Alignment of Liquid Crystals by Ion Etched Grooved Glass Surfaces

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The alignment properies of the nematic liquid crystal (LC) 4'-n-pentyl-4-cyanobiphenyl (5CB) on glass substrates with parallel grooves are studied. The U-shaped grooves with a variety of depths and periods were prepared by the reactive ion etch method. Surface morphology of the grooved glass was examined by an Atomic Force Microscope. An LC cell consisting of a pair of parallel grooved substrates with 5CB sandwiched in between was assembled. The alignment quality for the LC was studied by measuring its surface azimuthal anchoring strength. The effect of the groove period and depth were studied. Strong anchoring with strengths larger than 10^{-5} J/m^2 can be achieved with groove depths of 56 or 121 nm and periods less than 4 μm.

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I. INTRODUCTION

The surface of the glass substrate plays an important role in the physics of liquid crystals (LC) and their industrial applications. It constrains the LC and orients the surface LC director, which is the unit vector representing the average orientation of the LC molecules. The equilibrium director orientation, determined by anisotropic molecular interactions between the LC molecules and the surface in the absence of any external fields, is called the "easy axis". In LC display technology, anchoring strength is an important parameter for designing the display mode. There are two types of surface anchoring involved: polar and azimuthal anchoring. Polar anchoring concerns the out-of-plane tilt of the LC director on the surface from the easy axis. Azimuthal anchoring concerns the in-plane angle displacement from the easy axis. In this work, the alignment quality for an LC on a grooved glass surface is studied by measuring its azimuthal anchoring strength. There are various methods of surface alignment for LCs. The characteristics of these methods have been investigated extensively [1]. Rubbed polymer layers are widely used in the LC industry because of their efficient performance in large-area displays. The rubbing process leads to a surface anisotropy, either in surface morphology or polymer molecular alignment, which aligns LC molecules in contact with the rubbed polymers [2, 3]. However, the fiber residues and static charges introduced by rubbing can also cause trouble for devices with fine patterns. Other alignment methods, such as photo-alignment [4] and ion beam bombardment [5], have also been intensively studied recently. The applications of LCs, however, would be much further extended if the alignment process can be carried out with common semiconductor lithographic processes. The characteristic small area and multi-domain properties of

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such processes can allow the LC devices to be integrated with other devices, such as microelectromechanical system (MEMS). The functionality of these hybrid devices can also be much increased by including LC components. There are two recognized mechanisms for the alignment of LCs on rubbed polymer film. The first one was suggested by Berreman: the elongated LC molecules prefer to align parallel to the induced grooves to reduce the total surface free energy [2]. On the other hand, Geary et al. suggested that LC molecules are anchored to buffed polymer chains of the polymer surfaces. The alignment of the LC then follows in an epitaxial manner [3]. In a previous work, we have studied the LC alignment to the substrates with polyimide films modified by an atomic force microscope (AFM) tip. The tip was scanned to scribe the polyimide-coated substrates line by line with various line densities. A better alignment effect and a higher anchoring strength could be obtained by increasing the line density. The number of times of modification, on the other hand, has little effect on the anchoring strength. In this work, we study the alignment of LCs on etched bare glass substrates without any coating. The U-shaped grooves are formed on the substrate with variable depths and spacing by using the reactive ion etching (RIE) method. Anchoring strength is measured for each condition. In section II, the glass etching method, surface characterization, and LC cell preparation are described. The anchoring strength measurement and its principle are described in section III. The results together with the discussion are presented in section IV. A conclusion is given in the last section.

II. SUBSTRATE PREPARATION

Two common processes in the semiconductor integrated circuits industry, lithography and reactive ion etching (RIE), were used to create parallel grooves on an uncoated glass surface. The STN LCD (super-twisted nematic liquid crystal display) grade glass was obtained by removing the Indium-tin-oxide (ITO) coating from industrial-quality ITO-coated STN LCD glasses. A positive photo-resist (FH-6400L) was then coated on the glass with a spin coater and afterwards softly baked at 80°C. An exposure process followed to induce, by using a contact method, a photochemical transformation of patterns on a mask having nine grating-like patterns with various periods. The exposed photo-resist was then developed for 20 seconds, followed by hard baking at 110°C for 20 minutes, to form photo-resist stripes on the glass. The part of the glass surface uncovered by the photo-resist was etched away from the bulk by using the RIE method. The etching time of the RIE was varied to give different groove depths. Surface morphology of the grooved glass was examined by a tapping-mode AFM (Digital Instruments Nanoscope 3100). Fig. 1 shows an example of the AFM image of our etched glass surface. In this example, the groove depth is 13.6±0.3 μm and the period is 7.0 μm. The root mean square roughness for the top surfaces and bottom surfaces are 0.37 nm and 0.46 nm, respectively.

