Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

Molecular Orientation Structures of Surface Stablized States and Their Switching Processes in Ferroelectric Liquid Crystals

Hideo Takezone [a] , Yukio Ouchi [a] , Ken Ishikawa [a b] & Atsuo Fukuda [a]

[a] Department of Textile and polymeric Materials, Tokyo Institute of Technology, O-okayams, Meguro-ku, Tokyo, 152, JAPAN

[b] Department of Applied Physics, Hongo, Bunkyo-ku, The Unversity of Tokyo, Tokyo, 113.

Version of record first published: 20 Apr 2011.

Mol. Cryst. Liq. Cryst., 1986, Vol. 139, pp. 27–46
0026-8941/86/1392–0027/$20.00/0

Printed in the United States of America

Molecular Orientation Structures of Surface Stabilized States and Their Switching Processes in Ferroelectric Liquid Crystals

HIDEO TAKEZOE, YUKIO OUCHI, KEN ISHIKAWA† and ATSUO FUKUDA

Department of Textile and Polymeric Materials, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo 152, JAPAN

(*Received October 11, 1985; in final form December 24, 1985*)

Possible molecular orientation structures and their boundaries in surface stabilized ferroelectric liquid crystals are described. The existence of pre-tilt on both glass surfaces is pointed out to explain the color difference between two twisted states and the origin of the lateral driving force of the boundary. Switching processes between the surface stabilized states are discussed on the basis of stroboscopic micrographs taken by applying triangular voltage waves of several frequencies.

Keywords: ferroelectric, liquid, crystal, chiral, smectic, switching

1. INTRODUCTION

The synthesis of a ferroelectric liquid crystal by Meyer et al.[1] opened a new field of liquid crystals, leading to the proposal of a fast electro-optical switching device by Clark and Lagerwall.[2] This proposal initiates extensive surveys for the possible use of ferroelectric liquid crystals as a large, flat, panel display. Ferroelectric liquid crystal displays have already been manufactured for trial[3] and will be on the market within one or two years in Japan. Besides such application research, many efforts have also been devoted to basic research for the understanding of ferroelectric liquid crystals.

† Present Address: The University of Tokyo, Department of Applied Physics, Hongo, Bunkyo-ku, Tokyo 113.

In this article, we will focus on the dynamics of domain boundaries, which is important not only in the application but also in the basic research. To describe the dynamics, we first summarize the plausible models of the molecular arrangement and their boundaries in surface stabilized ferroelectric liquid crystal (SSFLC) cells. We will come to the details of the molecular arrangement near glass surfaces on the basis of our recent experimental findings and some theoretical calculations, showing the existence of molecular pre-tilt on the glass surfaces. We have to emphasize here that the dynamics is governed by many factors, such as temperature, cell thickness, surface condition, the shape of the applied electric field and even material constants, such as the tilt angle and polarization. Therefore the present characteristics are the results observed under the present experimental condition. Nevertheless they are still important since most of the individual findings are quite typical in SSFLC cells.

2. EXPERIMENTAL PROCEDURES

Experimental results are confined to optical microscope observations. The dynamic behaviors of the switching between surface stabilized (SS) states under a triangular voltage wave were photographed stroboscopically. The triangular voltage waves were generated by a microcomputer-(Fujitsu FM-7) based oscillator and amplified by an operational amplifier (Kepco BOP-1000M). Stroboscopic pictures were taken with an optical polarizing microscope (Nikon Optiphotopol) by illumination with a xenon flash lamp (Sugawara Laboratories PS-240S) (25 μs in duration) triggered by the oscillator.

For typical studies in S_C^*, DOBAMBC (*p*-*n*-decyloxybenzylidene *p*-amino 2-methylbutyl cinnamate) was used. For additional studies related to the S_C^*–S_I^* transition, 8SI* (4-(2′-methylbutyl)phenyl 4′-*n*-octylbiphenyl-4-carboxylate)[4] was also used. In order to investigate the switching characteristics, it is necessary to use sample cells of high quality, free from defects, such as focal conics and dislocations.[5] Such cells were obtained with epitaxial growth of the smectic phase from a polyester spacer edge under an appropriate temperature gradient.[6] The technique is effective both for DOBAMBC (Iso–S_A–S_C^*) and 8SI* (Iso–N–S_A–S_C^*).[7] We used two kinds of ITO-coated glass plates, which gave rise to different switching behaviors because of different surface interactions.[8] We designated them as *S* and *W* surfaces, according to strong and weak dipolar surface interactions. Both the ITO-coated glass surfaces satisfied a random planar con-

dition, which constrains each molecule to align parallel to the surface without any preferable direction. The cell thicknesses were in the range between 5 μm and 8 μm, since all the possible SS states were well observed in such cells and relatively bright interference colors in these cells helped to identify them.

3. STRUCTURES OF SURFACE-STABILIZED STATES AND THEIR BOUNDARIES

After the finding of simple bistable states in very thin cells,[2] another kind of SS state was found to exist in rather thicker cells.[9,10] In such a state, the molecules are not uniformly oriented but are tilted to the opposite directions on both surfaces, where the polarization points either inward or outward. Inside the cell, the molecular orientation continuously varies along the normal of glass surfaces with splay, twist and bend deformation. Since the projection of the molecules on the glass surfaces twists from the top to the bottom surface, the state is often called a twisted state. At least six SS states are expected to exist as illustrated in Figure 1.[7,11] In UU and UD states, polarizations are uniformly up and down, respectively. In TI and TO states, the polarizations on both surfaces are inward and outward, respectively. Note that the rotation senses of the projection of the director onto the surfaces are right-handed for TI and left-handed for TO in the present case. On the other hand, two TI or TO states are distinguished by the rotation sense of the projection of the director onto the layer (C-director)—one is right-handed (TI1 and TO1) and the other is left-handed (TI2 and TO2) from the top to the bottom surface.

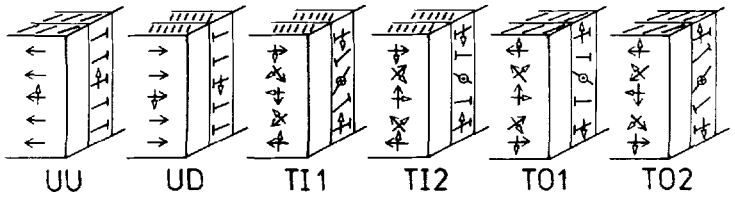

FIGURE 1 Six kinds of surface-stabilized states. TI and TO are specified by the polarization orientation (open arrows) on both surfaces, inward and outward, respectively. Note that the projection onto the surface twists from the top to the bottom. In this case, the handedness is right for TI and left for TO. Two TIs or TOs are distinguished by the rotation sense of the C-director or the polarization. One is right-handed (TI1 and TO1) and the other is left-handed (TI2 and TO2) from the top to the bottom surfaces.

