The Effect of Siox Alignment Layer Thickness on the Switching of Smc* Bistable Liquid Crystal Devices

Mitya Reznikov
Kent State University - Kent Campus

Philip J. Bos
Kent State University - Kent Campus, pbos@kent.edu

Michael J. O'Callaghan

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The effect of SiO$_x$ alignment layer thickness on the switching of SmC$^*$ bistable liquid crystal devices

Mitya Reznikov,$^{1,4}$ Philip J. Bos,$^1$ and Michael J. O’Callaghan$^2$

$^1$Liquid Crystal Institute, Kent State University, Kent, Ohio 44242, USA
$^2$Displaytech, Inc., 2602 Clover Basin Drive, Longmont, Colorado 80503, USA

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SiO$_x$ alignment layers have been shown to allow defect-free SmC$^*$ devices with near optimum bistable orientation of the director. In this paper we investigate the effect of the thickness of this type of alignment layer on the required amplitude of an applied voltage pulse to cause bistable switching. The results of an experimental investigation and simple model are presented. We find that for thicker layers, the amplitude is controlled by the voltage drop across the alignment layers and by the effect of polar interactions between the liquid crystal (LC) and the alignment layers. For thin alignment layers the amplitude is weakly dependent on the details of the alignment layer, being more strongly influenced by the properties of the LC material. © 2010 American Institute of Physics. [doi:10.1063/1.3273482]

I. INTRODUCTION

In recent years low power display technologies have risen in importance due to the growth of portable electronic products. Low power, bistable, liquid crystal display devices, such as bistable twisted nematic,$^1$ bistable cholesteric texture,$^2$ and ferroelectric liquid crystal polymers,$^3$ have been demonstrated. Since the discovery of surface stabilized ferroelectric liquid crystals (SSFLCs),$^4$ bistable ferroelectric liquid crystal displays have been a promising candidate for e-paper and liquid crystal on silicon (LCoS) backplanes and for low power consumption. In this paper, we report experimental studies and a simple model of the influence of SiO$_x$ alignment layer properties on the pulse response threshold voltage of SSFLC devices.

II. THE SiO$_x$ ALIGNMENT LAYER

The alignment properties of shallow angle SiO$_x$ alignment layers are related to the columnar structure that these layers have. The main mechanism responsible for a columnar structure of SiO$_x$ films is self-shadowing: random nuclei on the substrate prevent particles in the vapor stream from reaching substrate in the geometric shadow of each nucleus. As the evaporation proceeds and the growth deposits increase in size, vacant regions are left in the film and individual columns create a two-dimensional array on the surface. The Brett group at the University of Alberta has used simulation software GROFILMS to demonstrate the growth of obliquely evaporated films as an effect self-shadowing and surface diffusion, showing excellent agreement with the experimentally obtained images of such films.$^7$ Earlier, Monkade et al.$^8$ used transmission electron microscopy to explore the cross section of the SiO$_x$ film and show dependence of deposition parameters on the surface topography.

We used scanning electron microscope (SEM) images to quantitatively estimate the morphology of our obliquely evaporated SiO$_x$ films, which affects properties of liquid crystal cell that is aligned by this film. In our experiments, we studied the SiO$_x$ film evaporated in the neighborhood of 5°. Details of this experiment and obtained SEM images can be found in Ref. 9 that will be published soon. These images were used to estimate geometrical parameters of the SiO$_x$ structure: column height (h), thickness (d), column tilt angle (γ), and distance between shadowed regions (D). For the evaporation angle of 5° and detector reading of film thickness of 1000 Å (typically the most frequently used SiO$_x$ films), we obtained the following values of these parameters: $a \sim 30$ nm, $\gamma \sim 45°$, $d \sim 300$ nm, and $h \sim 50$ nm [Fig. 1(a)]. For thicker films used for SEM imaging, the typical column height was $\sim 400-600$ nm.

We compared our estimates with the results of computer simulations of the University of Alberta group.$^7$ This simulation was made for deposition parameters that are very similar to ours (4° evaporation angle) and has good agreement

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Author to whom correspondence should be addressed. Electronic mail: mitya22@gmail.com.
with our data, except for the tilt angle of the columns (simulation result 27° versus 45° estimated by us from the SEM images). This model for the SiO$_x$ films suggests that thin films (<10 nm) consist of small hills rather than columns [Fig. 1(b)], leaving large areas of exposed indium tin oxide surface. The obtained results can help better understand the specific properties of highly topographical 5° SiO$_x$ films. As suggested by Monkade et al., the morphology of the film could lead to a decrease in nematic liquid crystal order parameter in the close vicinity of the surface (surface melting). Melting of smectic phase at the rough surfaces is studied less, although it was shown that in many cases, effective decrease in smectic ordering occurs at the rough surfaces and in the confined geometries. In particular, Durand predicted a decrease in surface order for strong surface disorientation and discussed roughness-induced surface transitions. This allows us to suggest for the smectic phase in the close vicinity of very rough surface the possibility of a strong decrease (or elimination) in the smectic order parameter and a decrease in the nematic order parameter. This effect could lead to a low anchoring energy of the surface director on a SiO$_x$ alignment layer.

