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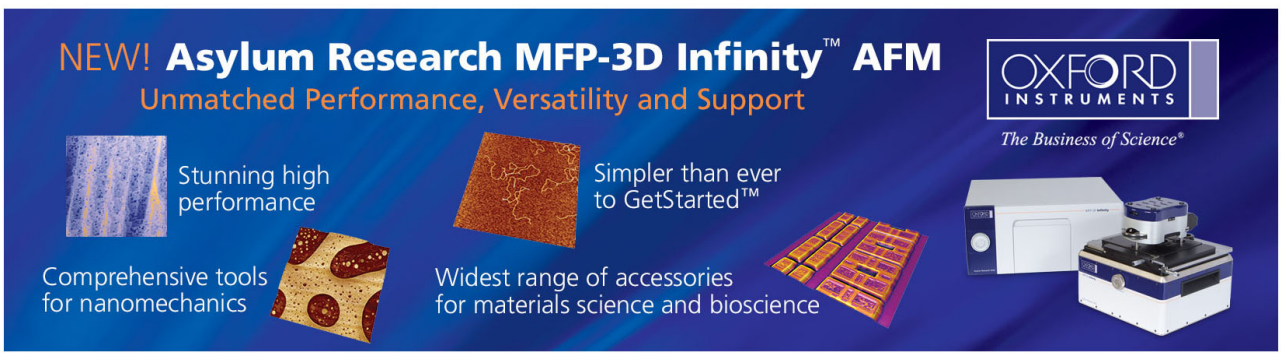

Free alignment defect, low driving voltage of half-V ferroelectric liquid crystal device

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The horizontal chevron alignment defect in half-V mode ferroelectric liquid crystal (FLC) cell can be reduced by asymmetrical alignment hybrid cell. The low free energy level generated from the interaction between spontaneous polarization and opposite polar alignment surfaces was found. As a result, uniformly aligned FLC cell can be achieved without applied external voltage. The R3206 FLC material is applied as model compound. The contrast ratio of R3206–70 is greatly enhanced from 76 to 780 with 1.0 ms response time under 5 V. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3211108]

Ferroelectric liquid crystals (FLCs) have been vigorously studied since surface-stabilized FLC (SSFLC) was first reported in 1980.[1] The characteristics of submillisecond response time and bistability in FLCs have greatly attracted the public attention for exploring numerous applications in fast response devices. Although FLCs possess these interesting properties, their drawbacks, such as high driving voltage, inability of obtaining gray scale, difficulty in achieving well LC alignment, etc., have hindered them from becoming mainstream materials. Numerous FLC modes were previously proposed to provide gray scale ability.[2–8] In particular, the half-V mode FLC (HV-FLC) (also known as continuous director rotation FLC) was developed to achieve continuous gray scale in the 1990s, and the FLC active matrix display application became feasible thereafter.[7,8] The horizontal chevron alignment defect, however, remains unresolved in HV-FLC devices, owing to the indistinguishable free energy from the spontaneous polarization (P_S) up and down domains when the LC is cooled down from N*-SmC* phase,[9,10] as shown in Fig. 1. The horizontal chevron alignment defect is suggested to be suppressed when a dc electric field is applied during the N*-SmC* phase transition.[9,10] This dc voltage annealing process, however, is difficult to implement for the panel making due to the residual charges[11] and subpixels' electrode design. In this study, we approached the horizontal chevron alignment defect issue from the physical aspect of the FLC's elastic free energy. The alignment defect not only can be minimized by lengthening FLC's pitch but also can be further reduced by lowering FLC's free energy from asymmetrical alignment surfaces. The R3206 FLC material was applied as our model compound. The contrast ratio of pitch-lengthened R3206–70 was greatly enhanced from 76 to 780 in the asymmetrical alignment hybrid cell.

The coordinate system of a HV-FLC cell is illustrated in Fig. 1. The molecular director can be expressed as

$$\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta), \tag{1}$$

where θ and ϕ represent the cone angle and azimuthal angle, respectively. When the molecular director of uniformly aligned FLC is parallel to the z-axis, the one dimension total free energy per unit area of FLC cell can be expressed as[12,13]

$$F = \int_{-d/2}^{d/2} W_d dy + F_s, \tag{2}$$

where W_d is the elastic free energy density, F_s is the surface energy per unit area, and d is the cell gap. The elastic free energy density of such uniform state can be simplified as

$$W_d = \frac{2\pi^2}{p^2}\sin^2\theta(K_2\sin^2\theta + K_3\cos^2\theta), \tag{3}$$

where K_2 and K_3 are the elastic constants and p is the pitch length of FLC.

