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Suppressing Optical Bounce for Homeotropic Liquid Crystal Cells by Rubbing Treatment

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In this article, we propose a mechanical rubbing method to eliminate the optical bounce and decrease the response time of homeotropic liquid crystal cells. After gently rubbing the inorganic alignment film (sputtered silicon oxide, SiO_2), the decreasing polar anchoring energy results in a smaller pretilt angle giving liquid crystal a toppling direction to shorten the transition time while liquid crystal cell is applied by an external electric field. The results of our work show that this rubbing remedy suppresses the optical bounce. This simple and efficient surface rubbing treatment could be applied to liquid crystal on silicon technique for projectors and portable displays.

Keywords Alignment; flow effect; optical bounce

1. Introduction

Homeotropic alignment of liquid crystals (LCs) is widely used for liquid crystal display (LCD) mass production due to its excellent contrast ratio. With compensation films and multidomain vertical alignment (MVA) technique, the oblique light leakage of homeotropic LC cell could be improved to offer a wide viewing angle in LCD application [1–3]. However, the long response time of homeotropically aligned LC cell is still needed to be solved. Pieranski *et al.* posed that the flow motion would occur to induce the twist structure of the LC cell when it undergoes transition from homeotropic to planar state [4]. It has been investigated that LC flow effect is a crucial factor for generating long response time in homeotropic cells. This phenomenon is also called the back flow effect. Figure 1 shows the process of flow motion. When the electric field varies rapidly, fast rotation of LCs in the middle of LC cell produces a torque which produces a tipping over of the LC director near the substrates [5]. The flow motion would lead the director of LCs near the upper and bottom substrates to tilt in the opposite direction, that is, the flow causes the tilt angle of LCs to be over 90° from the substrate. In 1970's, Berreman and van Doorn numerically derived the equation of motion for LCs based on the continuum theory of Ericksen and Leslie

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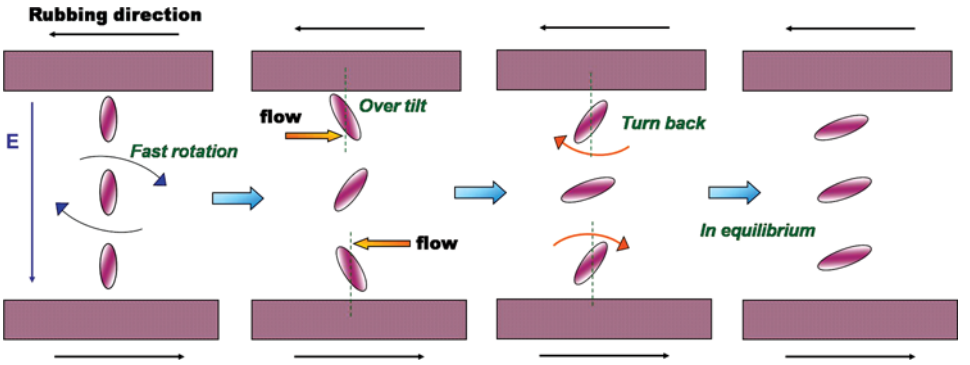

Figure 1. Schematic of the process of flow motion. While the electric field is applied, fast rotation of LC in the middle region would produce a torque to result in a tipping over of the LC director near the substrates. After a moment, LC would turn back to its equilibrium position. (Figure appears in color online.)

[6–9]. They proposed the calculated transient electro-optic (EO) curve has the optical bounce if the flow effect was considered [10]. It discloses that the flow motion plays the key role in the appearance of the bounce. In addition, low azimuthal anchoring energy of homeotropic alignment would produce the azimuthal alignment error. Recently, Chen *et al.* found that azimuthal alignment error is another important factor generating the twist structure throughout the LC cell [11]. In practice, the azimuthal alignment error could not be ignored even the angle is just as small as 0.1 degree. Combination of the flow motion and azimuthal alignment error would result in the optical bounce on the transient EO curve. Once the flow motion or azimuthal alignment error was omitted, the bounce disappears and the transmission coefficient T varies monotonically. The optical bounce induced from LC twist structure increases the response time of LC cells to several hundred milliseconds which is unsuitable for motion-image LCDs. Many research groups and manufactures are devoted to the issue of dissipating optical bounce. Though multidomain alignment with a protrusion could circumvent the optical bounce, it requires several lithographic steps. On the other hand, controlling the wave forms of the applied voltages in the rising period has been proposed to slow down the fast rotation of LCs in the middle region and remove the flow effect. However it is not a simple task for LCD application [5,11].

