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## Liquid Crystals

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### Visible polarized light transmission spectroscopy of the electro-optic switching behaviour of surface stabilized ferroelectric liquid crystal cells

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## Visible polarized light transmission spectroscopy of the electro-optic switching behaviour of surface stabilized ferroelectric liquid crystal cells

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We present in this paper an experimental and theoretical modelling study of the switching characteristics and electro-optic behaviour of chevron surface stabilized ferroelectric liquid crystal cells with planar (low pre-tilt) and non-planar (high pre-tilt) surface conditions. The visible polarized light transmission spectra were taken of the cells with glass plates coated with films of either rubbed polymer or obliquely evaporated silicon monoxide (SiO) at various applied voltages and in various stages of switching and compared with the theoretical values calculated numerically based on our director-polarization structure model for the aforementioned cells. The results provide evidence for the origin of differences in domain shape and contrast in the switching process between planar and non-planar chevron surface stabilized ferroelectric liquid crystal cells.

### 1. Introduction

Domain switching of surface stabilized ferroelectric liquid crystal (SSFLC) cells under the application of external electric fields has been investigated experimentally and dealt with theoretically by many research groups [1-5]. The switching characteristic differences between cells with planar surfaces treatments (low surface pre-tilt), such as clean indium tin oxide or rubbed polymer and non-planar surface treatments (high surface pre-tilt), such as obliquely evaporated silicon monoxide (SiO) have been reported by different investigators [3, 6]. It was observed that in planar cells the chevron interface switches [7-9] with the characteristic boat-shaped domains produce significant contrast [2] whereas in non-planar cells this chevron interface switching produced little contrast and exhibits irregularly shaped domains [3, 6]. On the other hand in non-planar cells the surface switching produces significant contrast with the switching domains having a characteristic triangular or wedge shape [3, 6]. In this paper we provide director-polarization (*n-P*) configurations of planar and non-planar cells revealed through visible polarized light transmission spectral measurements of polymer and SiO coated SSFLC cells which provide evidence for the origin of these differences in the switching processes.

### 2. Experimental observation

Switching processes in SSFLC cells with the chevron structure show many interesting properties. The surface alignment treatment in cell preparation and the consequent director structure plays an important role in determining the switching

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characteristics. In an effort to understand this role, we have studied two kinds of cell with different surface treatments: some with rubbed polymer coating, and others with obliquely evaporated SiO coating. For those cells with an aligned polymer layer, both plates were coated with nylon buffed with a buffing wheel and the cells were assembled with the buffing direction on the two plates parallel to each other. For those cells with an aligned SiO layer, both plates were deposited with SiO at an 82° angle of incidence and the cells were assembled with the evaporation direction on the two plates parallel to each other. The ferroelectric liquid crystal material used was Chisso 1014 (Chisso petrochemical Corp.) with the phase sequence



Cells were made approximately 1  $\mu\text{m}$  thick.

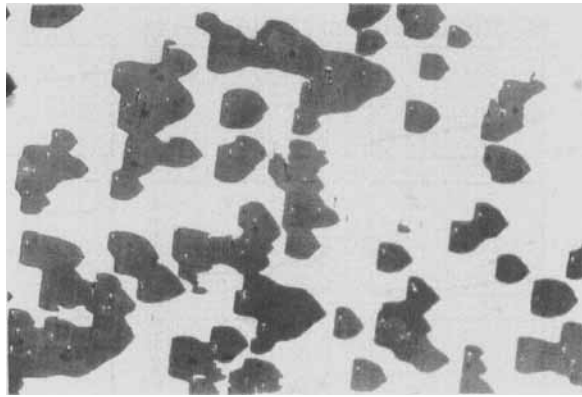
These two kinds of cell show distinctly different switching processes. The chevron interface switching in the polymer coated cell clearly gives the boat shaped domains [2] with good contrast as shown in figure 1(a) while the chevron switching in the SiO coated cell in figure 1(b) produces little contrast and exhibits random shaped switching domains. On the other hand the surface switching (liquid crystal–solid interface) switching in the SiO cell generates significant contrast with surface switching domains having a characteristic triangular shape, see figure 1(c). We could not make the liquid crystal–solid interface switch in the polymer coated cell before destroying the cell structure with high field.

