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The authors fabricated a no-bias pi cell using a dual alignment layer with an intermediate pretilt angle via a rubbing. In the dual alignment layer system, the competition between crest region favoring the vertical alignment and trough region favoring planar alignment made it possible to achieve various pretilt angles, and adjusted pretilt angle from 90° to 20° with rubbing. In addition, as the intermediate pretilt angle plays a role in eliminating the activation energy and thus allowing formation of the initial bend state in pi cell fabrication, this approach achieved a no-bias pi cell for a liquid crystal display with both low power consumption and fast response. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2757121]

The pi cell has been interesting due to its fast response property and wide viewing angle characteristics.[1,2] These distinguishing properties result from the unique liquid crystal (LC) configurations of the pi cell.[3] For example, when driving a pi cell in the bend state, the LC molecules in the center of the LC experience zero elastic torque during the off-state relaxation process, thus producing a fast display response. Generally, a pi cell is fabricated using the alignment layers with the same rubbing directions on the two substrates, and the initial LC configuration is a splay state.[4] Then, an applied voltage transits the pi cell from the splay state to the bend state, and the pi cell presents the image by switching between two kinds of bend states. However, the initial setting voltage, which is the voltage required to set the LC cell into the bend state, is so high that the power consumption property is poor. A simple method to reduce the initial setting voltage is to use the alignment layer with an intermediate pretilt angle.[5]

Numerous methods to achieve an intermediate pretilt angle, including the typical SiO_2 oblique evaporation method, have been developed.[6] Several methods in particular have shown potential for application to large areas and mass production: modification of the polyimide alignment layer by trifluoromethyl moietries,[7] photoirradiation of the photosensitive alignment layer containing azobenzene,[8] a solvent dipping method of the polyimide layer,[9] the mixing of planar and vertical polyimides,[10,11] a nanotexture formation by an atomic force microscope local oxidation,[12] and a nanoimprinting technique containing local deposition of a surface coupling agent.[13] However, there remain several technical difficulties to be overcome such as stability, fidelity, high cost of the manufacturing process, and so on.

The dual alignment layer is a better alternative because one can easily achieve the intermediate pretilt angle through a conventional process without modification of the polyimide or changing the alignment process. In the dual alignment layer, both the underlayer and the upper layer affect LC molecules, thereby determining the pretilt angle. Therefore, if the competition between two interactions, one between the under layer and LC molecules and the other between the upper layer and LC molecules, is adequately controlled, the dual alignment layer can enable the LC to achieve the intermediate pretilt angle. This competition may be described by the dual easy axis model.[14,15] However, while most studies concerning the dual alignment layers have focused on the screening effect of the upper layer on the interaction between LC molecules and the under alignment layer,[16,17] they have not shown feasibility for achieving an intermediate pretilt angle for a no-bias pi cell due to the difficulty of coating the thin upper layer.

In this study, we presented a simple strategy: the introduction of a dual alignment layer to achieve the intermediate pretilt angle. The polyimide favoring planar alignment and poly(dimethylsiloxane) (PDMS) favoring vertical alignment were selected to compose the dual alignment layer, and the upper vertical alignment layer was thin enough to allow for interaction between the LC molecules and the under layer. Eventually, various pretilt angles ranging from 90° to 20° were achieved with rubbing. Then, we fabricated a pi cell using a dual alignment layer with an intermediate pretilt angle. While there is an initial setting voltage in a general pi cell with a low pretilt angle, the pi cell with an intermediate pretilt angle initially showed a bend state without the initial setting voltage.

When the dual alignment layer for the intermediate pretilt angle was introduced, we had to carefully consider the

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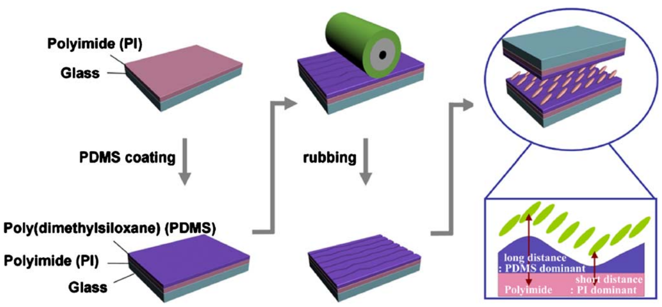

FIG. 1. (Color online) Schematic illustrations for the fabrication of the dual alignment layer and surface morphology of the rubbed dual alignment layer.