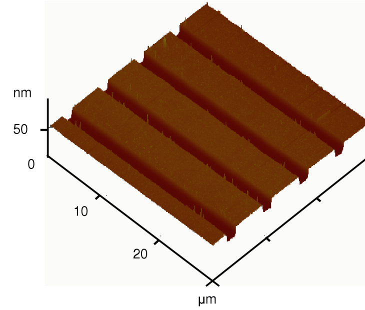

FIG. 1: AFM image of parallel grooved glass surface, which were prepared by the RIE method with a depth of 13.6±0.3 nm and period of 7.0 μm.

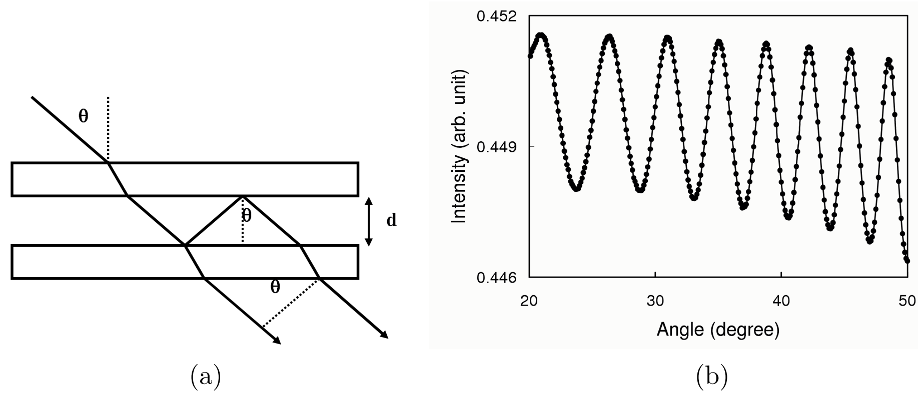

FIG. 2: The rotational interferometric method for LC cell gap measurement. (a) A sketch of the optical path through a cell. (b) An example of the transmittance through an empty cell (θ_1=31.0°, θ_2=26.4°, Δm=1, λ=632.8 nm), from which we can obtain d=8.2 μm.

III. ANCHORING STRENGTH MEASUREMENT

Two substrates with parallel grooves, created as described in the previous section, were placed together with a Mylar spacer to form an empty cell. The cell gap between the two substrates was measured by a rotational interferometric method [6, 7]: A He-Ne laser beam was incident on the empty cell, and the transmittance was measured as a function of the incident angle. In Fig. 2(a), we show a sketch for the optical interference from the cell. An example of transmittance for the empty cell is shown in Fig. 2(b). The peaks correspond to incident angles satisfying the following condition:

$$2d\cos\theta = m\lambda\,, \tag{1}$$

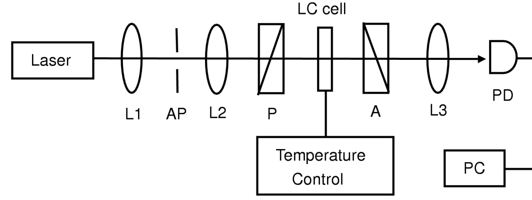

FIG. 3: Setup for anchoring strength measurement. L1, L2, L3: lenses; AP: aperture; P: polarizer; A: analyzer; PD: photo-detector; PC: personal computer.

where m is a positive integer and d is the cell gap. We choose two peaks with angles θ_1 and θ_2, respectively, in the transmittance curve. From Eq. (1), d can be calculated by

$$d = \frac{\Delta m \lambda}{2(\cos\theta_2 - \cos\theta_1)}\,, \tag{2}$$

where Δm is the number of minima between the two chosen peaks. The accuracy of the cell gap measurement and the uniformity of the cell gap on each cell are both under 0.2 μm. Among all of the samples used in this study, the gaps varied between 7 and 10 μm.