In this article, we utilize cloth rubbing on silicon oxide surface to eliminate the optical bounce. Gently rubbing increases the azimuthal anchoring energy and induces LCs near the substrates to align with a higher azimuthal accuracy and smaller pretilt angle (the angle between the LC director and the substrate). Winkler *et al.* have investigated analogous phenomena for LCs aligning in the splay geometry [12]. The transient EO curve rising smoothly verifies that we perform a successful mechanical method removing the optical bounce efficiently. This method could be applied to liquid crystal on silicon (LCOS) for its reduction in processing complexity.

2. Experiments and Discussions

2.1. *Sample Preparation*

Instead of employing vertical alignment (VA) polyimide, we utilized sputtered SiO_2 film for LC alignment [13]. This inorganic alignment layer has above average

durability avoiding damage from high-temperature environment and long-time UV light exposure. Here, we used the indium tin oxide glass as the substrates and sputtered-SiO_2 film as alignment film on the substrates with 90° deposition angle (RF $\sim$ 13.56 MHz, pressure $\sim$10 mtorr, and power $\sim$200 watts). Because the sputtered-SiO_2 film is thin and transparent, it could be applied to both transmissive and reflective LCDs. The induced dipole-dipole interaction deduced from Van der Waals force dominates the LC alignment on the SiO_2 film. This vertical sputtering deposition using SiO_2 keeps the negative LCs to be at the field-off homeotropic dark state under crossed polarizers [14]. After sputtering, the SiO_2 film (the thickness is $\sim$105 nm) was gently rubbed with velvet to enhance the LC azimuthal anchoring strength. Thus LCs would be leaded to align in the rubbing direction to decrease the transition time for the twist structure when the electric field is turned on. The LC material used here was MLC-6609 (from Merck) which has negative dielectric anisotropy (for laser wavelength $\lambda = 632.8$ nm, $n_e = 1.5514$, $n_o = 1.4737$, $\Delta\varepsilon = -3.7$, $K_{33} = 17.9 \times 10^{-12}$ N). Then the two substrates were assembled into anti-parallel cells with $\sim$4 μm cell gap to be observed under the crossed polarizers. And the angle between the rubbing direction and the transmitted axis of the front polarizer was 45°. Therefore the cell would be at the field-on bright state. The threshold voltage of our cells filled with MLC-6609 is measured around 2.3 volts, which is in line with the calculated result [15].

2.2. *Electro-Optical Curve Properties*

We fabricated several cells with different rubbing strength (see Table 1) to compare their electro-optical properties. Though glassy spacers in three cells are the same size (4 μm), there are still slight variations in these cell gaps after being fabricated by hands. In Table 1, the A cell is unrubbed and the rubbing depth of the C cell is 200 μm deeper than the B cell. Rubbing strength (RS) relates to the rubbing depth (M) as follow:

$$RS = M(2\pi nr/\nu - 1),$$

where n is the rotation frequency of the roller, r is radius of the roller and ν is translating speed of the substrate [15]. According to the relation, B cell has RS $\sim$ 187 mm (M $\sim$ 1 mm, r = 30 mm, n = 10 Hz, $\nu = 7$ mm/s) and C cell has RS $\sim$ 225 mm (M $\sim$ 1.2 mm, other parameters are identical to those of B cell). The larger rubbing depth corresponds to the larger rubbing strength. In Table 1, we describe the rubbing strength of A, B, and C cells to be unrubbed, mildly rubbed, and moderately rubbed which is easy for description as follows. Figure 2 shows the rising time versus applied voltage of these three LC cells. When the voltage is lower than 5.8 volts, the rubbing

Table 1. A B C cells with different cell gaps and rubbing strength

	Cell gap (μm)	Rubbing strength
A	3.9	Unrubbed
B	4.4	Mildly rubbed
C	3.8	Moderately rubbed