Based on previous studies of polymer and SiO coated liquid crystal cells in the nematic phase [10], we know the polymer surface treatment tends to align the molecules parallel to the surface plane while an obliquely evaporated SiO coating will give a surface pre-tilt angle (the angle the molecules make with the substrate plate) of about 20°. Since the two cells were made from about the same thickness of ferroelectric liquid-crystalline material and they both form the chevron layer structure with similar layer tilt (about 18°) according to high resolution X-ray scattering results [6], the surface pre-tilt angle is the only basic difference in layer and director structure between these two cell types. To confirm this and find out how surface pre-tilt affects the switching process in SSFLC cells, we carried out visible transmission spectral measurements on these two cell types and compared them with results of numerical model calculations in order to directly monitor how the director orientation changes with applied electric field.

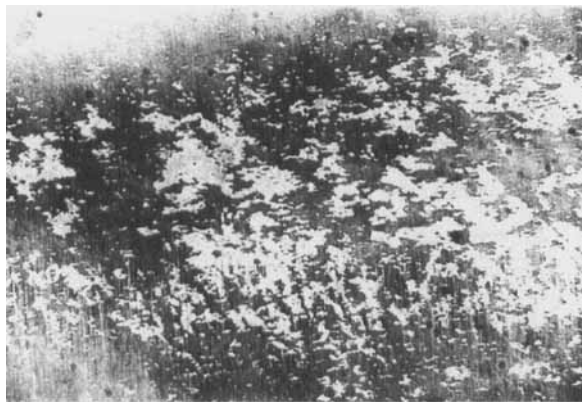
### 3. Visible polarized light transmission spectroscopy

The details of the experimental set-up for visible transmission spectroscopy and the numerical model we used in this paper to fit the experimental results have been discussed in a previous paper [8]. In our experiment the illuminating white light was incident about the normal to the cell plates with a numerical aperture NA of 0.05 through the SSFLC cell placed between crossed polarizer and analyser. The spectra were taken at different cell orientations with respect to the polarizer direction and at different switching stages. All spectra presented here were calibrated to an absolute scale, with an intensity of one being that expected for the case when polarizer and analyser are parallel to each other and along the optical axis of a uniformly oriented cell.

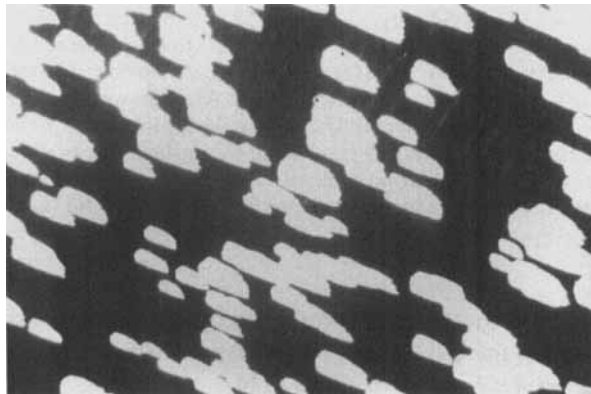
Figures 2 and 3 show the spectra for SiO and polymer coated cells, respectively. The dots in these figures represent the experimental data and the solid lines the best



(a)



(b)



(c)

Figure 1. Switching processes in SSFLC cells. The photograph shows three different switching domains seen in polymer and SiO coated cells: (a) the chevron interface transition in a polymer coated cell; (b) the chevron interface transition in a SiO coated cell; and (c) the ferroelectric liquid-crystal solid interface transition in a SiO coated cell. In the picture we can see that in the polymer cell the switching domains at the chevron interface transition have (a) high contrast and a characteristic boat shape but (b) in the SiO cell the same switching domains have very little contrast and irregular shape, while (c) the switching domains at the surface transition give significant contrast and the typical triangular (wedge) shape.

