

Eliminating optical bounce of homeotropic liquid crystal cells with sputtered silicon dioxide alignment films by rubbing treatment

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ABSTRACT

In this article, we propose a mechanical rubbing method to eliminate the optical bounce and decrease the response time of homeotropic liquid crystal (LC) cells with sputtered silicon dioxide alignment films. After gently rubbing the inorganic alignment film (sputtered silicon oxide, SiO₂), the decreasing polar anchoring energy results in slightly smaller pretilt angle which gives LC a toppling direction to shorten the transition time while LC cell is applied by an external electric field. The results of our work show that this rubbing remedy can suppress the optical bounce. This simple and efficient surface treatment could be applied to liquid crystal on silicon (LCOS) technique for high resolution microdisplays and portable electronic products.

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1. Introduction

Homeotropic alignment of LCs is widely used for 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 decreased 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 causing long response time in homeotropic cells. This phenomenon is also called the back flow effect. Fig. 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 results in a tipping over of the LC director near the substrates [5]. The flow motion would lead the director of LCs near the 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 1970s, Berreman and van Doorn numerically derived the equation of motion for LCs based on the continuum theory of Ericksen and Leslie [6–9]. They pointed out 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°. 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 100 ms which is unsuitable for motion-image LCDs. Many research groups and manufacturers 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). A smaller pretilt angle corresponds to a weaker polar anchoring energy but a stronger azimuthal anchoring strength. 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 LCOS for its reduction in processing complexity.

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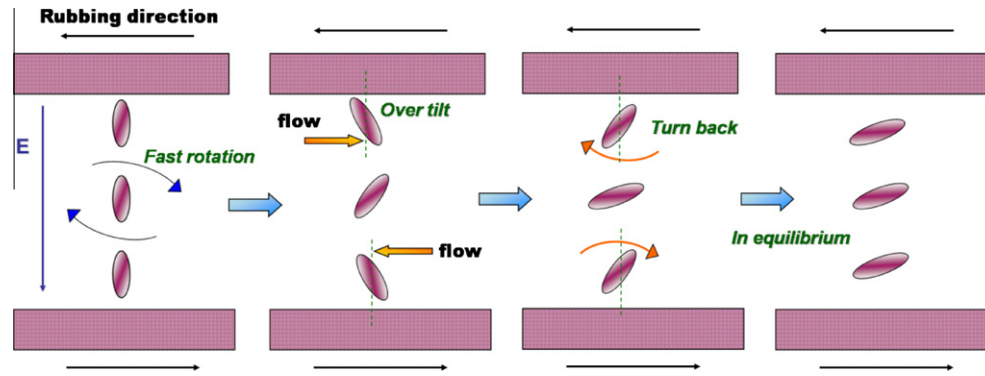


Fig. 1. Schematic of the process of flow motion. While the electric field is applied, fast rotation of LC in the middle region would produce a torque to result in a tipping over of the LC director near the substrates. After a moment, LC would turn back to its equilibrium position.

2. Experimental details

2.1. Sample preparation

Instead of employing vertical alignment (VA) polyimide, we utilized sputtered-SiO₂ film for LC alignment [12]. 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-SiO₂ film as alignment film on the substrates with 90° deposition angle (RF~13.56 MHz, pressure~10 mtorr, and power~200 watts). Because the sputtered-SiO₂ 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 SiO₂ film. This vertical sputtering deposition using SiO₂ keeps the negative LCs to be at the field-off homeotropic dark state under crossed polarizers [13]. After sputtering, the SiO₂ film (the thickness is ~105 nm) was gently rubbed with velvet to enhance the LC azimuthal anchoring strength. Thus LCs would be led 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, $n_e = 1.5514$, $n_o = 1.4737$, $\Delta\epsilon = -3.7$, $K_{33} = 17.9 \times 10^{-12}$ N/m). Then the two substrates were assembled into anti-parallel cells with ~4 μ m 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 consistent with the calculated result [14].