Usually, either of the TI or TO states is favored under a rather polar surface condition (*S* surface), while both of them are possibly observed between *W* glass surfaces, as will be mentioned later. The existence of four states is shown in Figure 2(a), where the polarizers are crossed so that a uniform state is dark.[7] Another uniform state becomes dark when the cell is rotated by twice the tilt angle as shown

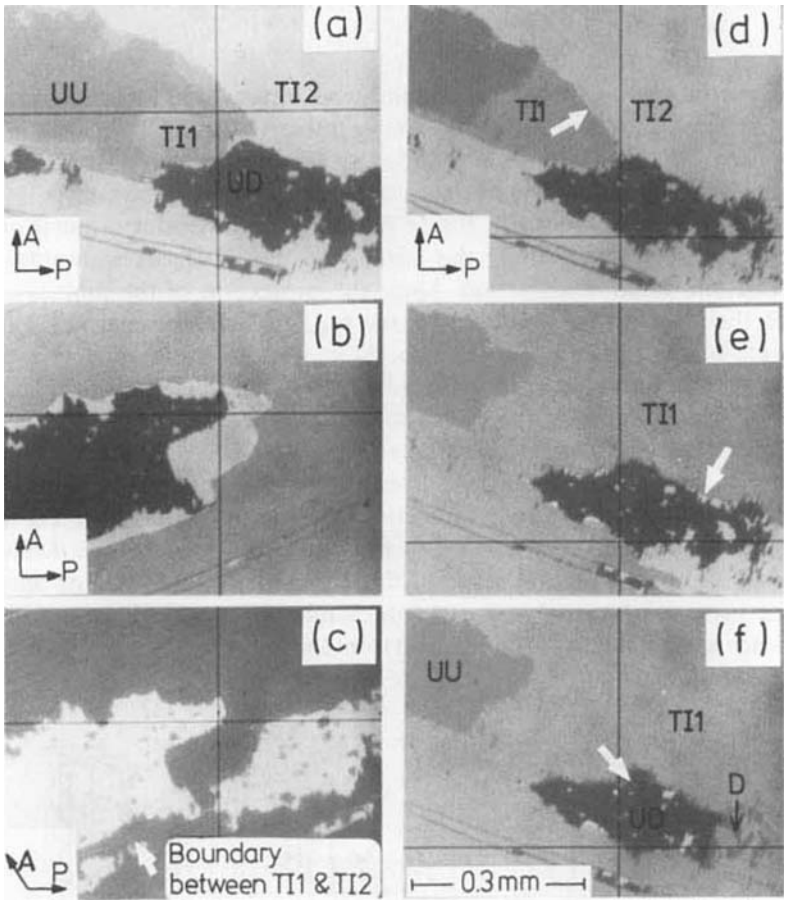

FIGURE 2 Micrographs showing four states. UD and UU are dark between crossed polarizers as shown in (a) and (b). Both of the other two regions are TI states, since they become dark by rotating the analyzer by twice the tilt angle as shown in (c). They are assigned to TI1 and TI2, although we cannot identify which is TI1 or TI2. Three micrographs (d), (e) and (f) show the movement of the boundary between TI1 and TI2. The boundary in each figure is shown by white arrows. Note that the boundary moves into the UD state, resulting in a color change from black to red. The red region is assigned to the D state. See Color Plate I.

in Figure 2(b). Two twisted states, TI1 and TI2, were confirmed by the fact that these regions become dark when the analyzer is rotated by twice the tilt angle from the crossed position as shown in Figure 2(c).[7] Note that a boundary can be seen between the two TI states. Thus we attributed four distinct states to UD, UU, TI1 and TI2. Handschy and Clark[12] also observed several SS states and tried to explain them by introducing the circular conical boundary condition with or without tilting the smectic layer normal away from the glass surfaces. You will find, however, that our simple models are reasonable enough to explain the experimental observations.

Note that there exist two kinds of boundaries in Figure 2; one is a rather smooth boundary between TIs as shown by white arrows and the other is a rather rough boundary separating TI from U. When we apply a voltage favorable to one of the uniform states, the smooth boundary moves and even enters into a uniform state as shown in Figures 2(d), (e) and (f). The process is experimentally observed as a color change from black to red, and is illustrated in Figure 3.[13] In the figure, the following observations should be made:

1) The two TI states are separated by a disclination line located in the interior of a cell, while the boundary between U and TI has a surface disclination line. Thus, there are two kinds of boundaries characterized by interior and surface disclinations, respectively. Experimentally the interior disclination looks rather smooth, while the surface disclination appears as dotted or rough boundaries reflecting the surface roughness as shown in Figure 2.

2) The illustration shows that the interior disclination can cross the surface disclination.

3) When the cell is rather thick and the Mauguin limit is satisfied, the deformed (D) state, which is observed as a red region in Figure 2(f), appears to be a uniform state because of the same molecular directions on both surfaces.

4) D and U are separated from each other by an interior disclination as between TI1 and TI2.

The interior disclination sometimes makes a loop as shown in Figure 4.[8,13] The loop consists of pairs of $\pm 2\pi$ wedge and $\pm 2\pi$ twist disclinations perpendicular and parallel to the layer, respectively. These models are supported by the fact that the shape and speed of the two opposing boundaries parallel to the smectic layer normal are different from each other.[8,13] Structural asymmetry between the $\pm 2\pi$ wedge disclinations is clear in both models, while the $\pm 2\pi$ twist disclinations are topologically the same. The existence of the $\pm 2\pi$

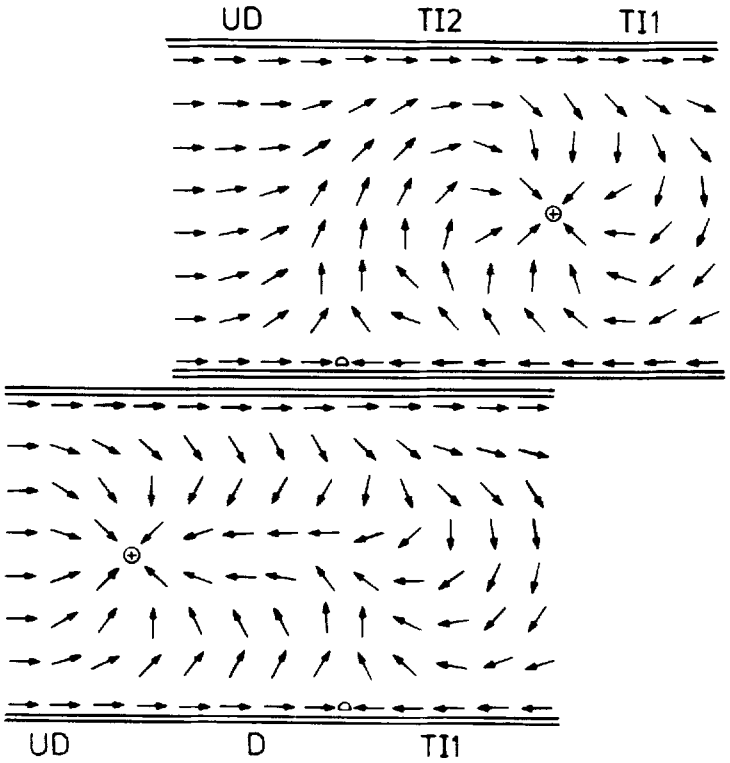

FIGURE 3 Model of the boundary movement shown in Figures 2(d), (e) and (f). Note that the interior disclination crosses over the surface disclination.

