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We studied liquid crystal (LCs) alignment effects on homogeneous polyimide (PI) surfaces induced by polarised UV (PUV) exposure and rubbing in different directions. We found that the LC orientation is not affected by PUV exposure times of less than 90 min after rubbing, and that PUV exposure times over 90 min after rubbing resulted in LC orientations that were more closely aligned with the direction of PUV exposure than the direction of rubbing. Short-term PUV exposure affects the variation of the pretilt angle of the PI and LC. In addition, as PUV exposure time increases, it can convert the LC alignment direction from the rubbing direction to the PUV direction.

Keywords: pretilt angle; liquid crystal alignment; homogeneous polymer; PUV exposure; rubbing

1. Introduction

Thin film transistor (TFT) liquid crystal displays (LCDs) have been widely employed in flat panel display applications. Understanding the behaviour of liquid crystals (LCs) on substrate surfaces is fundamental to the design research and the development of applications for LCDs [1–6]. Mechanical rubbing techniques have been widely utilised to align LC molecules on polymer layers for mass production of LCDs because of their simplicity, productivity and thermal stability [7–13]. Although the rubbing techniques have some advantages, their limitations include the influence of dust particles, electrostatic discharges and physical damage by the cloths used for rubbing that cause local defects, streaks and other adverse effects on the driver-integrated circuits [14, 15].

Recently, non-contact alignment methods such as oblique deposition [16], photo-alignment [17, 18], plasma treatment [19] and ion-beam bombardment [15, 20, 21] have been proposed to replace rubbing methods and eliminate these drawbacks. Among these methods, many studies have been devoted to the development of photo-alignment processes to align uniform LCs. Photo-alignment methods involving polarised or non-polarised ultraviolet (UV) exposure at the substrate surface offer the advantages of a clean process, a suitability for large-scale manufacturing and a multi-domain capability [22, 23]. The efficacy of the UV alignment process has been demonstrated on materials including poly(vinyl)-cinnamate films, poly(vinyl)4-methoxycinnamate and polyimide (PI), which can be very effective as an alignment layer [21, 24]. The three major mechanisms for achieving photo-alignment are photoisomerisation [25], photodegradation [26] and photocrosslinking [27].

Rubbing methods influence LC orientation through microgroove effects and the oriented polymer chains near the film surface [1, 5]. The generation of the LC pretilt angle on a PI surface may result from the formation of microscopic asymmetrical triangles during the rubbing process. The alignment characteristics of multi-directional LC cells using rubbing methods were reported by Huang *et al.* [28]. The direction of the final rubbing is found to initially dominate the orientation of the LC molecules in the multi-directionally rubbed LC cell because the final rubbing erases some of the grooves produced by the first rubbing. Most recently, the effects of ion-beam bombardment and rubbing on the directional behaviour and alignment mechanism of the LCs on homogeneous PI surfaces have been reported by Lee *et al.* [29]. In the report, the direction of LC alignment follows the direction of ion-beam bombarded alignment on the PI surface regardless of whether the ion-beam bombardment occurs before or after rubbing. However, the effects of the directional behaviour of the LCs on the PI surfaces with multi-directional alignment using UV exposure and rubbing treatments are unknown.

In the present study, we investigated the effects of the behaviour of LC molecules on multi-directional alignment using rubbing and UV exposure alignment on the homogeneous PI surface, as observed by polarisation microscopy, measurement of the pretilt angle

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of the anti-parallel cells and observation of the voltage–transmittance (*V–T*) characteristics of the twisted nematic (TN) cells.

