 for the cells with conventional PI, RM-257 and RM-ether, respectively. Controlling doping weight % of RM was tested but cannot escape from such type of light leakages. However, the cell with RM-ether easily exhibits much better dark state comparable to that in the conventional cell, unlike in the case of cell containing RM-257. We have carefully examined the light leakage in the cell with RM-257 with either POM or optical microscopy if it comes from LC deformation around spacers or not. Under optical microscopy, there are some undefined defects which might be associated with large-sized grain of polymerised RM. Interestingly, when the RM-ether is used with the same procedure, such defects almost disappear, as shown in Figure 3 (c). In addition, the POM images clearly show a maximal bright and dark state when the cell is rotated by 45° and 90°, respectively. This confirms that the uniaxial LC orientation is achieved even without using conventional alignment layer.

Next, voltage-dependent transmittance (V-T) curves have been measured in order to compare the electro-optic characteristics for three cells: rubbed cell with conventional PI layer, rubbed cells just using RM-257 and RM-ether. As shown in Figure 4, the rubbed cell with conventional PI exhibits a least light leakage in a dark state, and as expected, the cell with RM-257 shows relatively highest leakage in a dark state. In addition, V-T curves of the rubbed cells with RM-257 and RM-ether shift to the right, that is, threshold (V_{th}) and driving voltages increase compared to the cell with conventional PI. In the IPS device, V_{th} is inversely proportional to d and surface azimuthal anchoring energy W [28,29], such that the increase in V_{th} implies that the formed grain via polymerisation of RM may reduce a cell gap and increase W. Response times of all three kinds of cells have been