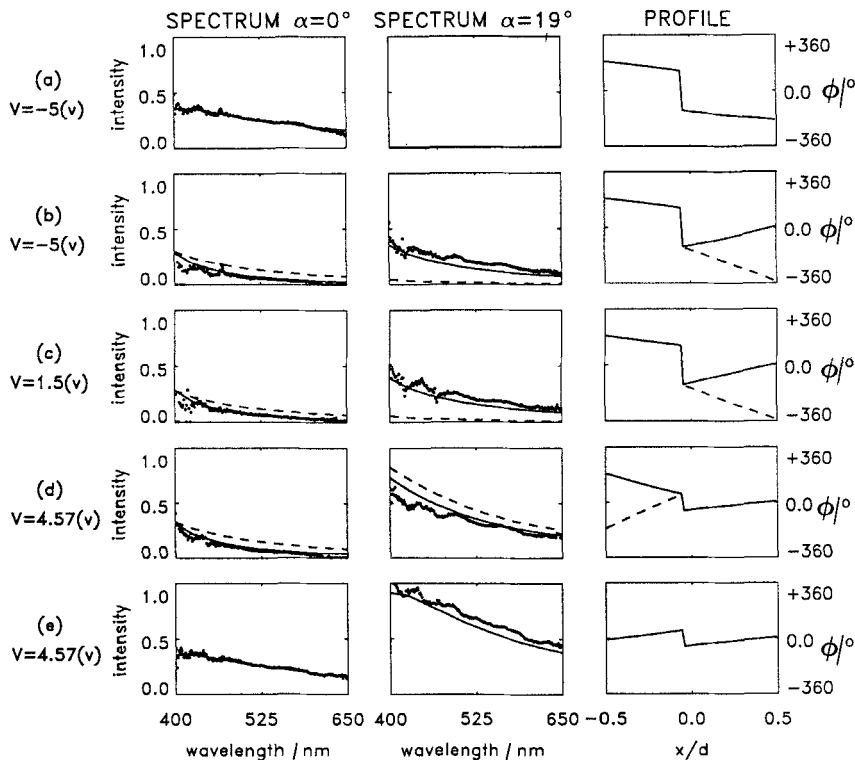


Figure 2. Visible light spectra of a SiO coated cell. The spectra of two cell orientations are shown here:  $\alpha=0^\circ$ , the LN position (see text); and  $\alpha=19^\circ$ , the position that the polarization up state is in extinction as shown in (a). The applied voltage across the cell is: (a)  $-5\text{ V}$ ; (b)  $-5\text{ V}$ ; (c)  $1.5\text{ V}$ ; (d)  $4.57\text{ V}$ ; (e)  $4.57\text{ V}$ . From the top plots to the bottom plots the cell is switching from the polarizations up state to the polarization down state through three interface transitions: (a) $\rightarrow$ (b) top surface transition; (c) $\rightarrow$ (d) chevron interface transition; (d) $\rightarrow$ (e) bottom surface transition. Also shown here are the corresponding polarization profiles inside the cell. The dots in these plots are experimental data, the solid lines are the best numerical fitting results and the dashed lines in the splayed states are the numerical results of the other possible director structures which maximized the director splay between the surface and chevron interface (see figure 4 for the pictorial polarization profiles).

numerically calculated spectra results obtained by varying the director orientation at the three interfaces of the cell. For a given chevron structure spectra were calculated using the Berreman  $4 \times 4$  matrix method [11].