2. Experiment

The glass substrates (Corning 1737) with indium–tin–oxide (ITO) coated electrode films were cleaned in a trichloroethyl–acetone–methanol–deionised water solution with a supersonic wave for 10 min and then dried with N_2 gas. Polyimide (SE-7492 homogeneous polymer form Nissan Chemical) was uniformly coated on the ITO electrode of the glass by the spin-coating method at 3000 rpm for 30 s. The PI layers with a thickness of 50 nm were soft-baked at 80°C for 10 min to evaporate the solvent and then imidised by hard-baking at 230°C for 60 min. The PI layers went through the rubbing process using a drum wrapped with a nylon cloth and were then exposed to UV light in different alignment directions. The rubbing strength (RS) was calculated using the equation [30]

$$\mathrm{RS} = NM(2\pi rn/V - 1),$$

where N is the number of rubbings, M is the depth of the fibres (in millimetres), r is the radius of the drum, n is the rotation rate of the drum and V is the moving speed of the substrate. In our experiments, the rubbing strength was calculated at 300 mm on the PI layers, which was strongly rubbed for LC alignment. The PI layers were exposed to oblique polarised UV (PUV) light. The schematic of the PUV exposure system (Oriel instruments), which included a 1000 W Xe lamp polarised using an Oriel UV sheet polariser, is shown in Figure 1. The PUV energy density was 8 mW cm^{-2} at the substrates and the incident angle between the direction of PUV light and the substrate was 30° [31]. The PI layers were exposed to oblique PUV light for periods ranging from 30 min to 120 min with increments of 30 min, at a wavelength of 365 nm. Figure 2 describes the LC ordering direction and the LC alignment method sequence. The PI layers on the substrate were aligned in a varying sequence of PUV exposure and rubbing process with a 45° difference between the PUV and rubbing directions to observe the exact orientation property of the LCs on the PI layers. The rubbing direction was the alignment direction using the rubbing method and the PUV exposure direction was parallel to the alignment direction using the oblique PUV light. The cells, upon which were conducted the two types of alignment method in varying directions, were fabricated in an anti-parallel configuration with a cell gap of 60 μm to examine the pretilt angle of the LC, and the TN cells were prepared with a cell cap of 5 μm to measure the electro-optical (EO) characteristics.

The cells were continuously filled into positive nematic LCs (mJ001929 from Merck Corp) with an isotropic transition temperature of 72°C, a refractive index (Δn) of 0.077 and a dielectric anisotropy ($\Delta\varepsilon$) of 8.2. To estimate the feasibility of display device fabrication, the LC alignment conditions between the PI layers and LC molecules were observed with a polarisation microscope (Olympus BXP 51) with a crossed polariser. The pretilt angle of the LCs was measured by the crystal rotation method (TBA 107 tilt-bias

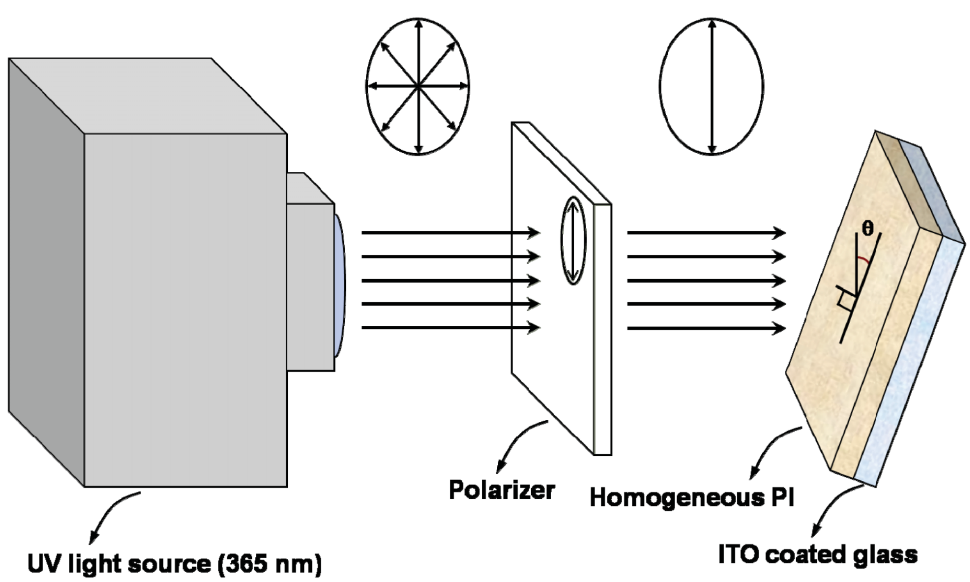

Figure 1. Schematic diagram of the PUV exposure system.