Another question that better understanding of SiO$_x$ morphology allows to answer is how to estimate dielectric properties of the SiO$_x$ film which, except being an alignment layer, serves as a voltage divider, affecting the threshold voltage of the device. Typically the capacitance of the alignment layer is calculated using standard expression for the capacitance of the dielectric:

$$C = \varepsilon_0 \varepsilon A / d,$$

where $\varepsilon_0$ is the vacuum permittivity and $\varepsilon$ is the permittivity of the dielectric of area $A$ and thickness $d$. For porous dielectric material of a capacitor, one may assume some effective value of dielectric permittivity $\varepsilon$ that is estimated knowing the dielectric permittivity of SiO$_x$ and the liquid crystal and distribution of the substrate’s surface area among them.

III. EXPERIMENT

A. Substrate preparation and cell assembly

For each cell, substrates were thoroughly cleaned and alignment layers were deposited. An UV-sensitive glue (Norland 68) was dispensed onto one of the substrates using an automated XY dispenser. The cell gap was controlled by 1.2 μm spacers that were sprayed over both substrates and also mixed in the glue (5 wt % concentration). Then two substrates were put together so that SiO$_x$ deposition directions on both substrates were parallel. After that, cells were placed on the vacuum plate, pressed down with the plastic film, and cured by UV irradiation for 7 min.

When cells were assembled, their reflection spectrum was measured prior to filling. Modeling software utilizing the Berreman method was used to calculate the cell gap. The typical measured cell gap was ~1.2–1.3 μm. Cells were filled in the vacuum chamber with FLC Felix 019/000 ($P_s \approx 9$ nC/cm$^2$) (Ref. 16) in the isotropic phase and then slowly cooled to the SmC$^+$ phase.

B. Measurements of the pulse response threshold voltage using bipolar waveform

To measure the electro-optical response, we applied a bipolar waveform to the cell’s electrodes. The cell is placed in the polarizing microscope between crossed polarizers. On the top of the microscope, we place a camera for taking texture pictures or photodiode to register the light signal. The result of the measurement is the optical response of the FLC cell to the applied waveform.

The typical electro-optical response of the bistable SS-FLC cell is shown in Fig. 2. Here the electro-optical response is plotted along with the applied bipolar pulse waveform (pulse width was 1 ms). We find the pulse response threshold voltage from the condition of saturation of the response, which corresponds to full latching of the director and maximum memory angle. In the example electro-optical response, the pulse response threshold voltage corresponds to

![Diagram](image-url)
the solid line on the response curve \(V=10.5\) V. The electro-optical response curves for lower applied voltages \(V=9.5\) and 10 V correspond to cases of partial latching. Microscopic observations of the FLC textures during switching at these voltages have shown that the FLC texture is not fully uniform, but consists of many small domains. Some of the domains are latched, and some are not, which reduces the overall electro-optical effect, turning the FLC texture grayish instead of black or white. We connect this to the nonideal uniformity of the SiO\(_x\) surface.

We have studied the effect of angle of deposition and film thickness of SiO\(_x\) on the threshold voltage. The range of tested deposition angles was 2°–8.5°, and the thickness range was 5–180 nm. Figure 3 shows the measured threshold voltage as function of the film thickness for various deposition angles. For most of the cells we measured the pretilt angle of the thick \((20\ \mu\text{m})\) antiparallel cell with equivalent alignment layers filled with nematic liquid crystal 5CB. The magnetic null method\(^{17}\) was used for measurements; the measured values of pretilt are denoted in the plots in Fig. 3.