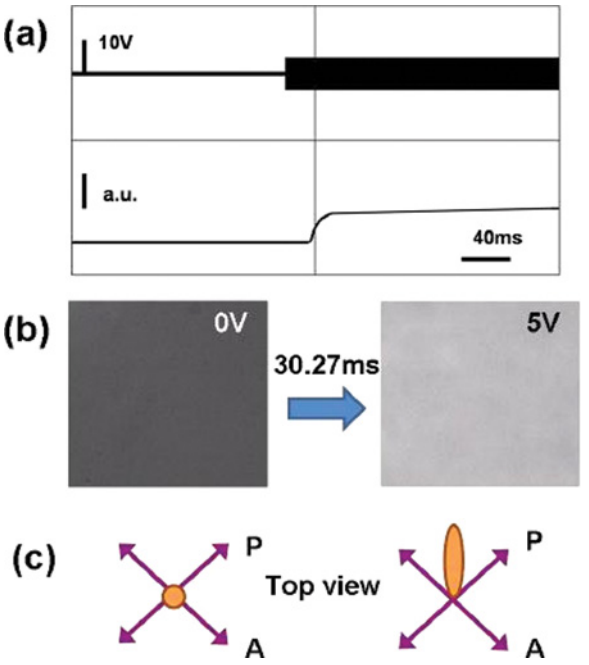

Figure 2. The rising time vs. applied voltage. When the voltage is lower than 5.8 volts, the cell gap dominates the rising time. Thicker cell gap (B cell) causes the rising time a little longer. With the applied voltage larger than 5.8 volts, the rising time of the rubbed-SiO_2 cells maintains less than 50 ms and that of the unrubbed-SiO_2 cells increases greatly to 500 ms. (Figure appears in color online.)

strength does not have significant influence on the rising time. In this situation, the rising time is basically dominated by the cell gap. Due to the lager cell gap, the rising time of B cell is a little longer than those of other cells. If the applied voltage is larger than 5.8 volts, the rising time of the rubbed- and unrubbed-SiO_2 cells would become very different. Upon increasing applied voltage, the rising time of the rubbed-SiO_2 cells maintains less than 50 ms, while that of the unrubbed-SiO_2 cells increases greatly to 500 ms. We argue that a sudden and large gradient of the electric field could cause a tipping over and disorder of LCs near the substrates in the unrubbed-LC cell and this makes the rising time much longer. The transmission curve of A cell (unrubbed) was measured at the applied voltage 5 volts in Figure 3(a). Although the SiO2 film was unrubbed, there is no appearance of the optical bounce and the transmission curve rises smoothly due to the smaller applied voltage (less than 5.8 volts). Based on the results in Figure 3(a) and (b), we find that it takes $\sim$30 ms for the cell to transform from its dark state into the field-on bright state under the observation via the polarizing optical microscope. Figure 3(c) is the top-view arrangement of LC director and the crossed polarizers. The left photograph is the field-off homeotropic state and the right one is the planar state under bias voltage. When A cell (unrubbed) was applied with voltage 10 volts, the optical bounce occurred in the rising period of the transmission curve (see Fig. 4(a)). This result is in good agreement with the tremendous increase of the rising time in Figure 2. Figure 4(b) shows the LC cell photographs under the polarizing optical microscope with increased applied voltage. From left to right, the LC cell undergoes the twist

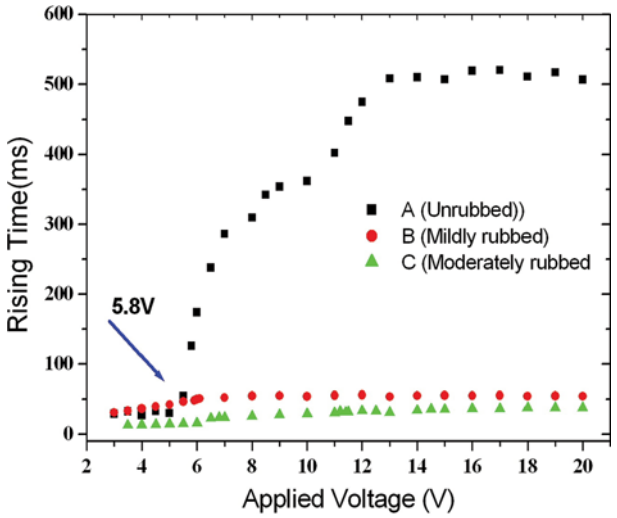

Figure 3. Transient EO curve and polarizing optical micrograph of A cell with applied voltage 5 volts. (a) Although the SiO_2 film was unrubbed, there is no appearance of the optical bounce in EO curve due to the applied voltage is smaller than 5.8 volts. (b) The A cell transforms its dark state into the field-on bright state under the optical microscope with crossed polarizers. And the time for this transformation is ~30 ms. (c) The arrangement of LC director and the crossed polarizers. The left photograph is field-off dark state and the right is field-on bright state. (Figure appears in color online.)