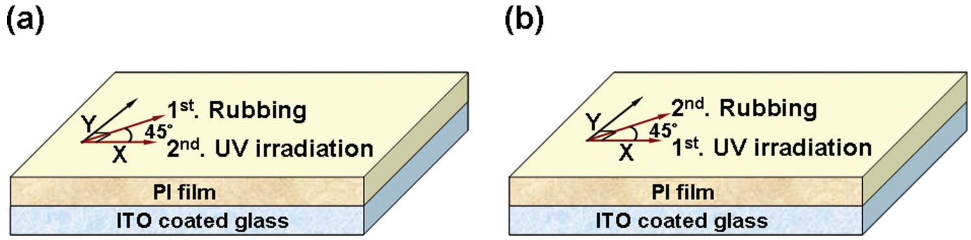

Figure 2. The two sequence of alignment methods on the homogeneous PI surface used in this experiment: (a) PUV exposure after rubbing; (b) rubbing after PUV exposure.

angle evaluation device, Autonic) at room temperature to obtain the uniform LC alignment. The transmittance of the LC cell with a latitudinal rotation from –70° to +70° was measured, and the oscillation of the birefringence was determined from the LC cell rotation. The EO characteristics of the TN LCDs were measured using a LCD evaluation system (LCD-700, Otsuka Electronics).

3. Results and discussion

Figure 3 shows polarisation microscopy images of the LCs on a homogeneous PI layer for the two types of alignment methods (in crossed Nicols). The preparation conditions for the LC alignment were PUV exposure after rubbing and rubbing after PUV exposure. The two types of alignment methods applied to the LCs were PUV exposure after rubbing, as shown in Figure 3(A), and rubbing after PUV exposure, as shown in Figure 3(B). The polarisation microscopy of the aligned LC molecules in the direction of rubbing are given in Figure 3(a) and those in the direction of PUV exposure are given in Figure 3(b) for PUV exposure times of 30, 60 and 90 min corresponding to Figures 3(c)–(e), respectively. Figures 3(c) and 3(d) show that LC alignment was parallel to the homogeneous PI surface of the rubbing direction for PUV exposure times of at most 60 min, regardless of the LC alignment sequence employed. Figure 3(e) demonstrates that LC alignment was parallel to the direction of PUV exposure when PI layers were irradiated for 90 min by PUV light. Although the minimum PUV exposure time was 30 min to align the LC on the PI layer [17], the direction of rubbing alignment is dominant over the direction of PUV alignment. In contrast, with a PUV exposure time of over 90 min, the direction of LC alignment gradually changed from the direction of rubbing to the direction of PUV exposure. From this result, we can conclude that a minimum PUV exposure time of 90 min is required for the influence of PUV to be greater than the influence of rubbing to align the LC on the