For the SiO cell we took measurements at two different cell orientations: one with  $\alpha=0^\circ$ , i.e. the layer normal parallel to the polarizer direction (we shall refer to it as the layer normal position, or LN position); the other with the layer rotating away from the LN position to an angle of  $\alpha=19^\circ$ , which is the position that the polarization UP state was in extinction. Five switching stages were investigated for each of these two cell orientations to include all states involved in the switching process. In figure 2 from (a) to (e) the SiO cell was switched from the polarization UP state to the polarization DOWN state through three interface transitions: (a) $\rightarrow$ (b) top surface, (c) $\rightarrow$ (d) chevron interface, and (d) $\rightarrow$ (e) bottom surface. The surface transitions (a) $\rightarrow$ (b) and (d) $\rightarrow$ (e) are strongly

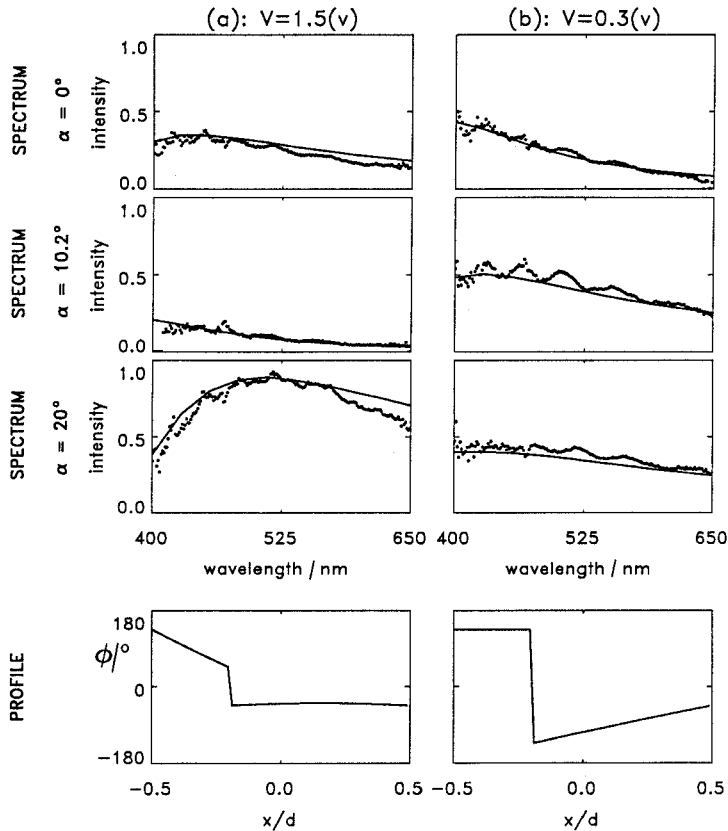


Figure 3. Visible light spectra for the polymer coated cell. Three cell orientations are shown here:  $\alpha=0^\circ$ , the LN position (see text);  $\alpha=10.2^\circ$ , the position that one of the states (down) gives best extinction; and  $\alpha=20^\circ$ . From (a) to (b) the cell is switched from the state having the polarization down at the chevron interface to that having the polarization up. The applied voltage across the cell is: (a) 1.5 V; (b) 0.3 V. The dots in the plots are experimental data and the solid lines are numerical fitting results.

first order and therefore their optical responses exhibit hysteresis. Hence, we can switch the surface by first increasing the applied voltage and then decreasing it to the pre-transitional value without switching the surface back. This procedure enabled us to compare the cell spectra before and after surface transitions at the same applied voltage. The top and bottom surface transitions occurred respectively at relatively large negative and positive voltages ( $-5$  V and  $+4.57$  V) because of polar surface interactions [12, 13]. The best fitting polarization profiles,  $\phi$  versus  $x/d$  [8, 14, 15], for these states are shown in the profile column in figure 2 as solid lines, where  $\phi$  is the angle which the polarization makes with respect to the downward  $x$  axis, and  $d$  is the cell thickness.

For the polymer cell three cell orientations were investigated:  $\alpha=0^\circ$ , the LN position;  $\alpha=10.2^\circ$ , in which one of the bistable states gave the best extinction at 1.5 V; and  $\alpha=20^\circ$ . The spectra and the best fitting results are shown in figure 3. We only took spectra at two switching stages for the polymer cell since we can only achieve chevron interface switching without alternating the layer structure: (a) half splayed down state and (b) half splayed up state.