2.2. Electro-optical curve properties

We fabricated several cells with different rubbing depth and rubbing strength (see Table 1) to compare their electro-optical properties. Though glassy spacers in three cells are the same size (4 μ m), 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 μ m deeper than the B cell. Rubbing strength (RS) relates to the rubbing depth (M) as follow:

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

where n is the rotation frequency of the roller, r is radius of the roller and v is translating speed of the substrate.[15] According to the relation, B cell has RS~187 mm ($M \sim 1$ mm, $r = 30$ mm, $n = 10$ Hz, $v = 7$ mm/s) and C cell has RS~225 mm ($M \sim 1.2$ mm, other param-

Table 1

A, B, and C cells with different cell gaps, rubbing depth and rubbing strength.

	Cell gap (μ m)	Rubbing depth (mm)	Rubbing strength
A	3.9	None	Unrubbed
B	4.4	1	Mildly rubbed
C	3.8	1.2	Moderately rubbed

eters 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. Fig. 2 shows the rising time versus applied voltage of these three LC cells. The rising time is defined as the period that the transmission curve undergoes from 10% to 90% while applying with a saturated voltage.[14] When the voltage is lower than 5.8 volts, the rubbing 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 larger 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-SiO₂ cells would become very different. Upon increasing applied voltage, the rising time of the rubbed-SiO₂ cells maintains less than 50 ms,

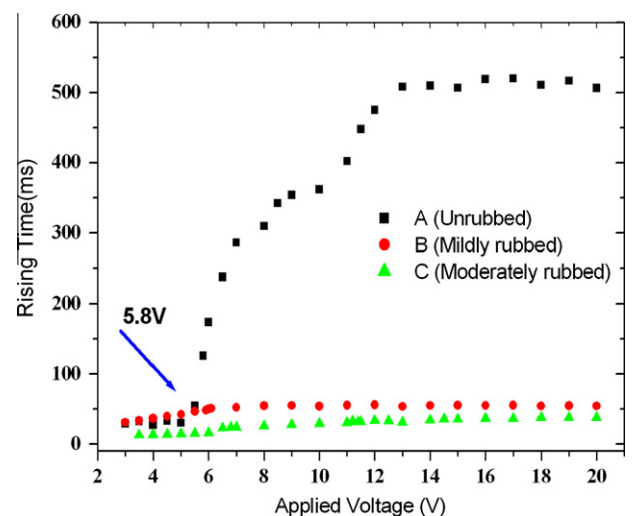


Fig. 2. The rising time vs. applied voltage. When the voltage is lower than 5.8 volts, the cell gap dominates the rising time. Thicker cell gap (B cell) causes the rising time a little longer. With the applied voltage larger than 5.8 volts, the rising time of the rubbed-SiO₂ cells maintains less than 50 ms and that of the unrubbed-SiO₂ cells increases greatly to 500 ms.

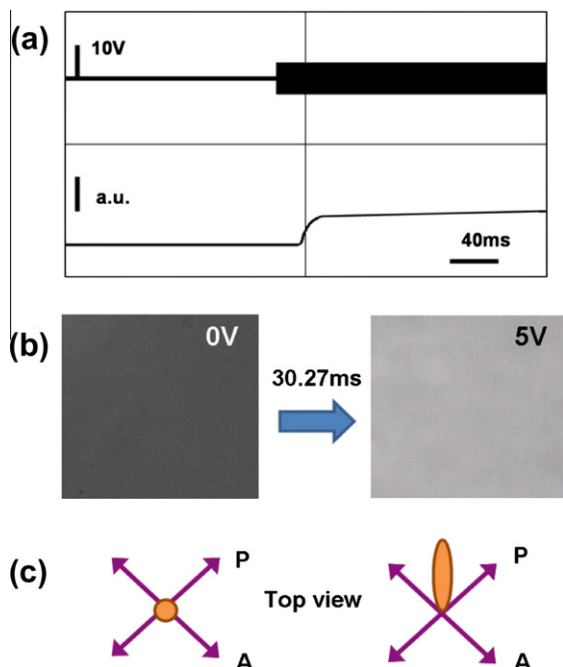


Fig. 3. Transient EO curve and polarizing optical micrograph of A cell with applied voltage 5 volts. (a) Although the SiO₂ film was unrubbed, there is no appearance of the optical bounce in EO curve due to the applied voltage is smaller than 5.8 volts. (b) The A cell transforms its dark state into the 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.