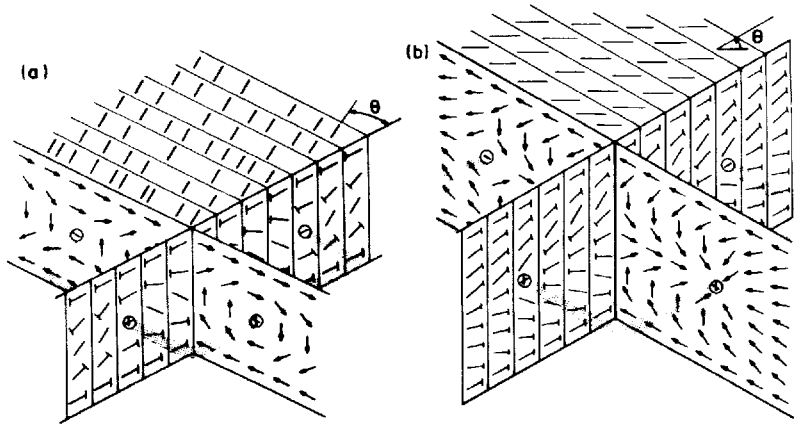

FIGURE 4 Two kinds of disclination loops formed in the T and U states, respectively. The loops consist of $\pm 2\pi$ twist and $\pm 2\pi$ wedge disclinations parallel and perpendicular to the layer, respectively. See a note added in proof.

twist disclinations was pointed out by Glogarová et al.[10] to illustrate the helicoidal structure in a thick S_C^* cell. They also illustrated the $\pm 2\pi$ twist disclinations between two TIs (or TOs) in a SSFLC cell. Lejček et al.[14] calculated the self energy of the $\pm 2\pi$ twist disclinations between two TIs (or TOs) and the influence of glass surfaces. The effect of a high electric field was also included in the calculation.[15] Defect lines which were assigned to a $\pm 2\pi$ twist disclination in the SSFLC cell in Ref. 14 seems to be different from ours shown in Figure 2. Recently Handschy and Clark[12] proposed a model involving the $\pm 2\pi$ wedge disclinations and associated layer tilt to explain defect lines in the T state. None of them, however, discussed $\pm 2\pi$ wedge disclinations, which must arise as boundaries perpendicular to the $\pm 2\pi$ twist disclinations when they form a loop. We will show that our model is quite reasonable in the next section.

4. EXISTENCE OF PRE-TILT

Two problems should be solved in the model of two TI states and their boundary shown in Figure 4(a): The first one is that there is no lateral driving force for the boundary, although it moves very easily indeed.[13] The second problem is the origin of the difference in colors of the two TI states. In order to explain the driving force, we tentatively introduced a selective pre-tilt on both glass surfaces.[13] Here we will show one piece of experimental evidence and two theoretical predictions for the pre-tilt, one of which is also related to the problem of color.

A calculation of the orientation structures was carried out to see if a finite pre-tilt could be predicted or not. For the calculation, we assumed that a helicoidal structure is suppressed by glass surfaces (SSFLC) and thus the molecular orientation does not vary in a plane parallel to the glass surface but varies along the normal to the surface. The calculations were made by minimizing the total free energies of bulk elastic distortion W_d and surface interaction W_s.[9] In describing W_d, we did not use one constant approximation ($K_1 = K_2 = K_3$) as Handschy et al.[9] did.

The qualitative results obtained by minimizing W_d are as follows:

1) The distortion energy may stabilize one of the TI and TO states depending on the handedness of the inherent helicoid and the sign of $K_3 - K_2$, although the U state is stabilized under the one constant approximation.

2) The rotation rate of the C-director is not generally uniform along

the cell thickness, although it is uniform under a certain approximation, such as the one constant approximation.[12,17]

3) Molecules in both glass surfaces are pre-tilted to reduce the total rotation angle of the C-director from π. It should be noted that the present pre-tilt means the opposite rotation of the C-director in both surfaces, while there exists another kind of pre-tilt, which means the same rotation in both surfaces as shown in Figure 5. We call them the first and the second kinds of pre-tilt, ϕ_1 and ϕ_2. The first kind of pre-tilt ϕ_1 increases with decreasing cell thickness to avoid a large deformation.

The surface energy W_s consists of two terms, one of which favors planar orientation with an equal probability of $+\theta$ or $-\theta$ and the other favors preferential planar orientation with either of $+\theta$ or $-\theta$ because of dipolar surface interaction.[9] W_s adds some other features on orientation structures.

4) The dipolar surface interaction stabilizes the TI or TO state according to the surface condition.

5) Under the influence of W_s and W_d, the T state with finite ϕ_1

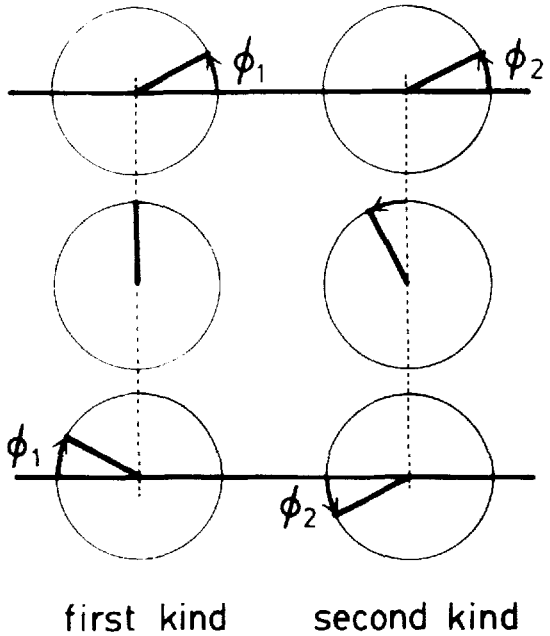

FIGURE 5 Models of two kinds of pre-tilt. The first and second kinds represent the pre-tilts of the opposite and of the same directions on both surfaces, respectively.

changes to the U state at a critical thickness d_c with decreasing cell thickness.