The surface energy per unit area is the energy summation of the top (t) and the bottom (b) substrates, which can be expressed as

$$F_s = \sum_i [\gamma_1^{(i)}(\hat{n}\cdot\hat{s})^2 + \gamma_2^{(i)}(\hat{p}\cdot\hat{s})] = \sin^2\theta(\gamma_1^{(t)}\sin^2\phi_t + \gamma_1^{(b)}\sin^2\phi_b) \mp (\gamma_2^{(t)}\cos\phi_t - \gamma_2^{(b)}\cos\phi_b), \tag{4}$$

where γ_1 and γ_2 are the nonpolar and the polar surface interaction coefficients, respectively, and $\hat{p}$ and $\hat{s}$ are the unit vectors of polarization and surface normal. The negative and positive values correspond to P_S up and P_S down domains in the horizon chevron defects. When FLC molecules are well

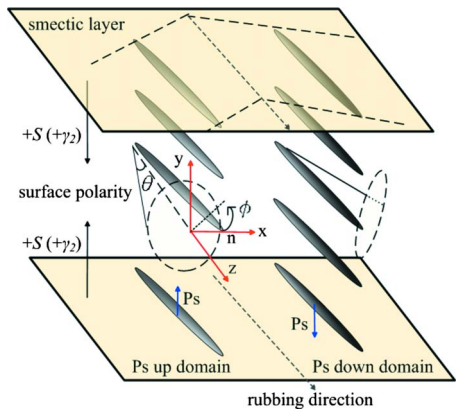

FIG. 1. (Color online) The coordinate system of half-V mode FLC device.

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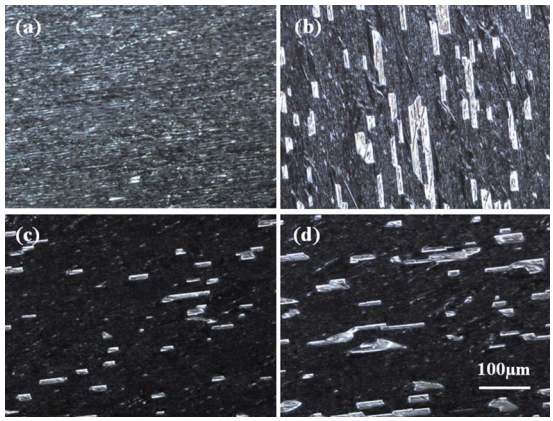

FIG. 2. (Color online) Polarizing optical micrographs of (a) R3206, (b) R3206–80, (c) R3206–70, and (d) R3206–50 in the 1.8 ± 0.1 μm PI cells.

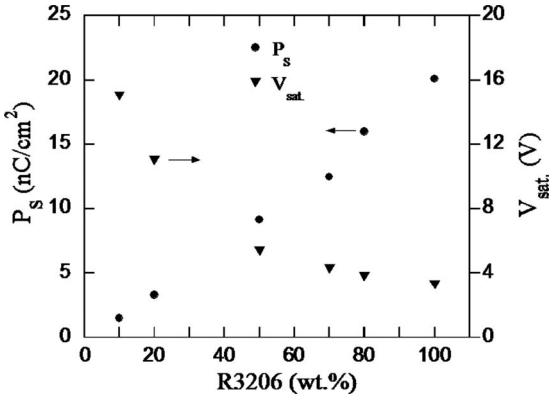

FIG. 3. Spontaneous polarizations and saturation voltages of R3206 and its mixtures.

oriented by rubbing direction in the SSFLC cell ($\phi_t = \phi_b = \phi$), the surface free energies can be rewritten as

$$F_s = \sin^2\theta(\gamma_1^{(t)}\sin^2\phi + \gamma_1^{(b)}\sin^2\phi) \mp (\gamma_2^{(t)} - \gamma_2^{(b)})\cos\phi. \quad (5)$$

Thus, the total free energy per unit area of P_S up and P_S down domains can be expressed as

$$F = \frac{2\pi^2}{p^2}\sin^2\theta(K_2\sin^2\theta + K_3\cos^2\theta) + \sin^2\theta(\gamma_1^{(t)}\sin^2\phi + \gamma_1^{(b)}\sin^2\phi) \mp (\gamma_2^{(t)} - \gamma_2^{(b)})\cos\phi. \quad (6)$$

Based on Eq. (6), lengthening the pitch (p) can lower the free energy and improve the molecular alignment. The P_S up and the P_S down domains, however, coexist in the cells due to the same minimum total free energy, yielding from the same polar surface interaction coefficients from the top and the bottom alignment surfaces, i.e., $\gamma_2^{(t)} = \gamma_2^{(b)}$. As a result, the different polar surface interaction coefficients, γ_2, holds the key to further reduce the FLC's free energy when both the top and the bottom surface polarities (S) stand opposite.[10,13–15] The total free energy of FLC is further degenerated into two energy levels when the term of polar surface energy is not zero. Thus, the uniform molecular alignment yielded from the uniform P_S direction can be obtained at the lowest free energy level in the asymmetrical alignment surfaces.[16]

