Effect of azimuthal anchoring strength on stability in a bistable chiral splay nematic liquid crystal device

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The stabilization of the metastable 180° twist state in a bistable chiral splay nematic liquid crystal device is studied. The stability of the metastable 180° twist state is explained using the azimuthal anchoring strength, which is a function of the twist elastic constant and the cell gap. A stable 180° twist state as well as the permanent retention time can be obtained by increasing the anchoring energy above a certain threshold.

A feature of all bistable liquid crystal (LC) devices is the existence of two different states under the condition of zero applied voltage. This property makes it possible for bistable devices to consume less power. However, the bistable LC devices using volume switching as their mechanism have a serious problem [1–4], in that the bistable states are merely metastable, and exhibit a short retention time. The bistable states of those devices that employ surface switching using the surface anchoring effect are stable [5–9]. In bistable LC devices that use volume switching, domains of the undesired state will grow after a few seconds, and erase the information present on the device. The information can be maintained by frequently refreshing the device, but this method increases power consumption. Although Bos and co-workers [10,11] attempted to increase the retention time of bistable states using a multidimensional alignment method, the manufacturing process was troublesome in comparison with that for conventional LC cells, and applications were rather limited. In addition to the mechanical approach for achieving permanent bistable states described in Refs. [10,11], the study of surface effects at the interface between nematic liquid crystals (NLCs) and specially treated substrates is important for an understanding of the physics of the bistable mechanism. Surface effect analyses promise better control of bistable states because the macroscopic behavior of NLCs depends primarily on conditions describing the orientation of the LC director along the boundaries of the display cell. The surface anchoring strength is a parameter that characterizes surface alignment. For nonpolar liquid crystals there are two contributions to the surface anchoring strength, the polar anchoring strength, which constrains out-of-plane motion of the director, and the azimuthal anchoring strength, which restricts the in-plane motion of the director [12–14]. In particular, the azimuthal anchoring strength is a key factor in devices that implement in-plane bistable switching.

In this article, we investigate the effect of the azimuthal anchoring strength on the pair of states encountered in a bistable chiral splay nematic liquid crystal (BCSN-LC) device using horizontal switching. One of the states is characterized by a nontwisted director field with stable 0° splay, and the second state is a director field with a metastable 180° twist [15]. The point here is to achieve a permanent BCSN-LC device by stabilizing the metastable 180° twist state. Because the appearance of bistability is, in general, sensitive to the choice of material parameters such as the Frank constant, pretilt angle, and dielectric anisotropy, and device parameters such as the cell gap and the cell gap over pitch (d/p) ratio, we first study the effect of various device parameters upon the stability and retention time of the 180° twist state. Next, we investigate the surface effect on the metastable 180° twist state using the relationship between the device parameters and the azimuthal anchoring strength. This results in surface conditions capable of permanently maintaining the 180° twist state.

Figure 1 illustrates the transition process of the BCSN-LC device, where the rubbing direction is defined by the *x* direction. By applying a voltage of appropriate amplitude and pulse duration, a bent state is formed (right top). Because of
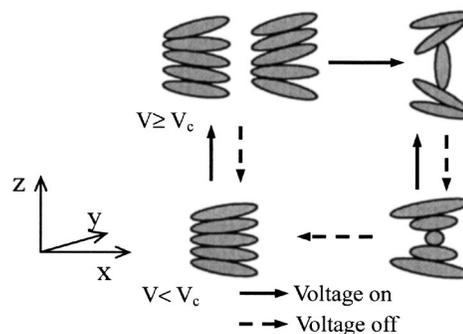
FIG. 1. The transition process for the BCSN-LC cell. In the bend state, removal of the applied voltage transforms the conformation to the twist state because of the flow-induced viscous torque (bottom right).