6) It is possible that W_d and W_s favor T states of opposite handedness, such as TI and TO, respectively. This is very important from the applicative point of view, since d_c could be relatively large in this case.

7) W_s possibly gives rise to a small but finite ϕ_2.

Thus it was found from the calculation of the orientation structure that the twisted state is usually associated with the first kind of pre-tilt and possibly with the second kind of pre-tilt.

The second kind of pre-tilt ϕ_2 was experimentally confirmed. Figure 6 shows a texture change from S_C^* to S_I^* and the reverse process in 8SI* without applying an electric field. In S_C^*, the SS cell is almost in TI1 and TI2, one of which is yellow, the other of which is purple. With decreasing temperature down to S_I^*, the two uniform states appear at the expense of the two TI states. The following two facts are important to note.[16] One is the one-to-one correspondence between two twisted states and two uniform states; black and green domains tend to appear in yellow and purple, respectively. The other is the fact that the molecular directions in the two uniform states make an angle of the tilt angle θ but not of the full cone angle 2θ. By applying an electric field, of course, two extinction positions make an angle of 2θ, although the extinction becomes less dark. A further interesting feature can be observed in the reverse process: When the temperature is raised up to S_C^* after the S_I^* without twisted states is realized, the two uniform states still remain without changing the angle between molecular directions, θ. Figure 7 is the model which explains the above experimental facts.[16] Roughly speaking, the average direction of molecules for each pre-tilted twisted state may decide an appropriate pre-tilted uniform state.

We now turn to the calculation of colors of twisted states. We adopted the 4×4 matrix method[18,19] and calculated transmittance spectra of the twisted states between crossed polarizers. The main results are the following: The two twisted states TI1(TO1) and TI2(TO2) show no color difference, if there is no second kind of pre-tilt, even if there exists any first kind of pre-tilt. The color difference becomes larger by increasing the second kind of pre-tilt. For instance, the model of two TI states shown in Figure 7 is expected to give purplish white and bluish green by using reasonable values in parameters such as a cell thickness and birefringence.

Thus it is experimentally shown that there exists a selective pre-

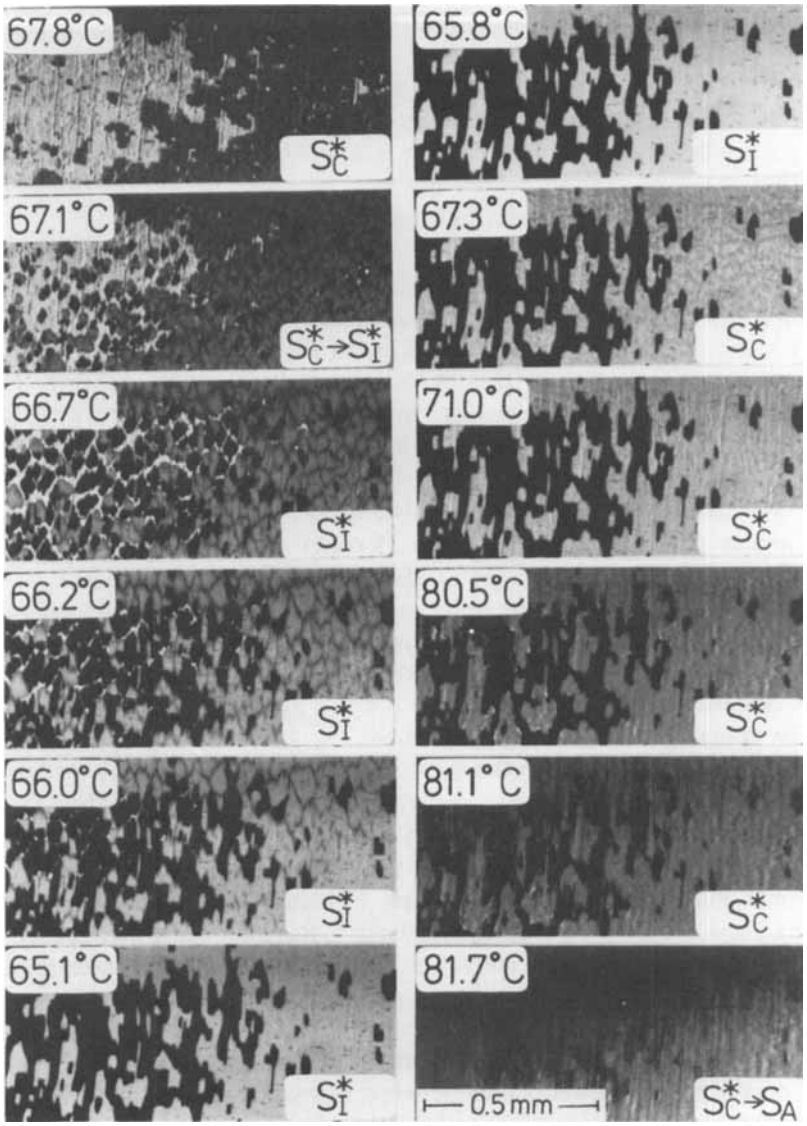

FIGURE 6 Texture change associated with decreasing the temperature from S_C^* to S_I^* and the reversed process from S_I^* to S_C^*. Note that two U's (black and green) tend to appear in two TIs (yellow and purple) selectively. See Color Plate II.

tilt in twisted states and possibly even in uniform states, although the free energy calculation predicts only small ϕ_2. The model is also suited to explain the color difference and the lateral driving force. The details will be reported in separate papers.[20,21]

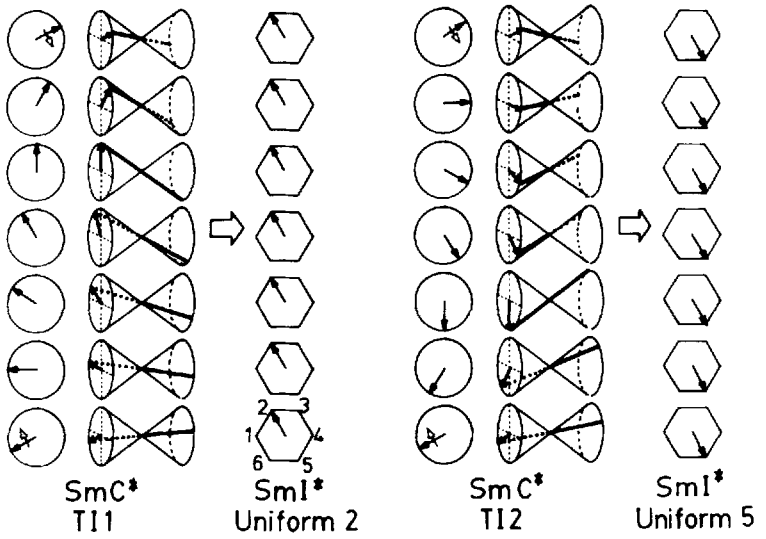

FIGURE 7 Possible model showing the one-to-one correspondence between two U and two T states in the texture change from S_C^* to S_I^*.