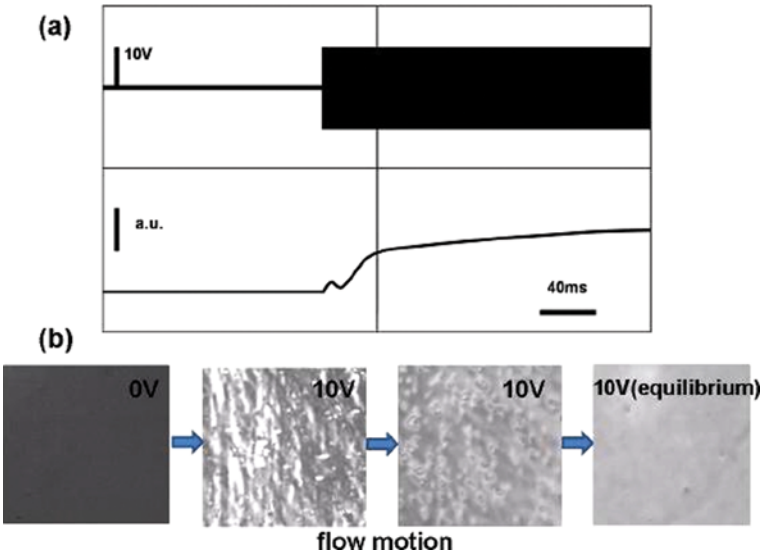

Figure 4. Transient EO curve and polarizing optical micrograph of A cell with applied voltage 10 volts. (a) When A cell (unrubbed) is applied with voltage 10 volts, the optical bounce occurs in the rising period of the transmission curve. (b) The LC cell photographs under polarizing optical microscope. From left to right, the LC cell undergoes the twist states with flow and transforms from the homeotropic to homogeneous state. The rising time of this complex transformation is ~361ms. (Figure appears in color online.)

states with flow and transforms from the homeotropic to homogeneous state. The rising time of this complex transformation is ~361 ms. On the contrary, there is no optical bounce found in the transmission curve when B cell was under bias with applied voltage of 10 volts (see Fig. 5(a)). Though the flow was still observed in these mildly-rubbed cells under the polarizing optical microscope (Fig. 5(b)), the rising time decreased to only 54 ms. The transient-state photograph observed under the optical microscope of the C cell is similar to the Figure 5(b) taken from the B cell. It presents that the mechanical surface treatment takes effect indeed. In the unrubbed cell the inclination of the director under the voltage (the azimuthal angle) is degenerate in the plane (the degree of the degeneracy is infinity). Contrary in the rubbed cells there is a preferred direction given by the rubbing and the degeneracy is lifted. We speculate that the time for the twist state between the transitions from homeotropic to planar state of the rubbed cell is much less than that of the unrubbed one. Therefore, the rising time of the rubbed cell drops drastically and the optical bounce disappears in the transmission curve.

2.3. *Measurement and Discussions of Pretilt Angle and Polar Anchoring Energy*

The polar anchoring energy and pretilt angle of the LC cells with different rubbing strength were measured and listed in Table 2 [15,17]. According to the results shown in Table 2, the polar anchoring energy decreases with the increased rubbing strength. The polar anchoring energy of the rubbed cells (B and C cells) is $1.87 \times 10^{-4}\,\mathrm{J/m^2}$