The pretilt angle does not depend drastically on the thickness of the SiO\(_x\) layer in the wide range of layer thicknesses but decreases quickly if SiO\(_x\) becomes very thin (<50 Å). Values of pretilt lower than 15° lead to the decrease in the memory angle and to the possibility of the C2 chevron formation in the cell, which results in the appearance of zigzag defects that cause poor texture quality and

![Figure 3](https://example.com/figure3.png)

**FIG. 3.** Characteristic dependence of threshold voltage on the thickness of SiO\(_x\) alignment layers for different deposition angles: (a) 2°, (b) 3°, (c) 4°, (d) 5°, (e) 6.5°, and (f) 8.5°. Numbers shown next to data points are measured nematic pretilt angles.
light leakage. We found that good alignment quality and bistability are only achievable for the SiO$_x$ layers thicker than approximately 50 Å.

We noticed that the tendency for the appearance of twist states in the SSFLC strongly depended on the thickness of SiO$_x$, and it is known that FLCs have a polar interaction with SiO$_x$ surfaces. In order to have better understanding about the effect of polar interaction on the switching behavior, we studied uniform and twist states of our cells in more detail. It is well known that the SSFLC cell with a chevron structure effectively has three boundaries (two solid surfaces and chevron interface). During switching, the director can switch on any of these surfaces. Optically surface and chevron switching look different between crossed polarizers due to the shapes of switching domains and the colors of the FLC texture.

At zero field states, before any voltage is applied to the cell since it has been cooled to the SmC* phase from the isotropic phase, stable configurations of the SSFLC cells depended on the thickness of the SiO$_x$ aligning layer. Figure 4 shows micrographs of the FLC texture between crossed polarizers for various thicknesses of the SiO$_x$ alignment layer. For thin SiO$_x$ layers (<25 nm), a uniform structure consisting of black and white domains is stable [Fig. 4(a)]. For thick cells (>100 nm), the twisted structure that has a bluish color is stable [Fig. 4(c)]. For intermediate thicknesses both uniform and twisted structures coexist in the cell [Fig. 4(b)].

To understand the character of all switching transitions that we observe in our SiO$_x$ cells (either it is surface or chevron), we started out by looking at switching by slow triangular waveform ($f=0.05$ Hz) to look at domain shape and texture color as a function of the SiO$_x$ layer thickness (polarizers are aligned along one of the memory states). Diagrams of these transitions are shown in Fig. 5 as the examples of three particular cells. Figure 5(a) shows transitions for the SSFLC cell with the SiO$_x$ aligning film evaporated at 5° and 20 nm thick; Fig. 5(b), 6.5° and 90 nm thick; and Fig. 5(c), 6.5° and 180 nm thick. Dots on the waveform correspond to the transition points between two uniform states “UP” and “DOWN,” and twist state if it is observed.

For thin SiO$_x$ layers [<25 nm, Fig. 5(a)], no twisted structure ever appears in the cell. Applying a triangular waveform leads to the following transitions: UNIFORM UP (bright) $\rightarrow$ TWISTED (blue) $\rightarrow$ UNIFORM DOWN (dark).

For intermediate SiO$_x$ layers [>25 nm, Fig. 5(b)], the twist structure is initially present in the cell, but after switching the cell to the uniform state, it stays uniform.

Applying a triangular waveform leads to the following transitions: UNIFORM UP (bright) $\rightarrow$ TWISTED (blue) $\rightarrow$ UNIFORM DOWN (dark).

For thick SiO$_x$ layers [>100 nm, Fig. 5(c)], the twisted state is stable and even though the FLC director latches on the surfaces, after turning the field off, it slowly (within seconds) goes back to twist structure. Applying a triangular waveform leads to the following order of structures in the cell: UNIFORM UP (bright) $\rightarrow$ TWISTED (blue) $\rightarrow$ UNIFORM DARK (dark).

These observations show that for thicker alignment layers the effects of a polar surface interaction are important, and the definition of the pulse response threshold voltage needs to take into account the transitions between twist states. The twist states are known to form in the SSFLC under influence of polar or dipole-dipole interactions between FLC molecules and surfaces. Uniform states of the SSFLC (when dipole moments of the molecules point to the same direction on both surfaces) are energetically favorable.
if only smectic elasticity is considered. Polar surfaces make vector of spontaneous polarization $\mathbf{P}_s$ point into (or out from) the surface on both substrates, leading to splayed configuration of $\mathbf{P}_s$ throughout cell’s thickness and twisted director configuration. Twisted structures for typical SSFLC cell gaps have bluish color if the cell is between crossed polarizers.