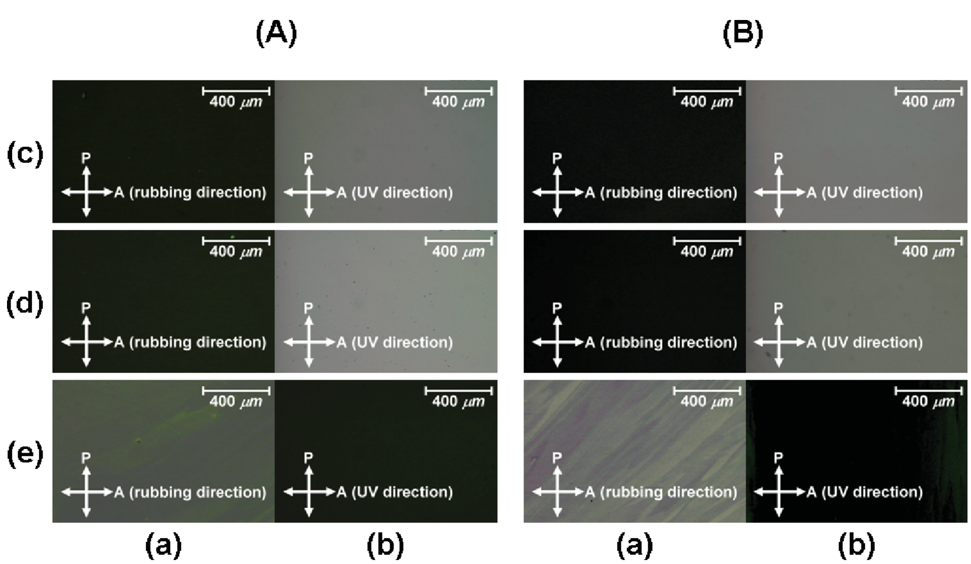

Figure 3. Polarisation microscopy images of the LCs on the homogeneous PI layer subjected to the two types of alignment methods (under crossed Nicols): (A) PUV exposure after rubbing; (B) rubbing after PUV exposure where (a) rubbing direction, (b) PUV exposure direction, with PUV exposure times of (c) 30 min, (d) 60 min and (e) 90 min.

homogeneous PI layer. Figures 3(A) and 3(B) show the same LC orientational behaviour regardless of the LC alignment sequence. Because of this result, we omitted rubbing after PUV alignment from the following experiments.

Figure 4 shows the transmittance characteristics as a function of the incident angle for measuring the pretilt angles of the LCs on the homogeneous PI surface using PUV alignment. Figure 4(a) depicts the pretilt angle measurements of the LCs for a PUV exposure time of 30 min after rubbing. A stable graph of pretilt angle was observed in the direction of rubbing, while the LC was oriented randomly in the direction of PUV exposure. Figure 4(b) depicts the pretilt angle measurements of the LC for a PUV exposure time of 90 min after rubbing. In this case, a stable pretilt angle was produced in the direction of PUV alignment but no pretilt angle is shown in the direction of rubbing, which is opposite to the case of Figure 4(a).

Figure 5 shows the EO characteristics of the TN cells on the homogeneous PI layer produced by PUV alignment. In Figure 5(a), superior EO characteristics were observed in the direction of rubbing when compared to those of PUV alignment with a PUV exposure time of 30 min after rubbing. In contrast, in Figure 5(b), the EO characteristics of the LC in the direction of PUV alignment at a PUV exposure time of 90 min after rubbing were superior to those in the direction of rubbing. The trends in Figures 3–5 confirm that the PUV alignment more effectively aligns the LC on the PI layers at exposure times of over 90 min than does rubbing, while rubbing predominates over PUV for alignment of the LC at exposure times of less than 90 min.