5. STROBOSCOPIC OBSERVATION OF SWITCHING

The domain switching under an electric field has been dealt with theoretically. The static aspect was calculated by minimizing the free energy W_d, W_s and ferroelectric interaction W_e.[9,17] The transition, T $\leftrightarrow$ U, was obtained under a critical electric field. The dynamic response of the molecular orientation under a pulsed field was also calculated by taking account of viscous torques.[22] Lejček[23] dealt with the transition U $\rightarrow$ T and T $\rightarrow$ U as a formation of a π twist (surface) disclination loop in U and T, respectively, and showed the existence of two critical fields E_1 (T $\rightarrow$ U) and E_2 (U $\rightarrow$ T), where $E_1 > E_2$. The actual experimental observation, however, is far more complicated than those theoretically predicted, and will be shown in the following.

We confined ourselves to the switching process under triangular voltage waves of low frequencies, although stroboscopic observations have also been made by applying a reversed field.[24,25] Experiments were made in various experimental conditions. The increasing or decreasing rate of the triangular waves were 0.32 V/s (0.1 Hz, $\pm$1.6 V), 20 V/s (1 Hz, $\pm$10 V) and 200 V/s (10 Hz, $\pm$10 V), two kinds of polarizer directions were chosen and two kinds of glass surfaces (*W* and *S*) were used.

Figures 8 and 9 are two series of stroboscopic pictures taken by applying negative and positive slopes of 0.1 Hz triangular field to a *W* surface cell of 7 μm thickness, respectively. The polarizer and analyzer directions are shown in these Figures and are chosen to be dark in the TI state. We can observe several features in two series of micrographs. With decreasing voltage in Figure 8, only a uniform color change is observed at the first stage. When the voltage is decreased down to -0.42 V after changing the polarity, two kinds of domains are formed, whose boundaries are rather smooth and rough. We first discuss a characteristic domain with a smooth boundary seen at -0.55 V in Figure 8. The domain is ascribed to an asymmetric loop of the D state in the UD state. The same kind of asymmetric loop is also observed at $+0.35$ V and $+0.48$ V in Figure 9, although the shape is reversed because of the different slopes of voltages. The shape is similar to the loop observed in the TI states,[13] and is explained by the asymmetry of two $\pm 2\pi$ wedge disclinations illustrated in Figure 4(b). Because of such a sudden color change associated with

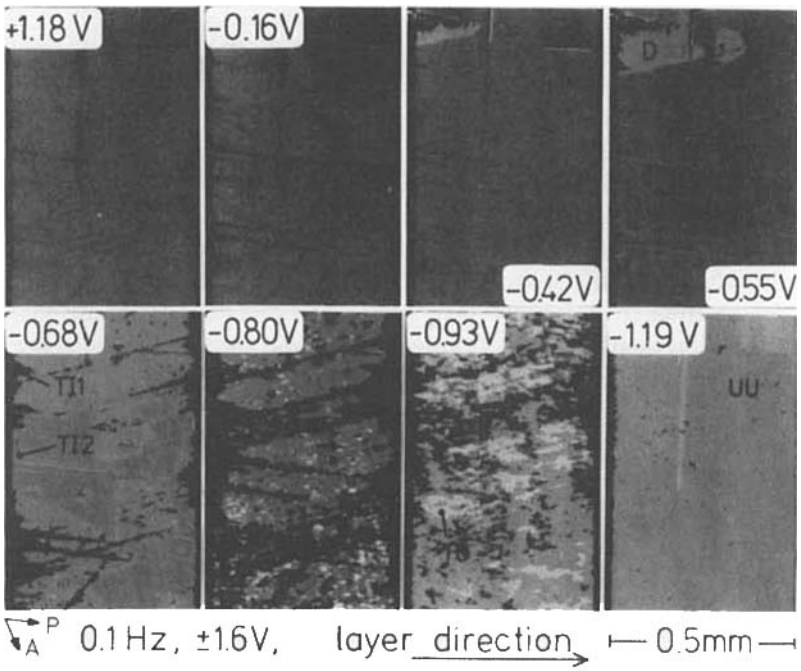

FIGURE 8 A series of the stroboscopic micrographs taken under a negative slope of a triangular wave of 0.1 Hz. The directions of polarizers are chosen to be dark in the TI state, as shown in the figure. See Color Plate III.

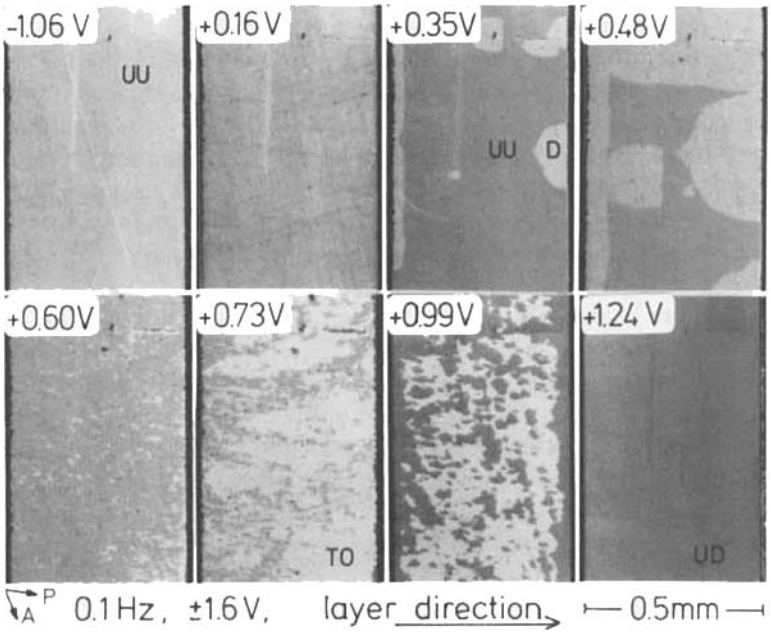

FIGURE 9 A series of the stroboscopic micrographs taken under a positive slope of a triangular wave of 0.1 Hz. See Color Plate IV.