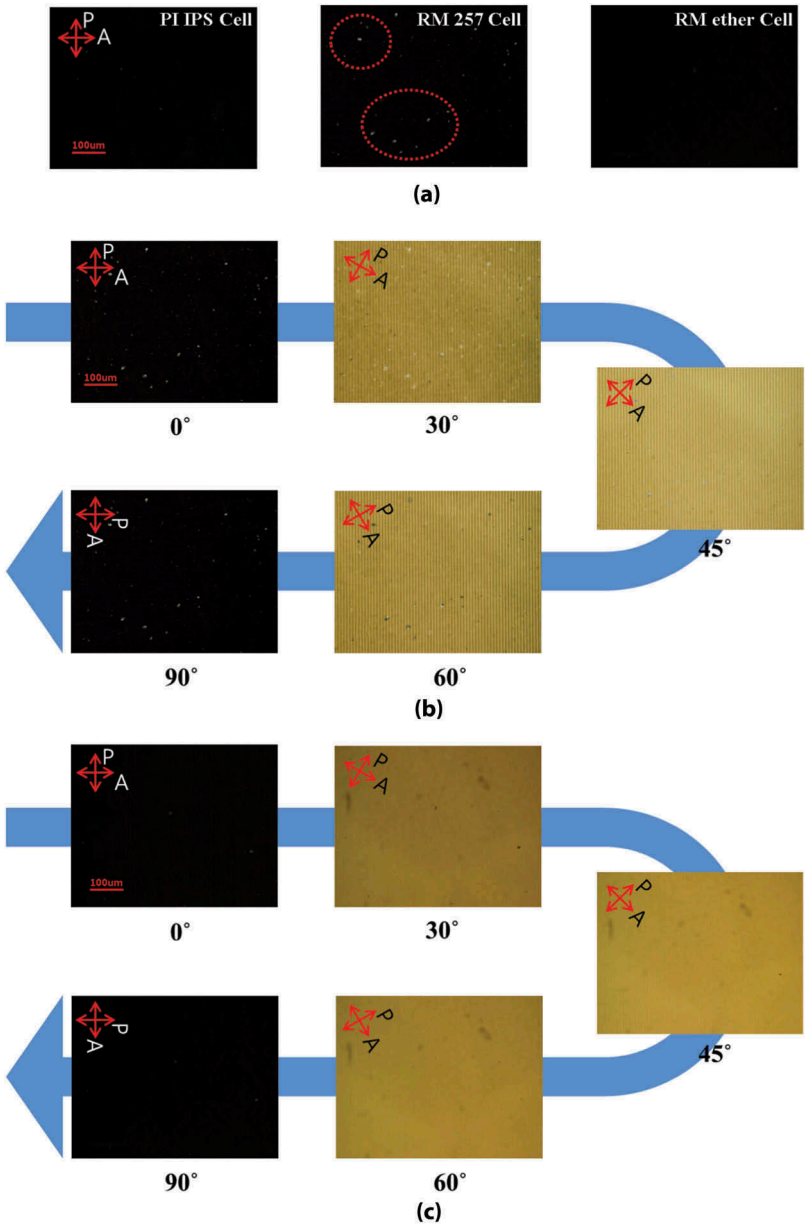

Figure 3. (colour online) (a) The dark state POM images of IPS cell with PI, and PI-less IPS cells with RM-257 and RM-ether, when the cell rubbing direction is coincided with one of the crossed polariser axes. The dotted circles in the dark state in red ink indicate light leakage coming from polymer grains. The POM images at different cross polariser angles (0°, 30°, 45°, 60° and 90°) for the PI-less IPS cell with (b) RM-257 and (c) RM-ether.

measured with 80% transmittance changes. In case of rubbed cell with RM-ether (RM-257), decaying response time (τ_d) is 4.2 (5.1) ms and rising response time (τ_r) is 2.3 (2.3) ms. On the other hand, the decaying and rising response times of the cell with rubbed conventional PI are 7 and 6.7 ms, respectively. Clearly, τ_d becomes shorter in the cells without using conventional PI and fast τ_rs in the cells with RM are associated with increase in the applied voltage due to increased operating voltage.

Next, in order to find out if the cell gap is reduced by polymer layer, we investigated surface morphology of polymer layer formed by RM. In procedure to examine the surface morphology, the cells were dipped in hexane for overnight. In general, LC is well soluble in hexane so that all the LCs inside the cells are removed. Then the top and bottom substrates were un-assembled and the electrode bottom substrates were taken for FE-SEM to observe the polymer structures. As shown in Figure 5(a), one could easily observe the number of the polymer fibril following the rubbing direction of about 20° in the proposed cells using RM-257. Even in the cell using RM-ether was the polymer fibril observed although the number of fibrils was

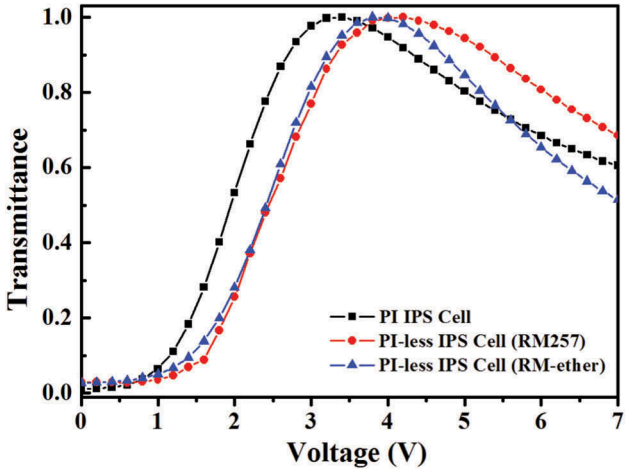

Figure 4. (colour online) Voltage-dependent transmittance curves of IPS cells with PI and PI-less with RM-257 and RM-ether.

much reduced compared to the cell using RM-ether (see Figure 5(b)). From the experiment results, we could conclude that neat polymer networks formed along the rubbing direction stabilised the LC molecules near the surface and formed homogenous alignment in LC layer. In this experiment, untreated rubbed substrates were used and LC cells were made using those rubbed substrates without any additional layer of aligning agent. In fact, this is a well-known phenomenon that rubbing on a solid substrate induces alignment of LC directors [1,17,18]. However, only rubbing is not stable enough to anchor the LC molecules for a longer duration of time so that its anchoring degrades with time and also with temperature. In other words, only rubbing on solid substrate gives a weak anchoring of LC molecules, but formation of additional polymer layer formed by UV curable monomer can give rise to enough anchoring strength of LC molecules on the surface. Cross-sectional images of the polymer on both substrates were also taken with FE-SEM, and the thickness of the polymer layer with RM-257 and RM-ether was measured to be 196.2 and 172.7 nm, respectively, as shown in Figure 5(c,d). In addition, surface of the polymer with RM-ether was more smooth than that with RM-257, implying that the degree of aggregation is rather week in RM-ether.