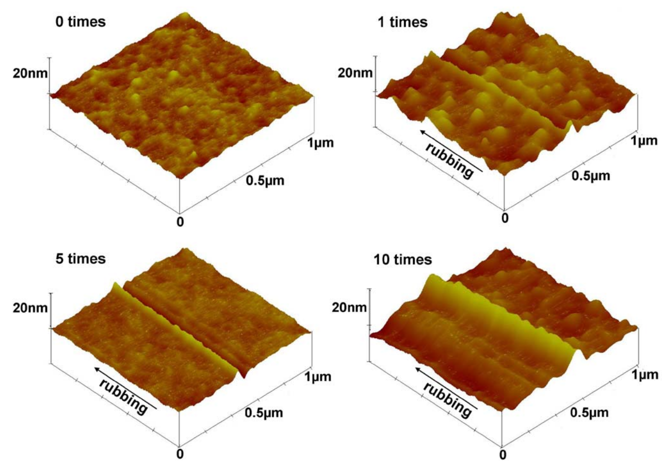

FIG. 2. (Color online) AFM images of the rubbed PDMS surface in the dual alignment layer for the different numbers of rubbings.

thickness of each layer. If the upper layer is too thick, this negates the effect of the underlayer on the interaction between the LC molecules and the alignment layer. When the upper layer is thin enough, however, it allows for the interaction between the LC molecules and under layer, helping to obtain the intermediate pretilt angle. However, it is difficult to uniformly coat a very thin vertical alignment using a conventional spin-coating method. Recently, we reported on a coating technique of the thin PDMS alignment layer by chemical reaction.[18] Its thickness was approximately 10 nm, which is thin enough for the under layer to affect the LC alignment. Here, we used the polyimide (AL2001, JSR) favoring planar alignment as an under alignment layer and the PDMS favoring vertical alignment as an upper alignment layer in the dual alignment layer geometry. Figure 1 shows the schematic illustration of coating of the dual alignment layer and rubbing for the intermediate pretilt angle. First, the polyimide was spin coated on the glass substrate for 5 s at 500 rpm and then for 70 s at 2600 rpm. The coated polyimide was cured on a hot plate for 1 h 30 min at 250 °C. Then, the thin PDMS was coated on top of the polyimide surface through a chemical reaction. To coat the thin PDMS layer, the polyimide surface was treated with oxygen plasma for 1 min at 25 W and then immersed in a 0.5 wt % aqueous solution of 3-(aminopropyltriethoxysilane) (APTES) for 10 min. After washing the untreated APTES with distilled water, the monoglycidyleter-terminated PDMS (Aldrich, USA) was dropped onto the polyimide surface and heated for 4 h at 80 °C to react the monoglycidyleter-terminated PDMS with the amine-terminated surface. After washing the nonreacted monoglycidyleter-terminated PDMS with isopropylalcohol, a thin uniform PDMS layer was obtained. Thus, we achieved a dual alignment layer composed of polyimide and PDMS with approximate thicknesses of 150 and 10 nm, respectively. After coating the two alignment layers, the surface was rubbed with a velvet cloth between zero and ten times to achieve the various pretilt angles.

The surface morphology of the rubbed dual alignment layer was examined with an atomic force microscope (AFM). Figure 2 shows the AFM images of the dual alignment layer with the rubbing. As seen in Fig. 2, the surface of the dual alignment layer gradually became rough with the rubbing in accordance with the results by Kumar *et al.*[19] The effect of rubbing induces to create a physical groove and orient the polymer chain along the rubbing direction in the alignment layer. Although both the groove and oriented polymer chain play roles in aligning the LC molecules, the pretilt angles are mainly determined by the oriented polymer chains.[20] However, in a single alignment layer system, the limit of the area fraction of the oriented polymer chain and the increase in surface polarity produced by the rubbing make it difficult to continuously control the pretilt angle from a vertical alignment to a planar alignment.[21] By contrast, a dual alignment layer can easily generate arbitrary pretilt angles by the effect of the under layer on the interaction between the LC molecules and alignment layer. In the dual alignment layer system, the rubbing converts the upper layer to a tilted vertical alignment layer and makes a physical groove along the rubbing direction. The resultant physical groove results in trough region and crest region in upper alignment layer, inducing a distance difference between the under layer and LC molecules in each region. While the underlayer strongly interacts with the LC molecules in the trough region of the groove, the interaction between the under layer and the LC molecules is weak in the crest region due to their greater separation. Eventually, while the upper layer of PDMS favoring vertical alignment is dominant in the crest region, in trough region the LC molecules are mainly affected by the planar under layer leading to dual easy axis. The dual easy axis competes with each other, and consequently promotes an intermediate pretilt angle. In addition, as the number of rubbing increases, the alignment layer becomes rougher, increasing the influence of the planar region on the LC molecules due to increasing the number of groove and groove depth. The pretilt angle, therefore, becomes lower with rubbing, and the dual alignment layer may promote arbitrary pretilt angles with rubbing.