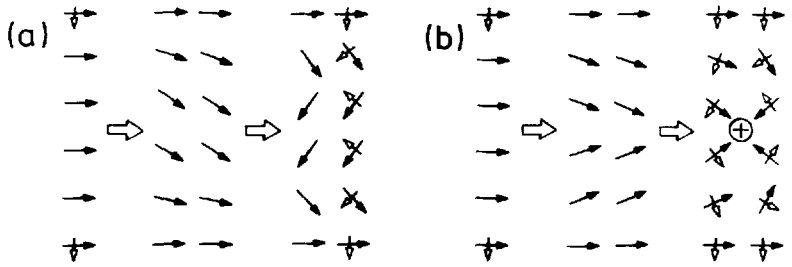

FIGURE 10 Two possible deformations of interior molecules leaving the surface regions. Note that the director deformation shown in (b) is always associated with the nucleation of disclination, while the one shown in (a) can take place continuously without nucleating a disclination.

the boundary motion, the process from U to D is predicted as in Figure 10(b) rather than in Figure 10(a).[8] The deformation of the directors shown in Figure 10(b) always associates with the nucleation of a disclination, while the one shown in Figure 10(a) can take place continuously without nucleating a disclination. Handschy and Clark[24]

considered the molecular rotation as in Figure 10(a) in thin cells, such as 1 μm under a reversed voltage. Amaya et al.[22] also postulated the slightly distorted state as shown in the middle of Figure 10(a) as an initial condition in their calculation of a dynamic domain switching. Our observation suggesting the process in Figure 10(b) is different from theirs. Both processes may be possible in different experimental conditions. The theoretical calculation of the dynamic response should be performed by taking into account a dipole-dipole interaction, since two molecular orientations give different polarization orientations as shown in Figure 10.

Another characteristic in the same micrograph (-0.55 V) is two different colors, orange and brown. These regions are attributed to two TIs, although they are not simple but distorted TIs, judging from the lack of darkness. The formation of the TI state gives orange and brown colors when it is formed in UD and D states, respectively. Hence the crossing of the boundary between UD and D over the boundary between UD and orange TI induces a color change from orange to brown. The color change is understood by a conversion from TI1 to TI2 (or from TI2 to TI1), as illustrated in Figure 11. The

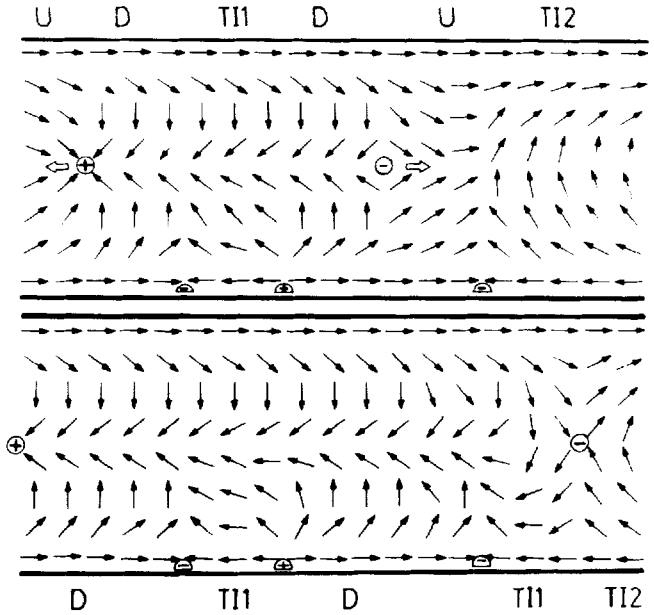

FIGURE 11 Model of the color change from orange to brown in Figure 8 (-0.55 V). An interior disclination separating U and D moves and crosses a surface disclination between U and TI2. By this movement, TI2 is changed to TI1.

pre-tilted and distorted feature is not included in the figure for the sake of simplicity.

Four distinct colors at −0.93 V in Figure 8 clearly show the existence of TO (bluish white) in addition to TI (brown), D (bluish green) and UU (purplish pink). From the sequential point of view, TO always appears in D and transforms into UU. The appearance of D and TO is a consequence from the use of the *W* surface. If we use an *S* surface cell, U transforms to TI by the switching of the unfavorable surface. In the present case, however, there is only a slight difference in favorable and unfavorable surface energies. Hence UD changes to D as well as to TI, and D changes to TO as well as to TI.

With a decreasing field, these changes, UD → D and UD → TI, occur simultaneously, as shown in Figure 8. With an increasing field, on the other hand, the change UU → D precedes, and the change D → TO occurs after the complete change to D, as shown in Figure 9. Such a difference between the sequential changes in positive and negative slopes was observed in every frequency used, although two glass surfaces with ITO are expected to be the same. This fact suggests that the switching process is very sensitive to the glass surfaces used, although the true reason for the different sequential changes cannot be understood. In Figure 9, the existence of the TI state is not clear, probably because of the subsequent change to the UD state, which gives a similar color to the TI state.

In Figures 12–15, the switching sequences under 1 Hz and 10 Hz triangular voltages are shown for negative and positive slopes. The polarizer and analyzer were set to be dark in the TI state at 0 V. The sequences are more or less the same as the ones for 0.1 Hz, although the following differences are observable:

1) In the sequence with a positive slope of higher frequencies (Figures 13 and 15), the UU state seems to be formed directly from the D state without passing the T state, although it can be considered that the process from D to T is hard to see because of the lack of resolution of time and/or color. Actually, the color change between +2.0 V and +2.8 V in Figure 14 seems to be ascribed to the change from D to T.

2) The switching pattern, such as loops, is finer in higher frequencies, as typically shown in Figure 16.

3) The loop of D in U is asymmetric in 0.1 Hz but is of a rather symmetric, elongated hexagonal shape in 1 and 10 Hz.

As the final experimental findings, we emphasize an effect of glass

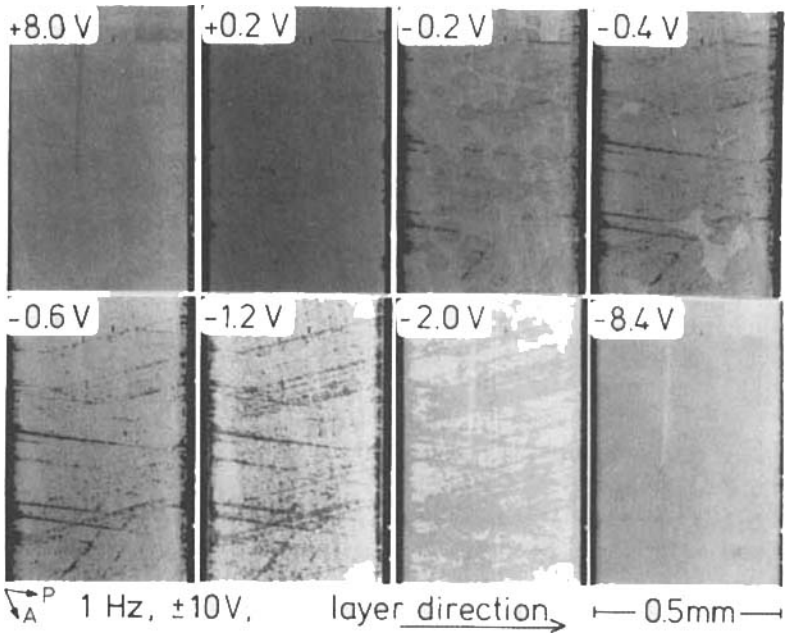

FIGURE 12 A series of the stroboscopic micrographs taken under a negative slope of a triangular wave of 1 Hz. See Color Plate V.