while that of the unrubbed-SiO₂ 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 Fig. 3a. Although the SiO₂ film was unrub-

bed, 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 Fig. 3a and b, we find that it takes ~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. Fig. 3c 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. 4a). This result is in good agreement with the tremendous increase of the rising time in Fig. 2. Fig. 4b shows the LC cell photographs under the polarizing optical microscope with increased applied voltage. 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 ~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. 5a). Though the flow was still observed in these mildly-rubbed cells under the polarizing optical microscope (Fig. 5b), 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 Fig. 5b taken from the B cell. It presents that the mechanical surface treatment takes effect indeed. 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 [14,16]. According to the curve of phase retardation versus applied voltage, the polar anchoring energy could be calculated from the slope of the curve. The relationship is

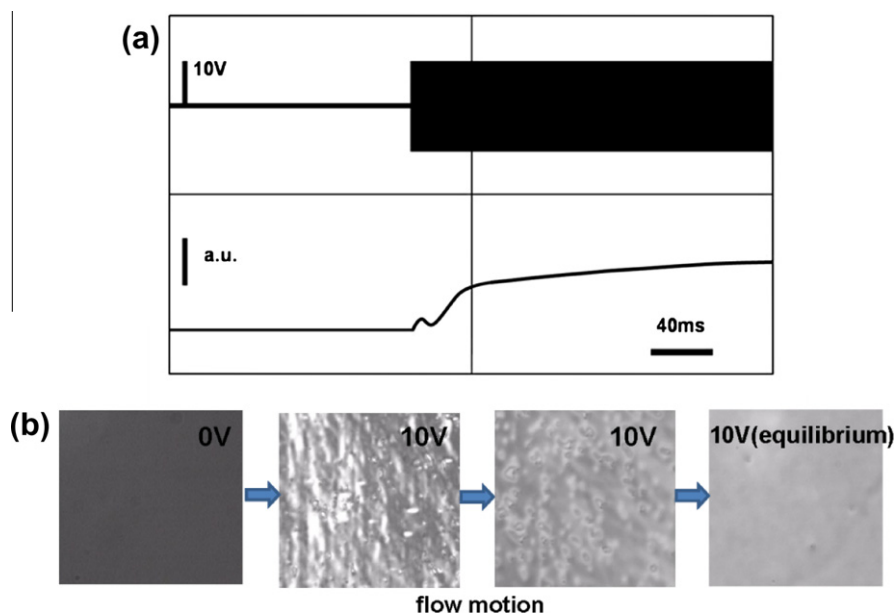


Fig. 4. Transient EO curve and polarizing optical micrograph of A cell with applied voltage 10 volts. (a) When A cell (unrubbed) is applied with voltage 10 volts, the optical bounce occurs in the rising period of the transmission curve. (b) The LC cell photographs under polarizing optical microscope. 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 ~361 ms.

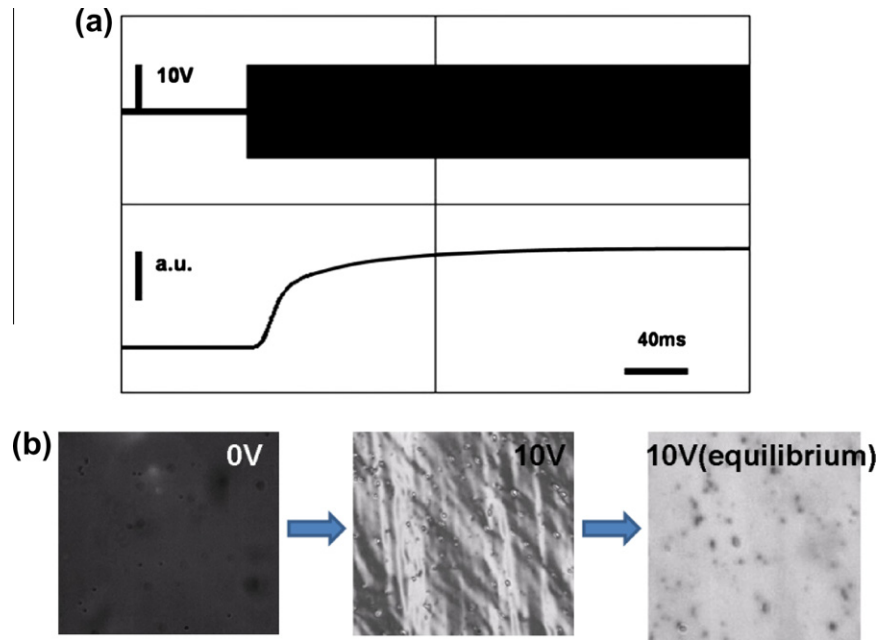


Fig. 5. Transmission curve and polarizing optical micrograph of B cell with 10 volts. (a) When B cell (mildly rubbed) was under bias with applied voltage of 10 volts, there is no optical bounce found in the transmission curve. (b) The flow effect generated by fast rotation of middle LC layer is inevitable 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.