The chevron interface switching occurred at positive voltages rather than around zero voltage for both SiO and polymer cases since the chevron interface is not centred in the cell (asymmetric chevron) [7, 9, 15, 16].

We can clearly see in these figures that when going through a surface transition, the SiO cell gives a significant spectrum change in both cell orientations when the surface was switched whereas its chevron interface transition only produces a small difference between the two spectra. In the polymer cell case, except in the LN position, the chevron interface transition produces a remarkable change in the spectrum. The small change in the LN position is expected since the two splayed states are more or less symmetric about the polarizer direction in this cell orientation [16]. When  $\alpha = 10.2^\circ$  or  $20^\circ$  the polymer case results (see figure 3) whereas  $\alpha = 19^\circ$  results in the SiO case (see figure 2); this gives an indication of the difference in contrast observed in the two cases when the chevron interface switches. For  $\alpha = 19^\circ$ , in the SiO case, there is little contrast in the chevron interface switching and this behaviour persists for essentially all cell orientations, i.e., any other values of  $\alpha$ . For the polymer case, which has a different surface interaction, significant contrast was observed for  $\alpha = 10.2^\circ$  and  $\alpha = 20^\circ$ . All these results are consistent with the microscopic observation shown in figure 1.

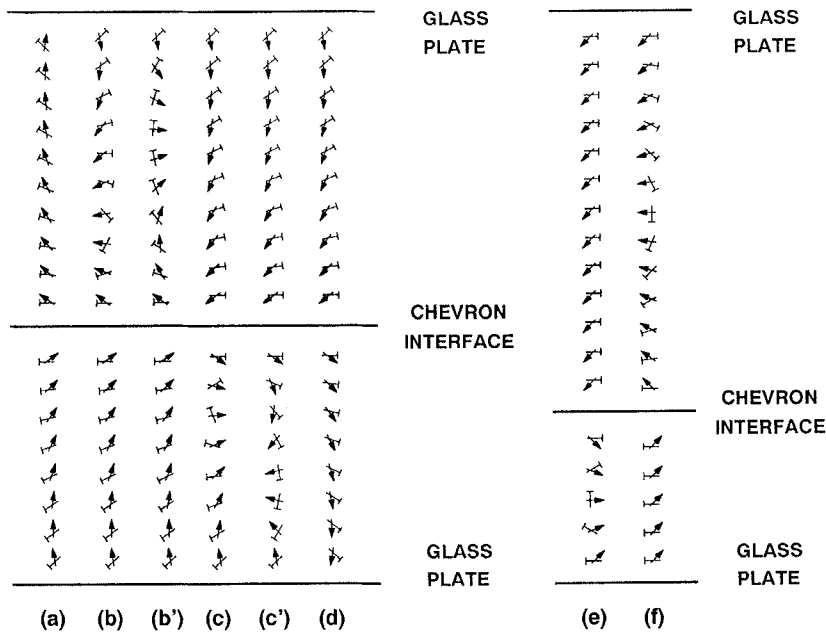


Figure 4. Pictorial representations of the various director-polarization ( $\mathbf{n}$ - $P$ ) configurations of figures 2 and 3. The chevron interface kink points out of the page and the configurations show here are projected on to the plane perpendicular to the boundary glass plates. The arrows indicate the polarization field and the line segments attached to the arrows shows the director field with a cross-bar denoting the end of the director projecting out of the page. For the SiO cell figure 4(a) corresponds to figures 2(a), 4(b) to 2(b), 4(c) to 2(d), 4(d) to 2(e), whereas for the polymer cell figure 4(e) corresponds to figure 3(a), and 4(f) to 3(b). Figures (b') and (c') are pictorial representations of the  $\mathbf{n}$ - $P$  configurations of the dashed curves in figure 2. Figure 4(b') corresponds to figure 2(b) and 4(c') to 2(d). The angle  $\phi$  shown in the profile plots in figures 2 and 3 is the angle which the polarization makes with respect to the downward axis.