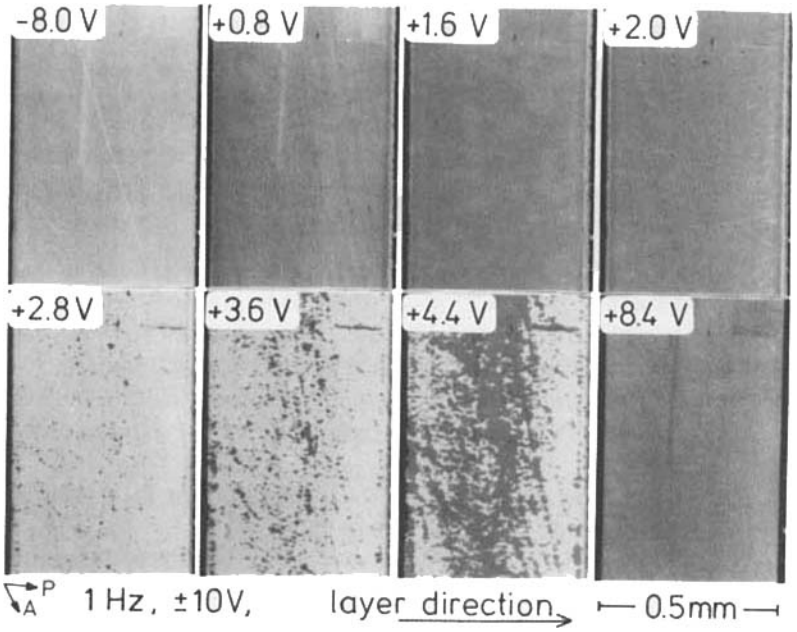

FIGURE 13 A series of the stroboscopic micrographs taken under a positive slope of a triangular wave of 1 Hz. See Color Plate VI.

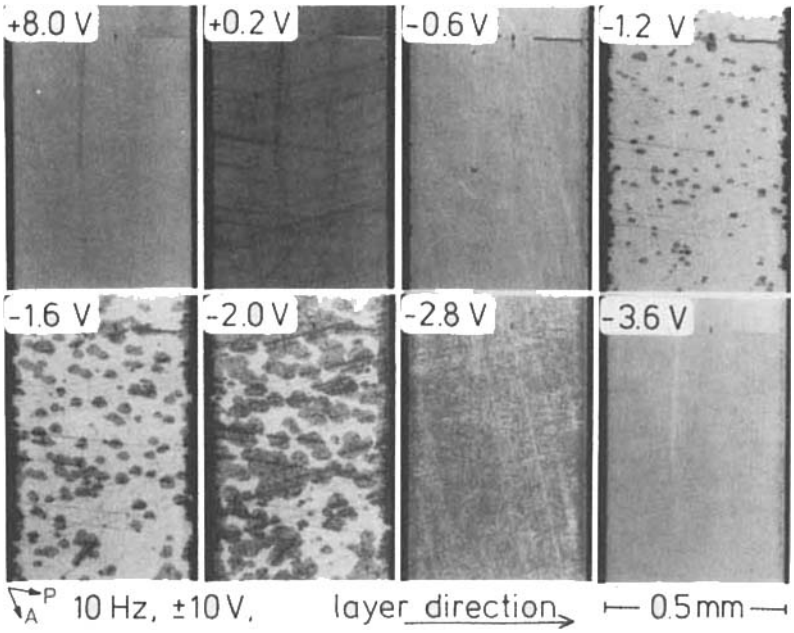

FIGURE 14 A series of the stroboscopic micrographs taken under a negative slope of a triangular wave of 10 Hz. See Color Plate VII.

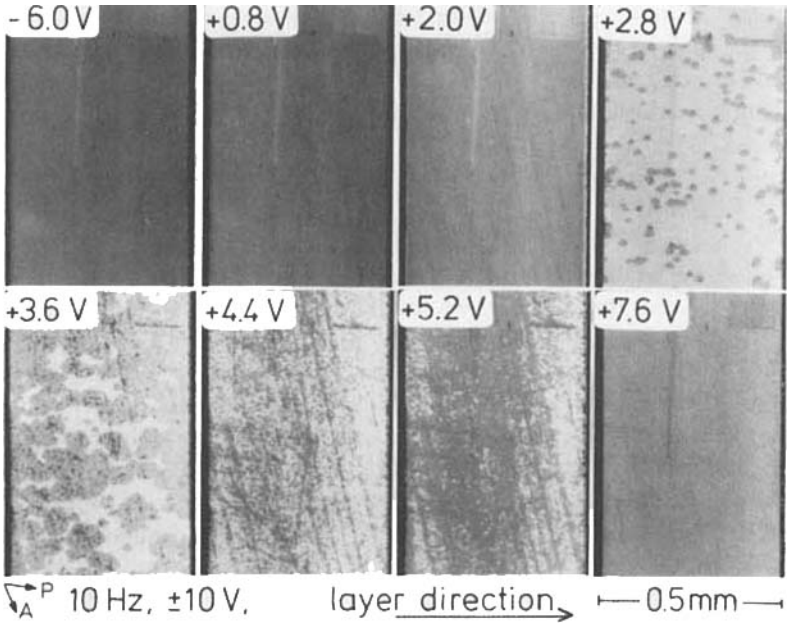

FIGURE 15 A series of the stroboscopic micrographs taken under a positive slope of a triangular wave of 10 Hz. See Color Plate VIII.