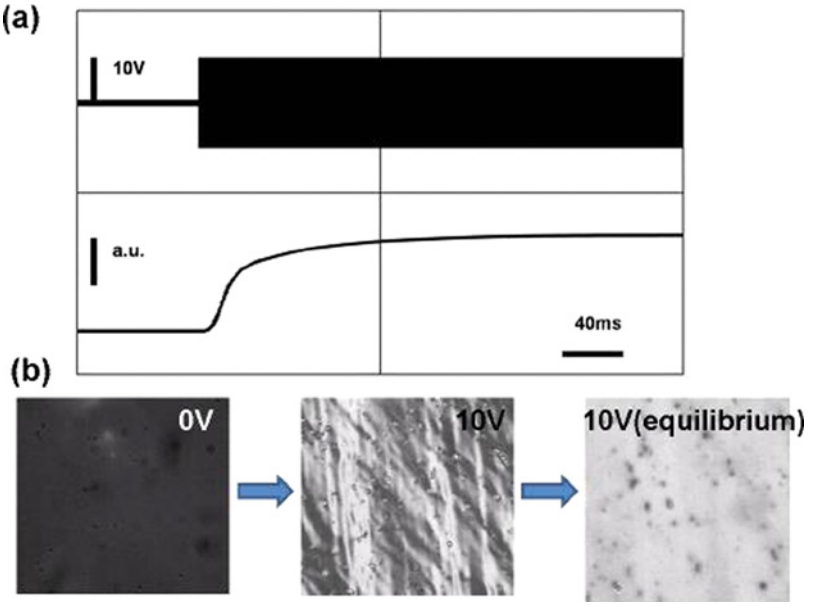

Figure 5. Transmission curve and polarizing optical micrograph of B cell with 10 volts. (a) When B cell (mildly rubbed) was under bias with applied voltage of 10 volts, there is no optical bounce found in the transmission curve. (b) The flow effect generated by fast rotation of middle LC layer is inevitable in rubbing remedy. Though the flow was still observed under the polarizing optical microscope (the middle photograph), the rising time decreased to only 54 ms which is only one seventh of that of unrubbed cell. (Figure appears in color online.)

Table 2. Different rubbing strength cause corresponding pretilt angle and polar anchoring energy

Rubbing strength	Pretilt angle	Anchoring energy (J/m^2)
(A) Unrubbed	87.5°	8.24×10^{-4}
(B) Mildly rubbed	86.2°	1.87×10^{-4}
(C) Moderately rubbed	82.9°	1.42×10^{-4}

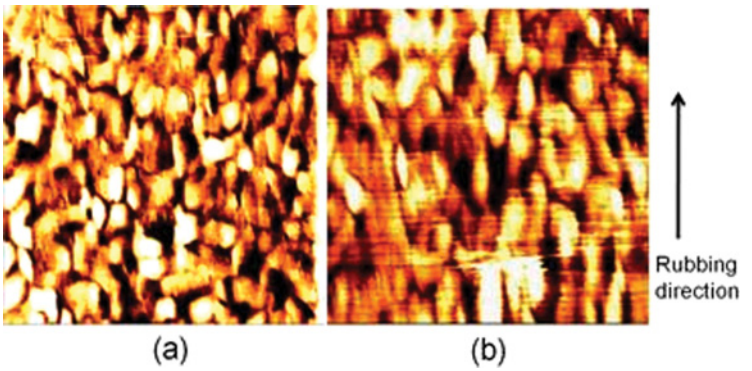

Figure 6. AFM images of SiO_2 surface. (The widths are both 3 μm) (a) SiO_2 surface without rubbing. (b) After rubbing, SiO_2 surface structure becomes anisotropic and leans towards the rubbing direction. (Figure appears in color online.)

and $1.42 \times 10^{-4}\,J/m^2$ respectively, which are both smaller than the polar anchoring energy $8.24 \times 10^{-4}\,J/m^2$ of the unrubbed A cell. After rubbing, SiO_2 surface structure varies to lower polar anchoring energy and changes the dipole direction which results in slightly smaller pretilt angle. Figure 6(a) is the AFM image of 90°-deposited SiO_2 surface without rubbing. Compared with unrubbed SiO_2, SiO_2 surface structure after rubbing becomes anisotropic and tends to lean parallel to the rubbing direction slightly (as shown in Fig. 6(b)). This results are similar to the tilt-evaporated SiO_2 which is used to control the pretilt angle in previous literature [14]. The pretilt angles are 87.5° for the unrubbed A cell and 86.2°, 82.9° for the two rubbed cells (B and C cells). With 90° deposition angle, SiO_2 tends to form columnar structure near vertically. This induces the pretilt angle of unrubbed LC cell slightly differs from 90°. Larger rubbing strength generates smaller pretilt angle and polar anchoring energy. The similar result of rubbing VA polyimide causing the change of pretilt angle has been published [18]. While the electric field is applied, slightly smaller pretilt angle leads LC a toppling direction which could lessen the opposite tilt effect. In equilibrium, LC tends to align along the rubbing direction to keep the total energy including LC itself, the electric field interaction and the elastic energy at its lowest.

3. Conclusions

Homeotropically aligned LCD has the excellent contrast, but weak azimuthal anchoring energy which results in a longer response time. In our work, we utilize

the rubbing treatment to slightly vary the tilted direction of SiO_2 and provide a smaller pretilt angle which could increase the azimuthal anchoring energy. Larger azimuthal anchoring energy improves the azimuthal accuracy of LCs near the substrates to decrease the transition time for LC twist state. Thus, the response time of rubbed cells drops more than the unrubbed one. Additionally, the transient EO curve reveals that this mechanical treatment suppresses the optical bounce effectively. For projection displays, rubbing remedy could avoid appearing the protrusion shadow of MVA technique and save complex nanolithography process. We believe this mechanical method could be applied to LCOS devices, such as projectors and portable displays, for its simple execution and efficiency.

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