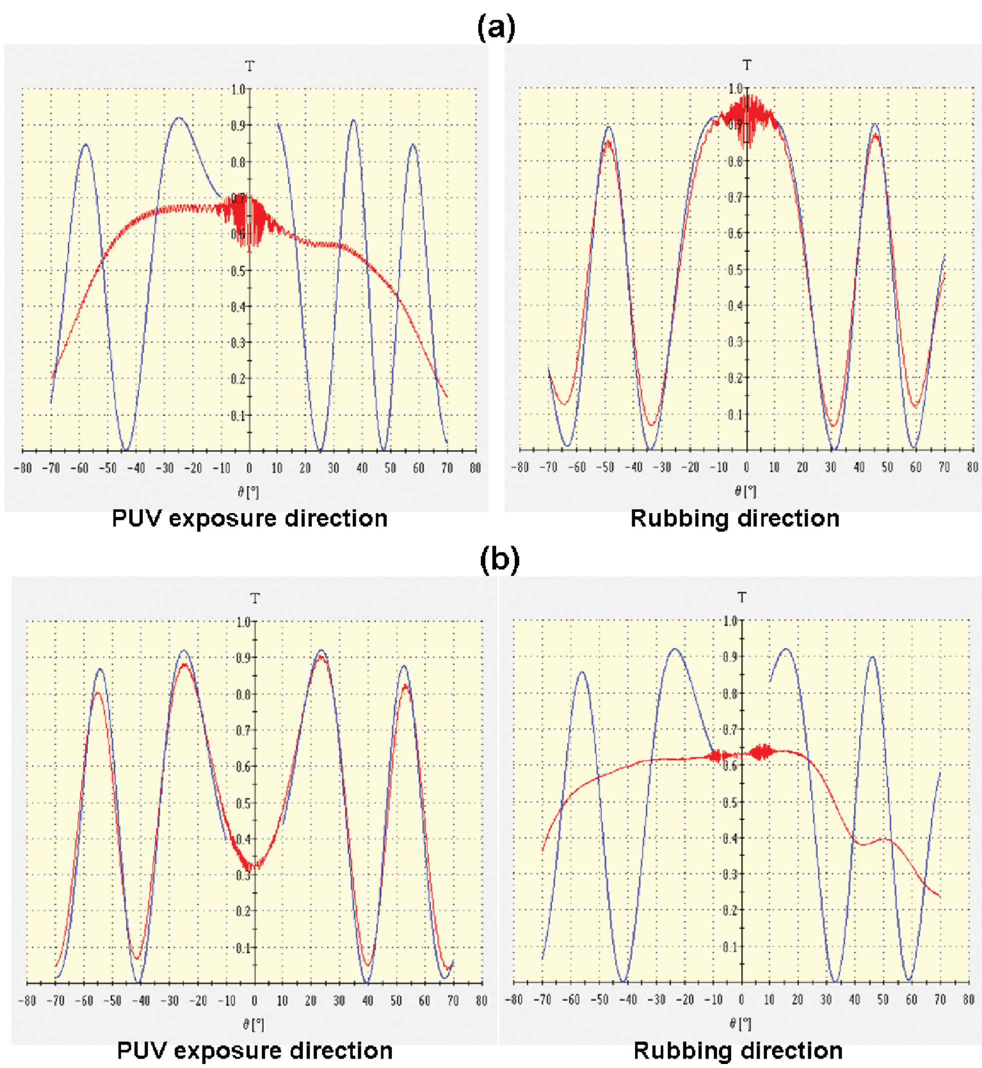

Figure 4. Transmittance as a function of incident angle on the homogeneous PI layer with PUV alignment after rubbing for a PUV exposure time of (a) 30 min and (b) 90 min.

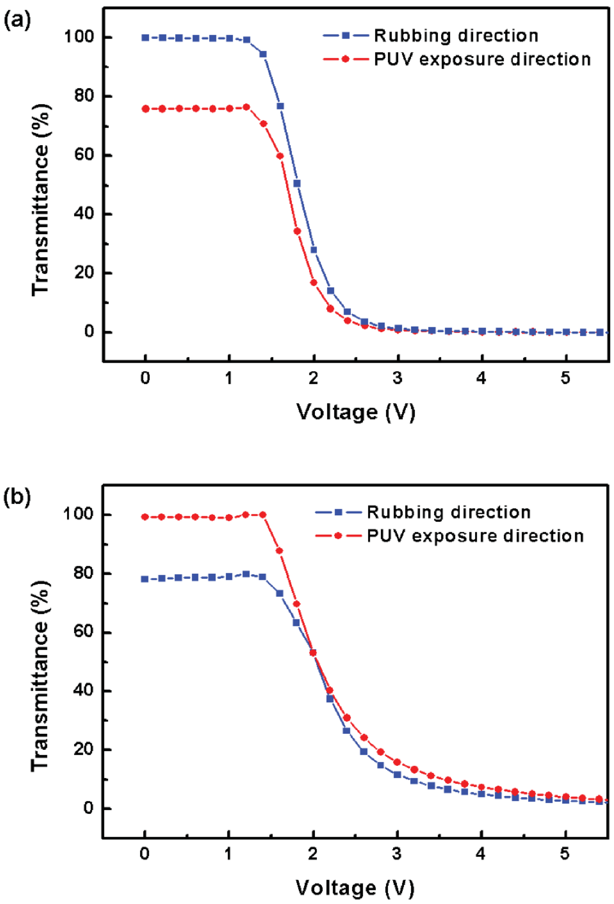

Figure 5. EO characteristics of the TN cells on the homogeneous PI layer with PUV alignment after rubbing for a PUV exposure time of (a) 30 min and (b) 90 min.