To observe the dual alignment layer effect on the LC pretilt angle, we fabricated an antiparallel cell for measurement of the pretilt angle. The cell gap was 50 μm, and a LC (MJ001929, Merck, German) with positive dielectric anisotropy was injected in the isotropic phase. The pretilt angle was measured relative to the planar direction. Figure 3 shows the pretilt angles and conoscopy images for different numbers of rubbings. The pretilt angle was easily controlled, ranging from 90° to 20° depending on the number of rubbings. With no rubbing, the dual alignment layer promoted the vertical alignment of LC molecules due to the hydrophobicity of the PDMS and the influence of the under layer being completely screened. However, when the dual alignment layer was rubbed, the competition between interactions in crest region and trough region promoted the change in the

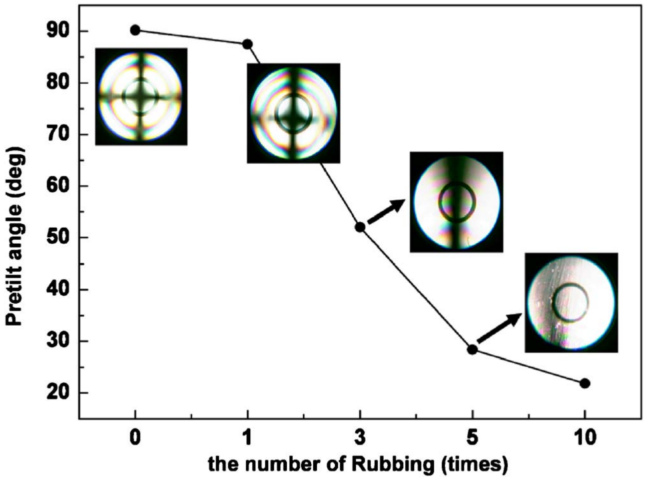

FIG. 3. (Color online) Variation of the pretilt angle with the number of rubbings. The inset represents the conoscopy images of the LC cell with various pretilt angles.

LC pretilt angle, changing the pretilt angle anywhere from 90° to 20°.

Using the alignment layer with an intermediate pretilt angle (52°), a pi cell was fabricated. The rubbing directions on both substrates were parallel to each other and the cell gap was about 4.2 μm. To contrast the behavior of the intermediate pretilt pi cell with a conventional pi cell, a second pi cell was constructed with single polyimide alignment layer (AL 2001) that promotes a pretilt angle of 4°. Figure 4 shows both the voltage-transmittance curves of the conventional pi cell with a low pretilt angle and the pi cell with an intermediate pretilt angle. While the conventional pi cell required an initial setting voltage to create an initial bend state, the dual alignment layer with an intermediate pretilt angle resulted in a no-bias pi cell. This is because the bend state is energetically more stable than the splay state when the pretilt angle is above 47°.[5] Although the stability problem of the intermediate pretilt angle suggests the need for future research, the dual alignment layer in this work shows considerable potential as a developed alignment layer for application in various LC modes.

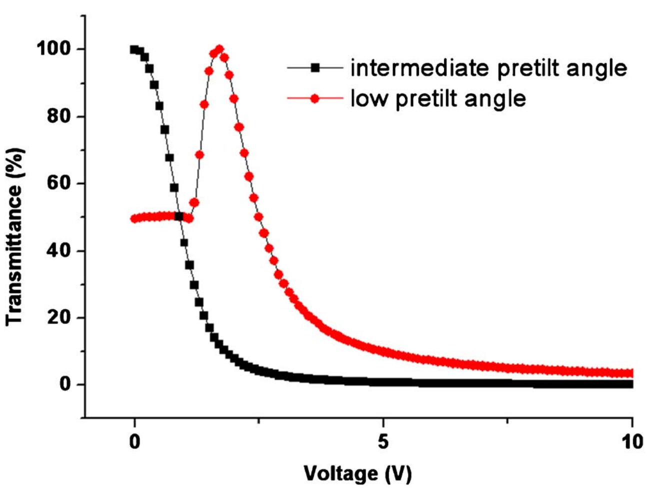

FIG. 4. (Color online) Voltage-transmittance curves of pi cells with a low pretilt angle (red dots) and an intermediate pretilt angle (black squares).

In conclusion, we fabricated a no-bias pi cell using a dual alignment layer with an intermediate pretilt angle via a rubbing. The introduction of dual alignment layers made it possible to achieve various pretilt angles ranging from 90° to 20° with rubbing through the under layer effect on LC alignment. Moreover, an intermediate pretilt angle played a role in overcoming the initial setting voltage in the pi cell. In addition, because the dual alignment layer can easily control the initial pretilt angle through the thickness ratio of the dual alignment layer and the rubbing conditions, it has potential for various applications, including the no-bias pi cell.

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