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the topological inequivalence between the bend and splay states, transformation between the states inevitably accompanies the bent nucleus, resulting from local nonuniformity such as the spacers maintaining the cell thickness and defects of the alignment-layer surface. In this bent state, if the voltage is turned off, it returns to the splay state (left bottom) through the 180° twist state (right bottom). The transition from the 180° twist state to the 0° splay state depends on the viscosity of the LC material and surface irregularities. While the retention time of the twist state is a few seconds in a pure splay cell without a chiral additive, in a splay cell blended with a chiral additive with a cell gap over pitch (d/p) of 0.1, it increases more than ten times. However, if the d/p ratio is above about 0.25, a careful treatment is needed since the initial state with no voltage may be the twist state. The twist state is more stable as the d/p ratio increases. As a result, since the voltage for transforming the twist state to the splay state is able to increase in switching the BCSN-LC cell, it is important to optimize the d/p ratio. In a previous Letter [15], numerical solution of the Ericken-Leslie hydrodynamic equations [16,17] for a nematic cell permits analysis of the flow velocity V_y in the y direction, which plays an important role in the formation of the 180° twist state. It seems that the origins of the twist state are also affected by the boundary conditions. Under parallel-rubbed boundary conditions, there are three possible alignment states: splay, bend, and the 180° twist. Because of the topological equivalence between the bend and the 180° twist states, it is possible to transform from the bend state to the 180° twist state. However, in the absence of a field the free energy of the 180° twist state is higher than that of the 0° splay state. As a result, the 0° splay state is the more stable one, and the 180° twist state will decay to it within a few seconds.

In order to obtain a permanent 18° twist state, we investigated (via both numerical simulations and experiments) the relation between V_y and the retention time of the 180° twist state along with the effect of parameters such as elastic constants, dielectric anisotropy, pretilt angle, and cell gap on the stability and retention time. Figure 2 shows the dependence of V_y on variations of the pitch in a chiral splay cell with a cell gap of 6.4 μm and a pretilt angle of 5°. As the pitch decreases, V_y increases. From the simulation, it can be expected that, as the pitch decreases, the twist state becomes more stable, and variation of the pitch has an effect on the retention time of the twist state. To confirm this influence of the d/p ratio on the retention time of the 180° twist state, several test cells filled with the liquid crystal ZLI-1557 (from Merck) were fabricated with varying values of the pitch. The cell gap in these test cells was fixed by the spacer thickness of 4.2 μm. As expected, decreasing the pitch increases the retention time of the twist state, as shown in Fig. 3.

Because of the above finding, we studied the effect of the LC parameters on V_y and the retention time of the 180° twist state in an actual BCSN-LC device. Figure 4 shows the value of V_y for variations of LC parameters such as the cell gap, d/p ratio, splay elastic constant K_{11}, twist elastic constant K_{22}, bend elastic constant K_{33}, dielectric anisotropy $\Delta\varepsilon$, and pretilt angle, where all of the parameters were normalized by the reference parameter values of ZLI-1557 shown in Table I. From Fig. 4, it can be seen that the effect of the twist
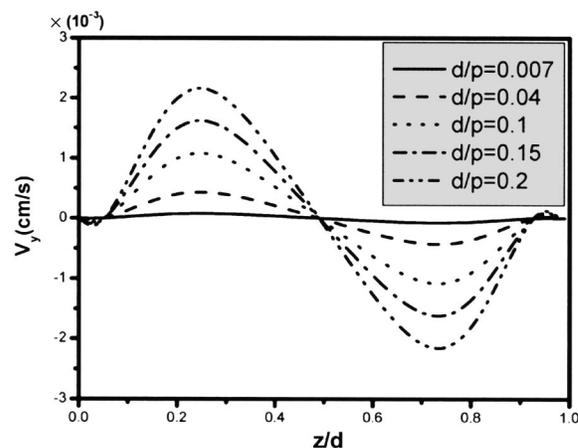
FIG. 2. Dependence of the flow velocity component V_y on variations in the pitch of a cell having a cell gap of 6.4 μm. As the d/p ratio increases, V_y increases. It is assumed that increments to the d/p ratio have a positive effect on the retention time, as well as the generation of the twist state.

elastic constant K_{22} upon V_y dominates the effects of the other parameters. If a LC material with a larger K_{22} is used, the retention time of the 180° twist state can be increased. Several test cells with d/p ratio of 0.2 and cell gaps of 4.2 μm were fabricated with several LC materials having different K_{22} values. The measured retention times are shown in Fig. 5. As expected, the retention time of a BCSN-LC cell fabricated using ZLI-2471 (Merck) where $K_{22}=8.1$ pN is longer than those of the other LC cells.