As SSFLC can switch on both solid surfaces and on chevron interface, it is useful to understand what kind of switching takes place at the given transition (among the ones shown in Fig. 5). Usually two types of cells are distinguished from the point of view of surface versus chevron switching: low-pretilt polyimide (PI) cell and high-pretilt SiO cells. Clark and Reiker et al. demonstrated how chevron and surface transitions are characterized by movement of domains in the direction of the smectic layers. The appearance of the domains is different for these two types of cells. For low-pretilt and high anchoring cells (usually with PI as an alignment layer), chevron switching occurs with lower voltages characterized by high contrast and distinctive smooth boat-shaped domains. At higher voltages, FLC-solid interface transition occurs via surface domains which are more irregular in shapes. For high-pretilt and low anchoring cells (usually with SiO as an alignment layer), low-voltage chevron switching occurs via irregularly shaped domains characterized by low contrast, while high contrast surface switching occurs via smoother domains with shoe-resembling shape.

In Ref. 9, we demonstrate the results of our computer simulation that describes the optical effect of the surface and the chevron switching for the high-pretilt cell. These results reach the same conclusion that in high-pretilt cells all high contrast transitions are surface transitions. They can be transition between two uniform states [Fig. 6(a), corresponding to both dots in the transition diagram shown in Fig. 5(a)] or between uniform and twisted states [Fig. 6(b), corresponding to the dots close to the zero voltage in the diagram in Fig. 5(b)]. On the other hand, chevron interface transitions are characterized by very low contrast. They can be transitions between two twisted states [Fig. 6(c)] or between two states, one of which is uniform and the other is uniform with switched chevron interface [Fig. 6(d)]. In Fig. 6(d), both the latter kind of transition (corresponding to the low contrast gray areas) and surface transition between two uniform states (high contrast black areas) can be seen. All the transitions that are denoted with the dots in Fig. 5 are the surface transitions.

A little more ambiguous question is the shape of domains. For the cells with thin SiO$_x$ shapes of the domains are typical for the surface transitions in high-pretilt SiO cells [Fig. 6(a)]. However, for cells with thick SiO$_x$ aligning film, we observed two slightly different types of domains at two different transitions: from uniform to twist [Fig. 7(a), corresponding, for example, to the lower dot on the left in the diagram in Fig. 5(c)] and from twist to uniform [Fig. 7(b), corresponding to the next dot in the same diagram]. The first type of domains is smoother, which is typical for surface transitions; the second one has a rougher shape, resembling chevron transitions (it is still surface transition because of its high contrast). Our hypothesis is that at the second transition, chevron and surface are switched virtually simultaneously, and surface switching is “led” by chevron switching, thus affecting the shape of the domains.

With the above considerations, we measured the dependence of threshold voltages of different transitions (e.g., uniform to twisted, twisted to uniform, and uniform to uniform) on SiO$_x$ thickness (Fig. 8). For this measurement, the waveform applied to the cell was chosen in such way so before testing pulse (1 ms wide) was applied, a large pulse of the opposite polarity had fully switched SSFLC. This allowed to make sure that all the transitions start from the same uniform state (dark state for the polarizer configuration used in the experiment). These two pulses were accompanied by the equivalent pulses of the opposite polarities to avoid the accumulation of the ion double layers on the surface. The pulse response threshold voltage corresponds to the value of the applied voltage when 50% of the viewing area has switched (unlike 100% switching in the measurements shown in Figs. 2 and 3). One can see that for the cells with thin SiO$_x$ aligning layers due to the absence of twist states, only one kind of transition is observed (dark state to the bright state). For thicker alignment layers, one can see two transitions (dark state to the twist state and twist state to the bright state).
threshold voltage. The evaporation angle for the films thinner than 500 Å was 5° and for the other films was 6.5°.

For these measurements, both SiO₃ cells with evaporation angles of 5° and 6.5° were used. This is related to the slight change in the measurement of the evaporation angle after the data for the part of the cells were taken. From the results shown in Fig. 3, one can see that such small change in the evaporation angle does not change the properties of the cell and does not considerably affect the pulse response threshold voltage.

IV. INTERPRETATION OF SWITCHING BEHAVIOR AND THRESHOLD MEASUREMENTS

Observations presented in Sec. III show domain switching in response to slowly varying voltages (0.05 Hz). This clearly indicates the presence of bistable surface anchoring energies responsible for the cell’s bistability. The conductivity due to the presence of ionic contaminants (not measured here) can be an important factor in switching behavior at these low frequencies, so the observed threshold voltages are probably upper limits for the cell’s intrinsic thresholds that would be seen in the absence of ions.

Bistability threshold measurements made at higher drive frequencies (e.g., 1 ms bipolar pulses and 40 ms period) should be less affected by ions but, as explained here, they can be strongly influenced by dynamical effects. Dynamical effects contribute to producing an effective threshold of which low frequency surface switching threshold is only a part.