Now, from understanding of the reduced cell gap effect by the RM, we try to correlate shortened τ_d in the proposed cells with d and W. In the IPS device, τ_d is associated with d, rotational viscosity γ, twist elastic constant K_{22} and W [30–32] following the relationship:

$$\tau_d = \frac{\gamma}{K_{22}\pi^2}\left(d^2 + \frac{4dK_{22}}{W}\right) \quad (1)$$

In the cell with RM-ether, the effective d can be about 2.75 μm assuming both substrates have the polymer layer. Therefore, only if the reduced d is considered, τ_d of the cell should be about 5.3 ms since τ_d in the conventional cell was 7 ms with d = 3.1 μm; however, the measured value was 4.2 ms so that we expect the amplitude of W is slightly enlarged compared to W with conventional PI.

Finally, to verify how the electronic properties of IPS cells are influenced by with and without conventional PI, we measured voltage holding ratio (VHR) of two cells with two different approaches, which are very important electrical characteristics to determine

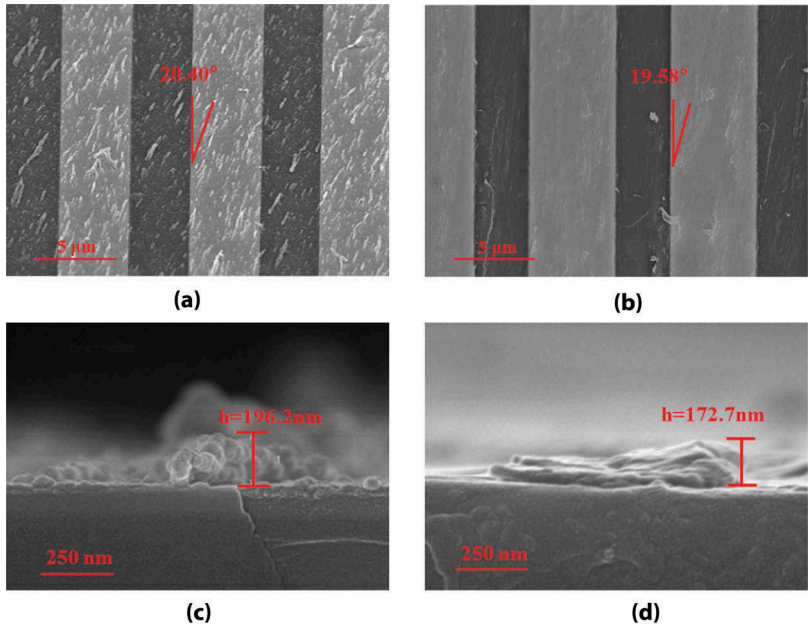

Figure 5. (colour online) SEM images of top and side views of rubbed cells with PI-less using (a)/(c) RM-257 and using (b)/(d) RM-ether.

the cell's voltage holding characteristic. The cell with PI showed about 83% whereas the cell without using PI showed reduced value of about 77% at an applied voltage of 1.3 V which is slightly higher Frederiks transition voltage. In order for the LC cell to be qualified for active matrix driving, it should be over 99% at room temperature. The low VHR of both cells may come from ions since both are made not in a clean room situation but the lower value in the cell without using PI seems to be originated from that the polymer layer formed by RM does not cover whole electrode layer. Therefore, further detailed studies on how to improve VHR are required.

4. Conclusions

We have proposed a novel fabrication method for homogeneous alignment of LCs in an in-plane switching cell with no polyimide type alignment layer. An excellent homogenous alignment of LCs was achieved by polymer stabilisation of premixed reactive monomers in a LC layer after simply rubbing a bare substrate. The polymer morphology embedded in the LC layer seems influencing reduction of the cell gap, so that it would enhance the decaying response time of LCs. By the proposed fabrication method, we can expect to eliminate a conventional fabrication process associated with PI coating, which can contribute to low-cost and energy-saving LCDs.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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