Aside from the twist elastic constant K_{22}, the cell gap can be considered as an external factor that is easier to control. The flow velocity V_y and cell gap are inversely related to each other as shown in Fig. 4. Thus, if we fabricate a BCSN-LC cell with an appropriately small cell gap using a LC material with larger K_{22}, it can be expected that the retention time of the 180° twist state can be significantly increased. In practice, we might realize a permanent twist state in the BCSN devices fabricated with the liquid crystal ZLI-
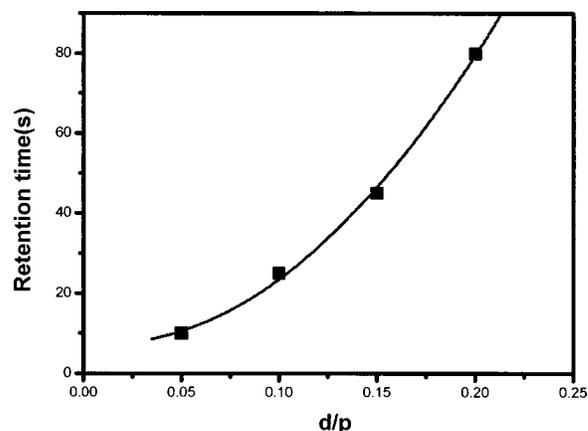
FIG. 3. The retention time of the 180° twist state as it depends upon pitch, in test cells with a spacer thickness of 4.2 μm. The d/p ratio is increased in steps of 0.05 up to 0.2. As the d/p ratio increases, so also does the retention time of the twist state.
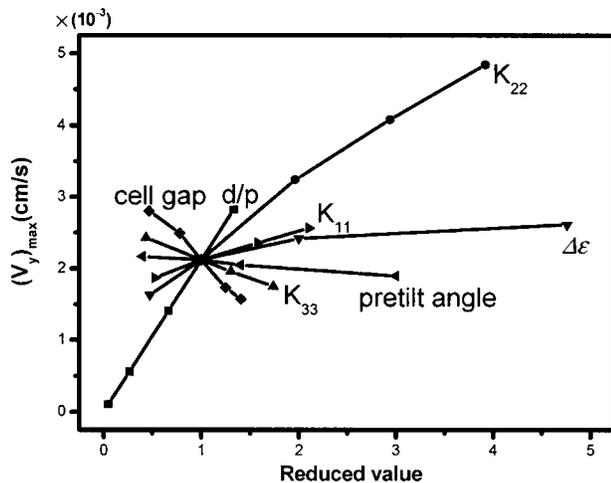
FIG. 4. The maximum value of V_y for the various LC parameters. The parameters of liquid crystal ZLI-1557 are used as reference values for the simulation. Reduced values are values that are normalized relative to each reference parameter.

FIG. 5. The retention time of the 180° twist state as it varies with twist elastic constant, in test cells with a spacer thickness of 4.2 μm. As the magnitude of K_{22} increases, the retention time of the 180° twist state increases.

2471 and a cell gap of 2.48 μm, as well as with ZLI-2293 and a cell gap of 2.38 μm.

A study of the azimuthal anchoring strength in BCSN-LC cells indicates why the twist state can be maintained permanently, and how the retention time of the 180° twist state is related to various parameters (particularly the cell gap and the twist elastic constant). In the model treated here, the total free energy of the LC cell is the sum of the bulk elastic free energy F_b and a surface contribution F_s, where the former is the Frank elastic free energy and the latter is the surface energy of the Rapini-Papoular form. The LC cell being considered exhibits a planar anchoring, and arbitrary alignment directions at the interface. For a finite anchoring strength, a competition between the surface anchoring strength and the volume elastic torque results in the deviation of the directors at the surface from their natural nematic orientation. The cumulative angle through which the LC directors twist as they adopt this deviation depends upon the azimuthal anchoring strength. The azimuthal anchoring strength can be obtained from the angular deviation using the equation [18–20]

$$W_\phi = \frac{2K_{22}\phi}{d \sin 2\phi} \qquad (1)$$

from Frank's elastic theory, where K_{22} is the twist elastic constant, d is the cell gap, and ϕ is the actual twist angle of the director through the cell. In the bend state, if the voltage

TABLE I. The parameters of ZLI-1557 used as reference values in the simulation.

Parameter	Value	Parameter	Value
K_{11}	9.5×10^{-12} N	Cell gap	6.4 μm
K_{22}	5.1×10^{-12} N	Pretilt angle	5°
K_{33}	11.5×10^{-12} N	$\Delta\varepsilon$	4.2
d/p	0.15		

is turned off, the 180° twist state is generated. Since the orientation of the directors in a nematic phase without external fields is governed by the boundary conditions at the interface, the retention time of the metastable 180° twist state may be increased by designing a cell to have its surface anchoring energy in the 180° twist state be comparable with the bulk elastic energy. As a result, higher azimuthal anchoring strengths lead to a more stable 180° twist state. In test cells that maintain a permanent twist state, the anchoring energies are calculated to be, respectively, 7.4×10^{-5} J/m^2 for the cell that was fabricated with a cell gap of 2.48 μm and $K_{22}=8.1$ pN (ZLI-2471), and 7.0×10^{-5} J/m^2 for the cell with a cell gap of 2.38 μm and $K_{22}=7.3$ pN (ZLI-2293). It is inferred that if an anchoring energy is obtained that is greater than or equal to 7.0×10^{-5} J/m^2, a permanent twist state should be observed.