The numerically fitted results were obtained by setting the director pre-tilt at the surface to be  $20^\circ$  for the SiO cell and  $0^\circ$  for the polymer cell and assuming director orientations immediately above and below the chevron interface to be parallel to the chevron interface plane [8, 9, 14, 15]. The model thickness is reasonably set as  $1\ \mu\text{m}$  for the SiO cell and  $1.3\ \mu\text{m}$  for the polymer cell.

There are two ways in which to vary the director structure in the splayed states in the SiO case due to the high surface pre-tilt arrangement as shown in the profile column of figure 2: (i) dashed lines: the splay is maximized between surface and chevron interface in the splayed part of the cell to make the average polarization direction parallel to the applied field as in cases (b) and (d); (ii) solid lines: the splay is minimized in favour of the elasticity (see the corresponding  $\mathbf{n}$ - $P$  configurations in figure 4). The corresponding spectra for these director structures are shown as dashed lines or solid lines in figure 2. The actual configuration which director will take in the cell is a result of competition between ferroelectric and elastic interactions which is characterized by  $\zeta = \sqrt{K/P_s E}$ , where  $K$  is the elastic constant,  $P_s$  is the spontaneous polarization and  $E$  is the applied field. If  $\zeta > d/4$ , where  $d$  is the cell thickness, the elastic interaction wins and vice versa. Our results show clearly that the case favoured by elasticity gives a much better fit which is consistent with our experimental conditions:  $P/K \approx 1\ \text{V}^{-1}\ \mu\text{m}^{-1}$ ;  $E \approx 5\ \text{V}/\mu\text{m}$ ; and  $d \approx 1\ \mu\text{m}$ . It is also worth mentioning that the dashed line case gives spectra which show little contrast change at the surface transition but a significant change when the chevron interface is switched; this is the opposite of experimental observation.

Figures 4(a)–(f) show the director-polarization ( $\mathbf{n}$ - $P$ ) configurations revealed through numerically fitting the data in figures 2(a)–(e) and figures 3(a) and (b), respectively. Figures 4(b') and (c') give the  $\mathbf{n}$ - $P$  configurations for the dashed lines in figures 2(b) and (d). These  $\mathbf{n}$ - $P$  configurations confirm the high surface molecular pre-tilt at the glass plate boundary in SiO cells and the low surface molecular pre-tilt at the glass plate boundary in polymer cells.

#### 4. Discussion

Figure 5 shows the three different switching processes occurring in the polymer and SiO coated cells that we discussed previously based on the polarization profiles shown in figure 4. Since the position of the chevron interface does not qualitatively change the switching characteristics for simplicity figure 5 was drawn for the symmetric chevron cases. Figures 5(a) and (b) depict the chevron interface switching processes (from up to down) in the polymer and SiO cells, respectively, and figure 5(b) shows that because of high surface pre-tilt the splayed part of the SiO cell (see the bottom half of the chevron in the figure) stays in a polarization average up state to minimize the elastic energy even when the chevron interface is switched down. This makes the chevron interface transition localized in a thin layer around the interface without associating any significant change in bulk polarization orientation, which explains the low contrast switching domains in figure 1(b). Conversely, the surface transition in the SiO cell (see figure 5(c)) and the chevron interface transition in the polymer cell (see figure 5(a)) are both associated with a change in the bulk polarization orientation in a thick region (closed by dashed lines in the figure) which is why they produce significant contrast (see figures 1(a) and (c)).

It is also worth noting in figure 5 that both the surface transition in the SiO cell and the chevron interface transition in the polymer cell have domain walls with an opposite sense of polarization splay at opposite domain sides, as shown in the region closed by