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

Rubbing strength	Pretilt angle	Polar 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}

$$m = \frac{2k_1}{wd} (1 + ky_p) R_0 \quad (2)$$

m is the slope, W is the polar anchoring energy, K_1 is the splay elastic constant, d is the cell gap, $y_p = \sin^2 \theta_p$, R_0 is the phase retardation without an applied voltage, $k = \frac{K_3 - K_1}{K_1}$. 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 1.87×10^{-4} J/m² and 1.42×10^{-4} J/m² respectively,

which are both smaller than the polar anchoring energy 8.24×10^{-4} J/m² of the unrubbed A cell. After rubbing, SiO₂ surface structure varies to lower polar anchoring energy and changes the dipole direction which results in slightly smaller pretilt angle. Fig. 6a is the AFM image of 90°-deposited SiO₂ surface without rubbing. Compared with unrubbed SiO₂, SiO₂ surface structure after rubbing becomes anisotropic and tends to lean parallel to the rubbing direction slightly (as shown in Fig 6b). The rubbed SiO₂ film forms oblique columnar structure which tends to align LC director parallel to the SiO₂ columnar direction via the dipole–dipole interaction between LCs and SiO₂. The rod-like LCs with a small pretilt angle would lie down parallel to the rubbing direction without tipping over the normal of the substrate. This could lessen the optical bounce and make the response time faster. These results are similar to that of the tilt-evaporated SiO₂ which is used to control the pretilt angle in the previous literature [13]. The pretilt angles are 87.5° for the unrubbed A cell and 86.2°, 82.9° for the

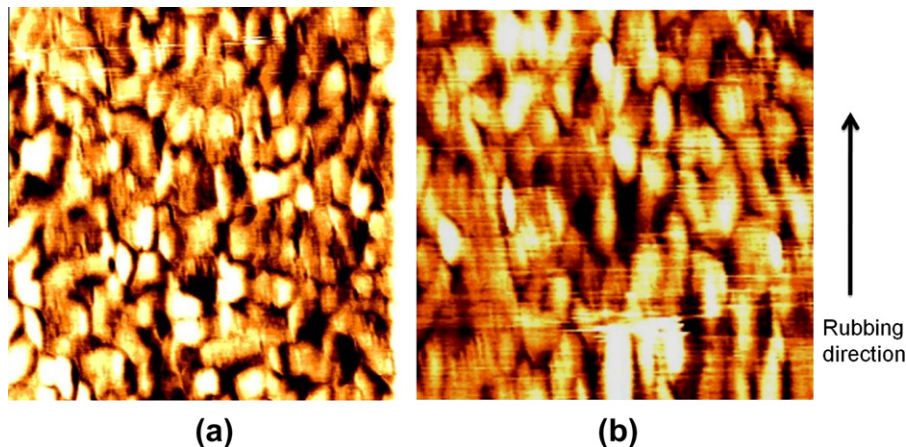


Fig. 6. AFM images of SiO₂ surface. (The widths are both 3 μm) (a) SiO₂ surface without rubbing. (b) After rubbing, SiO₂ surface structure becomes anisotropic and leans towards the rubbing direction.

two rubbed cells (B and C cells). With 90° deposition angle, SiO₂ 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 [17]. 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 SiO₂ 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 is smaller than that of the unrubbed ones. Additionally, the transient EO curve reveals that this mechanical treatment suppresses the optical bounce effectively. For microdisplays, rubbing remedy could avoid the protrusion shadow resulting from typical of MVA technique, and the necessity to employ other complex nanolithography process. We believe this mechanical method could be applied to

LCOS devices, such as viewfinders, virtual reality headsets, and substitution of PC monitors, for its simplicity and efficiency.

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