Figure 6 depicts the result of pretilt angle measurements of the LC at various PUV exposure times after the rubbing process. The pretilt angles corresponded with the direction of rubbing at PUV exposures of 30 min and 60 min, and with the direction of PUV exposure at exposure times of 90 min and 120 min. We observe a decrease of the LC pretilt angle as the PUV exposure time increases, which agrees with the results of a previous report from IBM [32]. Uniform LC molecules in the direction of rubbing were obtained with PUV exposure times of 30 min and 60 min. However, pretilt angles obtained after PUV exposure were similar. From this result, we conclude that a short period of PUV exposure after rubbing affects the variation of the pretilt angles between the PI and LC molecules. In addition, it can be reasonably deduced that exposure times over a certain threshold value can induce not only pretilt angle variations, but also alterations in the direction of alignment. We also assumed that the mechanism changing the LC alignment from the rubbing direction to the UV

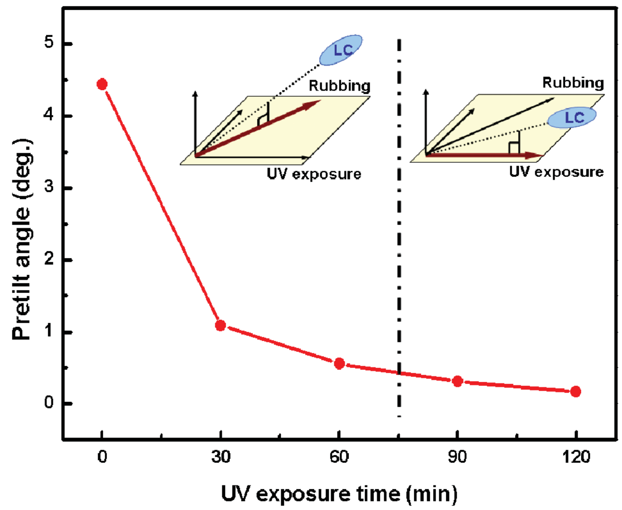

Figure 6. Pretilt angle of the LCs on the homogeneous PI layer as a function of PUV exposure time after rubbing (with a pretilt angle of the rubbing direction with PUV exposure times of 0, 30 and 60 min and a pretilt angle of the PUV alignment direction with PUV exposure times of 90 and 120 min).

exposure direction at sufficient PUV exposure was caused more by the chemical bonding between the LC molecules and the photo-dimerised polymer chains than by the physical processes such as the polymer chain orientation and the microgroove effect.

4. Conclusions

We have investigated the alignment characteristics of LCs on homogeneous PI layers resulting from two types of alignment methods, with PUV alignment after various exposure times and a rubbing process with different alignment directions. The LCs aligned in the direction of PUV exposure at PUV exposure times of over 90 min regardless of whether rubbing was applied before or after PUV exposure. Conversely, at PUV exposure times of less than 90 min, the LCs were seen to align in the direction of rubbing independent of the effects of PUV exposure. We conclude that PUV exposure after rubbing induces decreased LC pretilt angles. PUV exposure converts the pretilt angle and, with increasing exposure time, can transfer the LC alignment from the direction of rubbing to the direction of PUV exposure. We can translate this phenomenon as an expansion of the UV alignment effect in that exposure time is the dominant factor for controlling LC molecular orientation. Sufficient PUV exposure allows LC molecules to break their fixed interactions with the rubbed PI surfaces and assume new alignments parallel to the direction of PUV exposure.

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