To measure the anchoring strength of the grooved substrate, nematic LC 4'-n-pentyl-4-cyanobiphenyl (5CB) doped with a 0.15 wt% of left handed chiral dopant ZLI-811 (Merck) was filled into the gap of the above empty cell, and an LC cell was formed. The natural pitch of the mixture, P_o, was measured with the Cano-Wedge method [8] and was found to be 41.5 μm and 45.4 μm, respectively, for the two mixtures used in this study. The planar alignment and the uniformity of alignment of the LC in the cells were confirmed by using a polarizing microscope with crossed polarizers attached. The anchoring strength was measured by an optical method [9] with the system shown in Fig. 3. The temperature of the LC cell was controlled at 25.5±0.3°C during the measurements. We briefly describe our method here. At the boundary, the director deviates from the direction of the grooves by an angle Δ, due to the spontaneous twisting power of the chiral doped nematic LC. The anchoring strength A is defined with the surface free energy F_s by the following equation:

$$F_s = \frac{1}{2} A \sin^2\Delta\,, \tag{3}$$

where A is the anchoring strength. With a total twist angle, θ, in the cell the transmission, T, can be written as follows [10]:

$$T = [\frac{1}{\sqrt{1+u^2}}\sin(\sqrt{1+u^2}\theta)\sin(\theta-\Psi_{pol}) + \cos(\sqrt{1+u^2}\theta)\cos(\theta-\Psi_{pol})]^2 + \frac{u^2}{1+u^2}\sin^2(\sqrt{1+u^2}\theta)\cos^2(\theta+2\Psi_0-\Psi_{pol})\,, \tag{4}$$

and

$$u = \frac{\pi d}{\lambda\theta}(n_e - n_o)\,, \tag{5}$$

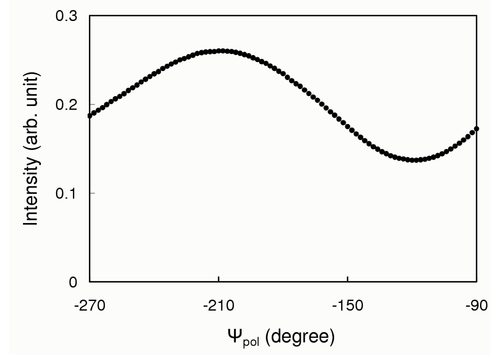

FIG. 4: The transmitted intensity versus the angle between the polarizer and analyzer, Ψ_{pol}. The minimum is obtained by a curve fitting. In this example, we obtain a minimum intensity angle,Ψ_{pol} $= -117.46°$.

where Ψ_0 and Ψ_{pol} are the angles of the LC director at the first surface and the analyzer (exit polarizer), respectively, with respect to the polarizer (entrance polarizer), n_e and n_o are the extraordinary and ordinary refractive indices of the LC, and λ is the wavelength of incident light (λ=632.8nm). The value of T reaches its absolute minimum with respect to the two variables Ψ_0 and Ψ_{pol}, where both of the two terms in Eq. (4) are zero, i.e., the two following conditions are satisfied,

$$\frac{1}{\sqrt{1+u^2}} \sin(\sqrt{1+u^2}\theta) \sin(\theta - \Psi_{pol}) + \cos(\sqrt{1+u^2}\theta) \cos(\theta - \Psi_{pol}) = 0 \,, \tag{6}$$

and

$$\theta + 2\Psi_0 - \Psi_{pol} = \pm\frac{\pi}{2} \,. \tag{7}$$

Our polarizer was parallel to the groove direction and the analyzer was perpendicular to the polarizer initially. Then we rotated the LC cell and the analyzer to vary Ψ_0 and Ψ_{pol} simultaneously with a ratio of 1 to 2. In this way, the second term of Eq. (4) was kept constant. The minimum of T occurred when Eq. (6) was satisfied. Then, we deduced θ from Eq. (6) by using the indices of refraction for 5CB from Ref. [12].

With the deduced twist angle θ, the azimuthal anchoring strength, A, was then obtained by using

$$A = \frac{2K_{22}}{\sin\theta}(\frac{2\pi}{P_o} - \frac{\theta}{d}) \,, \tag{8}$$

where k_{22} is the twist elastic constant. Fig. 4 shows an example of the transmittance measurement. The value for k_{22} (25.5°C) was obtained from Ref. [12].