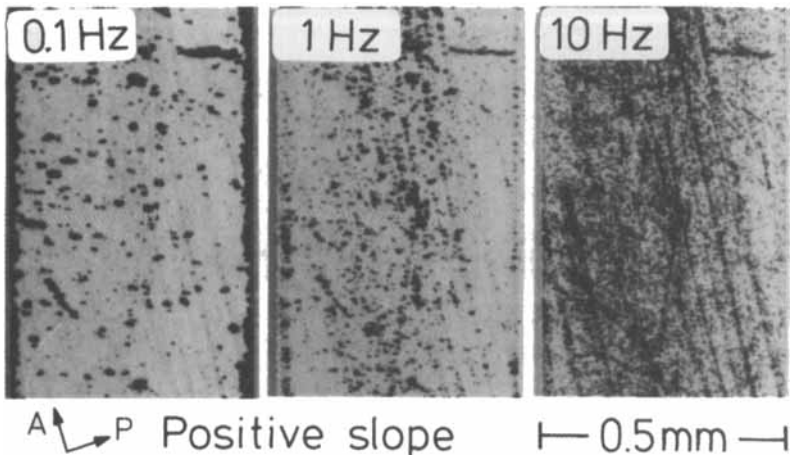

FIGURE 16 Characteristic frequency dependence of domain switching. See Color Plate IX.

surfaces on switching characteristics. In the stroboscopic studies mentioned above, we used *W* surfaces. In this case, the U and D states are favored more than the T state, and both TI and TO states appear. On the contrary, as reported previously,[11] the *S* surface favors either of the TI or TO states and the switching process is simpler because of the lack of the D state. Thus the switching process is sensitively affected by surface conditions, which suggests the possibility of designing a desirable surface condition.

6. SUMMARY

The dynamic behaviors of SS states under triangular waves were reviewed. For this purpose, we summarized the orientation structures of six SS states: UU, UD, TI1, TI2, TO1 and TO2. We also pointed out the existence of a deformed state, D, where a large deformation of the directors takes place in the interior of the cell, leaving the molecules near glass surfaces such that the upper and lower halves of the directors rotate more than $\pi/2$ azimuth angles on the corn in the opposite direction. Then we proposed the existence of molecular pre-tilt on both glass surfaces, especially in the twisted states, to solve some problems brought about by the too-simplified model of orientation structures, such as the color difference between TI1(TO1) and TI2(TO2) and the origin of the lateral driving force of their

boundary under an electric field. Switching processes were discussed on the basis of a series of stroboscopic micrographs taken under triangular voltages of low frequencies. It was emphasized that the glass surface condition affects the switching characteristics. For cells with weak dipolar surface interaction, the U state changes to the D state as well as to the TI and TO states, while either of the TI or TO states favorably appears in strong dipolar surface cells. In this article we confined ourselves to the switching processes under triangular voltages of low frequencies. The switching characteristics under a reversed field have been dealt with by Handschy and Clark,[24] and by Orihara and Ishibashi.[25] Further extensive studies under a reversed or pulsed field must be important and will be our future program.

Acknowledgments

We are indebted to many of our laboratory colleagues, Messrs. T. Tsuchiya, T. Hatano, T. Shingu, T. Kimura and also our colleagues from industry, Mr. T. Uemura from Matsushita Electric Industrial Co., Ltd. and Dr. K. Kondo from Hitachi Ltd. We gratefully acknowledge their collaboration. This work is partly supported by a grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture.

References

1. R. B. Meyer, L. Liébert, L. Strzelecki and P. Keller, *J. Phys.* (France), **36**, L-69 (1975).
2. N. A. Clark and S. T. Lagerwall, *Appl. Phys. Lett.*, **36**, 899 (1980).
3. T. Harada, M. Taguchi, K. Iwasa and M. Kai, *SID International Symposium*, Digest of Technical Papers, 8.4, pp. 131 (1985).
4. J. Budai, R. Pindak, S. C. Davey and J. W. Goodby, *J. Phys.* (France), **45**, L1053 (1984).
5. K. Ishikawa, T. Uemura, H. Takezoe and A. Fukuda, *Jpn. J. Appl. Phys.*, **23**, L666 (1984).
6. K. Ishikawa, K. Hashimoto, H. Takezoe, A. Fukuda and E. Kuze, *Jpn. J. Appl. Phys.*, **23**, L211 (1984).
7. K. Ishikawa, Y. Ouchi, T. Uemura, T. Tsuchiya, H. Takezoe and A. Fukuda, *Mol. Cryst. Liq. Cryst.*, **122**, 175 (1985).
8. Y. Ouchi, K. Ishikawa, H. Takezoe, A. Fukuda, K. Kondo, S. Era and A. Mukoh, *Jpn. J. Appl. Phys.*, **24**, Suppl. 24-2, 899 (1985).
9. M. A. Handschy, N. A. Clark and S. T. Lagerwall, *Phys. Rev. Lett.*, **51**, 471 (1983).
10. M. Glogarová and J. Pavel, *J. Phys.* (France), **45**, 142 (1984).
11. Y. Ouchi, T. Uemura, H. Takezoe and A. Fukuda, *Jpn. J. Appl. Phys.*, **24**, L235 (1985).
12. M. A. Handschy and N. A. Clark, *Ferroelectrics*, **59**, 69 (1984).
13. K. Ishikawa, T. Uemura, H. Takezoe and A. Fukuda, *Jpn. J. Appl. Phys.*, **24**, L230 (1985).
14. L. Lejček, M. Glogarová and J. Pavel, *phys. stat. sol.* (a), **82**, 47 (1984).

15. L. Lejček, *Czech. J. Phys.*, **B35**, 655 (1985).
16. Y. Ouchi, T. Uemura, H. Takezoe and A. Fukuda, *Jpn. J. Appl. Phys.*, **24**, Suppl. 24-2, 893 (1985).
17. J. Pavel, *J. Phys.* (France), **45**, 137 (1984).
18. D. W. Berreman, *J. Opt. Soc. Am.*, **62**, 502 (1972).
19. A. Sugita, H. Takezoe, Y. Ouchi, A. Fukuda, E. Kuze and N. Goto, *Jpn. J. Appl. Phys.*, **21**, 1543 (1982).
20. T. Tsuchiya, H. Takezoe and A. Fukuda, *Jpn. J. Appl. Phys.*, **25**, L27 (1986).
21. T. Singu, T. Tsuchiya, Y. Ouchi, H. Takezoe and A. Fukuda, *Jpn. J. Appl. Phys.*, **25**, L206 (1986).
22. P. G. Amaya, M. A. Handschy and N. A. Clark, *Optical Engineering*, **23**, 261 (1984).
23. L. Lejček, *Ferroelectrics*, **58**, 139 (1984).
24. M. A. Handschy and N. A. Clark, *Appl. Phys. Lett.*, **41**, 39 (1982).
25. H. Orihara and Y. Ishibashi, *Jpn. J. Appl. Phys.*, **23**, 1274 (1984).

Note added in proof: We noticed in proof that the sign of $\pm 2\pi$ twist disclinations in Figure 4 should be interchanged.