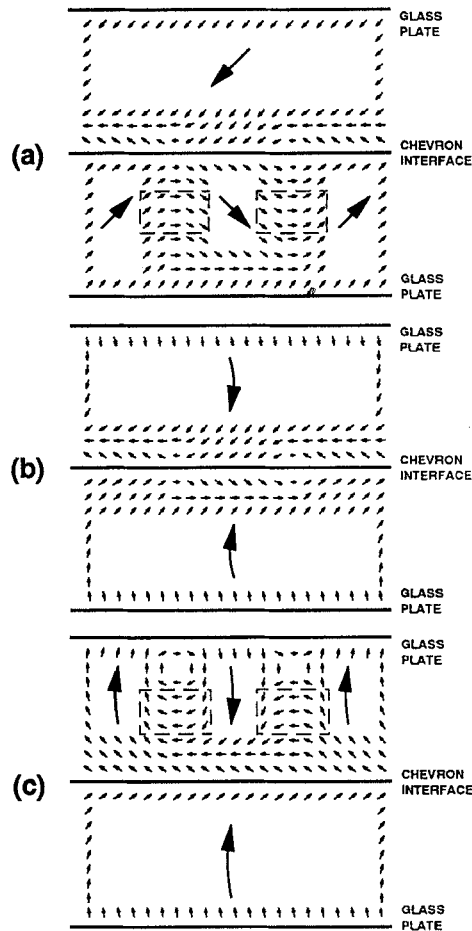


Figure 5. Polarization structures of different switching processes in SiO and polymer coated cells: (a) the chevron interface transition in a polymer coated cell; (b) the chevron interface transition in a SiO coated cell; and (c) the top surface transition in a SiO coated cell. The cells are initially in polarization up states. A down field is applied to force the polarization to reorient itself to minimize the energy. Because of high surface pre-tilt in the SiO coated cell, the chevron interface transition is localized in a thin interface layer (b), while the surface transition is associated with a change in the bulk polarization orientation in a thick region (c), as is the case with the chevron interface transition in polymer coated cells (a). (a) is reproduced from [4].

dashed lines, while the chevron transition in the SiO cell does not have this structure. This fact is consistent with the proposed model that the asymmetric shape of switching domains in the SSFLC cell is caused by the flexoelectric effect [4] rather than by  $2\pi$  wedge disclinations [2], and may explain why both surface switching in the SiO cell and the chevron interface switching in the polymer cell give regular shaped domains but the chevron interface switching in the SiO cell produces irregularly shaped domains (see figure 1). Figure 5 clearly shows that both  $+2\pi$  and  $-2\pi$  wedge disclinations exist in all three switching processes, but the shapes of their corresponding switching domains in figure 1 are quite different. This fact contradicts the model that the switching domain

asymmetry arises from the difference between  $+2\pi$  and  $-2\pi$  wedge disclinations [2]. On the other hand, according to the flexoelectric effect model, the opposite senses of polarization splay (and therefore the C director splay) at opposite domain sides as shown in figures 5 (a) and (c) generate flexoelectric vector fields with components in opposite direction along applied electric fields [4, 17]: one is coupled parallel to the applied field, the other is coupled antiparallel to the applied field. Hence one side of the domain boundary is energetically more favourable than the opposite one which results in a different growing speed of the switching domain at different growing direction. This asymmetry of growing speed of the switching domains determines their corresponding asymmetric shapes as shown in figures 1 (a) and (c), and the lack of the wall structure shown in figure 5 (b) results in its corresponding irregular switching domain shapes shown in figure 1 (b). The flexoelectric effect is weaker in the polymer case when the chevron interface is switched due to the symmetry above and below the chevron interface. In figure 5 (a) the asymmetry of polarization splay due to the existence of an external electric field is exaggerated to show this effect.

We need to point out that all the results mentioned are under the condition that the elastic interaction dominates other interactions in the cell which is true for a low polarization material like Chisso 1014 in an approximately  $1\ \mu\text{m}$  thick cell.

In conclusion we have carried out a visible light spectroscopy experiment on SiO and polymer coated cells which: (i) confirms that an obliquely evaporated SiO coating gives high surface pre-tilt in a SSFLC cell; (ii) reveals that surface pre-tilt is the origin of the contrast difference in the switching process between SiO and polymer coated cells; (iii) suggests that flexoelectricity may be the origin of asymmetric shaped switching domains in SSFLC cells.

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