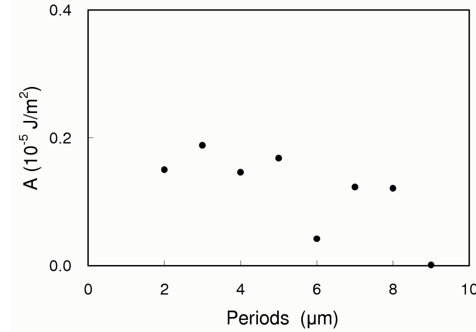

FIG. 5: Anchoring strength of RIE 1 minute substrates with different groove periods (2 μm $\sim$ 9 μm). The depth of grooves is 21 $\pm$ 5 nm.

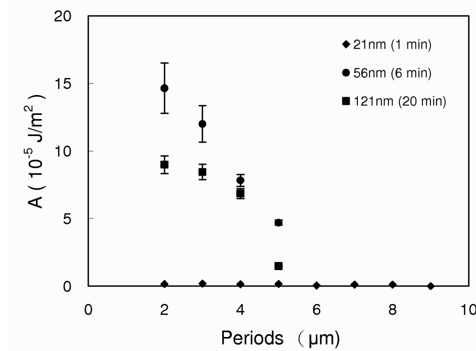

FIG. 6: Anchoring strength versus periods of grooves for various groove depths.

IV. RESULTS AND DISCUSSION

The periods of U-shape grooves were varied from 2 μm to 9 μm in this study. We obtained three different depths by changing the etching time in the RIE process. The depths were 21 $\pm$ 5 nm, 56 $\pm$ 6 nm, and 121 $\pm$ 5 nm for etching time 1, 6, and 20 minutes, respectively.

In Fig. 5, we show the measured anchoring strength versus the groove periods for the samples with substrates etched for 1 minute. The anchoring strengths are within the range of $1\times10^{-8} \sim 2\times10^{-6}$ J/m^2 with an uncertainty of less than 1%. A uniformly planar alignment was achieved, although the anchoring was weak compared to the conventional rubbed substrate (with A around 10^{-4} J/m^2). The effect of groove depth on anchoring strength is shown in Fig. 6 with samples having various etching depth. When the depths are larger than 50 nm, the anchoring strength (larger than 10^{-5} J/m^2) was more than an order of magnitude larger compared to the substrate with shallower grooves.

The anchoring strength of samples with a groove depth of 21 $\pm$ 5 nm (Fig. 5) do not show a dependence on its period. The effect of groove period on anchoring strength

for samples with groove depths of 56 ± 6 nm and 121 ± 5 nm, on the other hand, can be clearly observed in Fig. 6. The anchoring strength decreases with the groove periods and drops drastically when the period reaches 5 μm. The anchoring strength is compatible with that of a conventional rubbed PI substrate when the groove periods are less than 4 μm and the depths are above 50 nm. The major error of this measurement comes from the measurement of the twist angle and the misalignment of the two substrates. When the anchoring strength is less than 10^{-6} J/m^2, the method for measuring the anchoring strength employed here is very accurate with an error less than 1%. On the other hand, for strong anchoring (anchoring strength above 10^{-4} J/m^2), the anchoring strength measuring method employed here has a larger error bar. Because the surface anchoring becomes much stronger than the spontaneous twisting power caused by chiral doping in nematic LC, the director of the LC molecules near the surface deviates only by a small angle (less than 0.5 degree) from the direction of the grooves.

Fig. 6 shows that the anchoring strengths of samples etched for 20 minutes (groove depth of 121 nm) are smaller than those etched for only 6 minutes (grove depth of 56 nm). The mechanism for this phenomenon is not clear yet. It is possibly due to the roughness along the side surfaces within the grooves. Suffice to say that a preparation of the surface with an etching time of 6 minutes would yield excellent alignment results. This is important processing information for the fabrication of future devices requiring integration of LC devices with MEMS.

V. CONCLUSION

In this work we have developed an LC alignment process employing standard semiconductor processing steps. This is advantageous for integrating LC devices with other devices such as MEMS. We have etched U-shape grooves of micron scale with various periods and depths and studied their alignment property and anchoring strength to an LC. The periods of the grooves were varied between 2 and 9 μm. When the depths of the grooves is small (21 ± 5 nm), the anchoring strength ($< 10^{-6}$ J/m^2) is smaller than that of traditional rubbed polyimide surfaces. It can be increased by more than an order of magnitude by varying the groove depth and period. Strong anchoring with strengths larger than 10^{-5} J/m^2 can be achieved with groove depths of 56 or 121 nm and periods less than 4 μm.

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