To validate the theoretical prediction, a HV-FLC material R3206 (Iso 109.9 N* 79.5 SmC* −17.9 C, $P_S = 20.1$ nC/cm^2, $V_{sat.}$ at 3.5 V, pitch$= 0.8 \pm 0.2$ μm, from AZ Electronic Materials) was employed as our model compound. R3206 H (Iso 110.7 N 73.8 SmC −29.7 C), a racemic mixture of R3206, is prepared for adjusting R3206's pitch length. A series of R3206 H was mixed into R3206 at different weight percentages. The alignment textures of R3206 and their various mixtures from polyimide (PI) cells (1.8 ± 0.1 μm) were captured under a polarizing optical microscope. Polydomains are presented in the entire R3206 sample, as shown in Fig. 2(a). The diluted R3206 mixtures appeared to have better alignment than the pure R3206. The larger horizontal chevron domain defects were shown when the weight percentage of R3206 was lower than 70%, as in Figures 2(c) and 2(d). In the series of R3206 mixtures, P_S values were almost linearly depended on the R3206 weight percentage, as shown in Fig. 3. The saturation voltage ($V_{sat.}$), characterized by 100 Hz square wave under 1.8 μm cells, was increased while P_S value was decreased. Among all mixtures, the 70 wt % R3206 mixture, denoted as R3206–70 (Iso 109.4 N* 76.8 SmC* −21.9 C, $P_S = 12.5$ nC/cm^2, pitch $= 3.9 \pm 0.2$ μm), maintains low driving voltage with good alignment. FLC's alignment was improved by pitch lengthening mixture. The contrast ratio of R3206–70 was improved from 11 to 76 in PI cell, comparing with the original R3206. The horizontal chevron defects, however, were still present in the PI cell[12] as the theoretical prediction.

According to Eq. (6), asymmetrical surface polarity hybrid cell was applied to further reduce alignment defects. The P_S direction was drawn to the surface polarity direction, yielding two domains in the symmetrical PI cell, as shown in Fig. 1. On the contrary, the direction of P_S is attracted from the top alignment surface while the direction of P_S is repulsed from the bottom side of the alignment surface in the opposite surface polarities. Consequently, the overall P_S falls into the same direction. In our experiment, polyvinyl alcohol (PVA) and PI were applied for obtaining their opposite surface polarities, which were determined by the dissymmetric cell method.[15] In the PVA-PI asymmetrical surface polarity hybrid cell, the layer structure of R3206 appeared in uniform direction with microdomains, as shown in Fig. 4(a). The horizontal chevron defects were completely suppressed in the pitch-lengthened R3206–70 cell, as shown in Fig. 4(b). Electro-optical properties were characterized by 100 Hz square wave. R3206–70 possesses threshold voltage under 0.8 V with saturation voltages about 3.7 V, as shown in Fig. 5. After utilizing asymmetrical hybrid cell, contrast ratios of R3206 and R3206–70 were greatly improved from 11 to 86 and 76 to 780, respectively. Pure R3206 and R3206–70 demonstrated fast response under 700 μs (rise: 152 μs, fall:

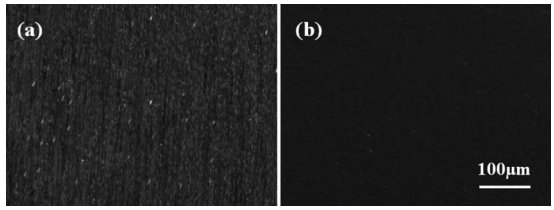

FIG. 4. Polarizing optical micrographs of (a) R3206 and (b) R3206–70 in the 1.8 ± 0.1 μm PVA-PI asymmetrical surface polarity hybrid cells.

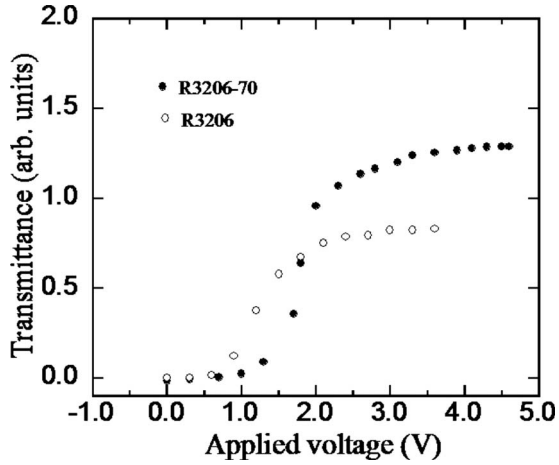

FIG. 5. Electro-optical properties of R3206 and R3206–70 in asymmetrical surface polarity hybrid cells driven by 100 Hz square wave.

520 μs) and 1.0 ms (rise: 240 μs, fall: 760 μs) at 5 V, respectively.

In summary, we have prepared a horizontal chevron defect free FLC device without the need of applying external voltage. The FLC's elastic free energy derived from theory indicates that the lower LC's free energy can be obtained from asymmetrical surface alignment layers in HV-FLC cell. The polar surface interaction is one of the most important parameters besides the pitch length to obtain a good alignment quality in the FLC cell. The contrast ratio of pitch-lengthened R3206–70 in an asymmetrical surface polarity hybrid alignment (PVA-PI) cell has been greatly improved over a factor of 11, compared with symmetrical PI cell. The saturated driving voltage and response time of R3206–70 are maintained at 1.0 ms below 5 V. Thus, the defect free, low driving voltage, fast response FLCs have great potentials to conserve the energy in field sequential color applications or motion-blur reduction in the active matrix thin film transistor (TFT) displays.[17]

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