To confirm the relation between the azimuthal anchoring strength and the retention time of the metastable 180° twist state, several BCSN-LC cells filled with the liquid crystal ZLI-5070 having $K_{22}=7.1$ pN were fabricated with a spacer thickness of 4.2 μm. The anchoring strength is proportional to the rubbing strength [21]. The rubbing strength was varied by changing the cumulative number of rubs [22]. In general, the rubbing strength n_f is given by

$$n_f \approx (2r\delta)^{1/2} 2\pi N \nu r \sigma_f / s, \qquad (2)$$

where the definitions for the various parameters are described in Ref. [22]. According to Eq. (2), several cells with different rubbing strengths were fabricated. Indium tin oxide coated glass was used for cell substrates, and rubbing strengths varied with changes in the cumulative number N of rubs. The polyimide SE-3140 (Nissan Chemical Co.) was coated on the bottom and top glass substrates, and rubs on the two substrates were laid down parallel to one another. The pretilt angle associated with SE-3140 is known to be about 5°. S-811 was used as a chiral additive to the base LC material so as to obtain the metastable 180° twist state.
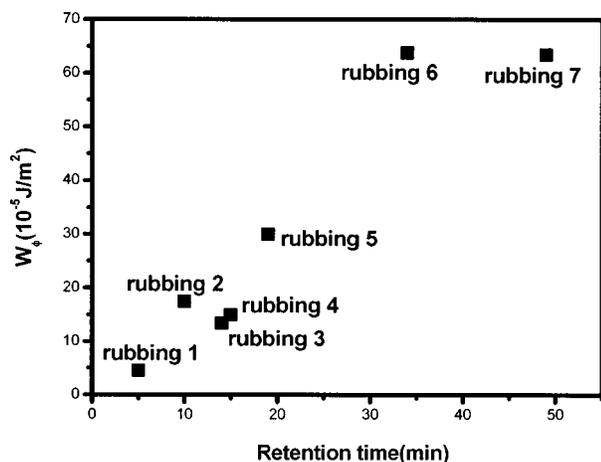
FIG. 6. The retention time of the 180° twist state versus the azimuthal anchoring strength. The azimuthal anchoring strength is controlled by cumulative number N of rubs.

The retention times measured for the 180° twist state, along with the varying cumulative numbers of rubs N, and the azimuthal anchoring strength found for each cell are shown in Fig. 6. Even though all of the cell gaps are the same (4.2 μm), we find that the retention time of the 180° twist state increases with the cumulative number of rubs. Considering that an anchoring energy of 7.0×10^{-5} J/m^2 or more is needed to obtain the permanent twist state, the azimuthal anchoring strength of the test cells is nearly saturated at about 6.3×10^{-5} J/m^2 when $N=6$ or $N=7$, which transforms the test cell from the twist state to a splay state within 1 h. In order to confirm the effects of the twist elastic con-

stant, the above experiments are repeated with BCSN-LC cells fabricated using a liquid crystal that has a twist elastic constant larger than $K_{22}=7.1$ pN. As a result, we could confirm that the retention time of the metastable 180° twist state is much longer than that of cells with $K_{22}=7.1$ pN. Because it is always possible to increase the strength of the azimuthal anchoring, the retention time of the 180° twist state is increased. Therefore, the twist elastic and cell gap parameters are sufficient to increase the azimuthal anchoring strength, resulting in a permanent bistable device. Some BTN device that especially makes use of the surface effect needs weak anchoring strength. However, a BCSN device needs strong anchoring strength to obtain the long term twist state. By controlling the rubbing strength, we have demonstrated the dependence on the strong anchoring.

In summary, we have investigated the stability of bistable chiral splay nematic liquid crystal devices by studying the effect of LC parameters on these bistable states. The relationship between the magnitude V_y of the flow velocity and the varying LC parameters allowed us to estimate the retention time of the 180° twist state. A study of the azimuthal anchoring strength permits an understanding of how the stable 180° twist state occurs, as well as how the retention time of the 180° twist state is related to the cell parameters. We confirmed that the twist elastic constant, cell gap, and rubbing strength are very efficient external factors for the creation of a stable 180° twist state that is retained permanently.

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