We can see from Fig. 8 that the threshold voltage versus SiO₃ thickness has two characteristic features. One are the two distinct threshold voltages (for thicker SiO₃ layers) related to the existence of twist states, and the other is the general decrease in threshold voltage with thickness. The first characteristic is evidence of the importance of polar interactions for thicker SiO₃ layers that do not appear to be manifested for thinner layers. The other, approximately linear dependence of the lower threshold voltage with thickness, can be qualitatively explained by the effect of the voltage drop across the SiO₃ layer.

It is clear that if a low threshold voltage is desired, that thinner values of SiO₃ are needed from the viewpoint of a lowered polar surface interaction and also from the viewpoint of a lower voltage drop across the SiO₃ layer. However, we need an explanation for the nonzero value of the threshold voltage at an extrapolated zero thickness of the alignment layer.

To understand the origin of this limiting value, we can consider the observed threshold voltage for bistable switching to arise from four mechanisms. First, consider the effect of alignment layers while the drive pulse is present. For simplicity, we will examine the case of a uniform director distribution with no chevron or surface interactions (bookshelf smectic layers). This is the case treated in the simple model of electrostatically controlled V-shaped thresholdless switching. The minimum voltage needed to fully switch the FLC cell is equal to $2A/P_S \approx 2d_A P_S / \epsilon_A$, where $A$ is the cell area, $C_A$ is the alignment layer capacitance, $d_A$ is the thickness of the alignment layer, $\epsilon_A$ is the alignment layer’s dielectric constant, and $P_S$ is the FLC’s spontaneous polarization. For example, in a case considered here $P_S = 8.3$ nC/cm$^2$, $d_A = 20$ nm, and $\epsilon_A = 4\epsilon_0$, so we have $V_{\text{min}} = 0.1$ V. This is much smaller than measured thresholds, so we conclude that this mechanism makes a negligible contribution unless much thicker alignment layers are used.

Second, consider the role of dynamics, i.e., how long it takes to switch the FLC for a given electric field $E_F$. For the above simple case of a uniform director field and no surface or chevron influences, it can be shown that the relationship between applied electric field and switching time $t$ is

$$E_{\text{rel}} = 2\frac{\eta}{P_S} \ln \left( \frac{2}{\phi_0} \right),$$

where $\eta$ is the Goldstone mode viscosity, the dipole switches between $\phi = \phi_0$ and $\phi = 180° - \phi_0$ ($\phi = 0$ has the dipole parallel to the applied field), and $t$ is the time that it takes to rotate the dipole from the initial position $\phi_0$ to the final position $(180° - \phi_0)$. For the FLC used here we have $\eta = 37$ mPa s, $d_f = 1.2$ μm, and other parameters set as above. Figure 9 shows curves of $t$ versus $V_F$ for values of $\phi_0$ ranging from 0.01° to 10°.

Before using the curves of Fig. 9 we need to take into account a third mechanism affecting bistable switching. Con-
sider the voltage remaining across the FLC layer with the cell voltage set to zero. The magnitude of the “reverse switching voltage” can be shown to be $V_R = \frac{AP_2}{(C_A/2 + C_F)} = P_2/(0.5\varepsilon_\lambda/\lambda d_\lambda + \varepsilon_F/\lambda d_F)$ which, for the same parameters as above, yields $V_R \sim 0.09$, driving “droop” of the so-called memory state. This voltage is known to work against achieving the bistability.22 If this value of $V_R$ were held constant, we would expect the dipole to switch completely to the opposite memory state in about 56 ms (assuming that $\phi_0 = 1^\circ$). However, the voltage felt by the FLC layer will drop as the dipole rotates, causing $\phi$ to asymptotically approach $90^\circ$. This is just what happens in thresholdless V-shaped switching.

If we require the FLC to remain more or less fully switched for up to 20 ms with 0 V applied to the FLC cell and an internal 0.09 V “reverse” switching voltage across the FLC layer (the criterion used to define the bistable switching in the measurements) and assume that the fully switched dipole orientation should be less than $1^\circ$, then Fig. 9 implies that a minimum pulse amplitude of 5 V and a width of 1 ms (the pulse width used for threshold measurements) is required for full switching of the cell to the opposite state.

The role of dynamics in bistable switching of FLC was also studied before6 by measuring dependence of the threshold voltage on the pulse width for the similar FLC on SiO₂ (Fig. 4 in Ref. 6). The obtained curve that asymptotically drops to a certain value of threshold voltage suggests that the switching behavior is dominated by dynamics and is relatively unaffected by threshold effects that would become apparent under different conditions.

The fourth mechanism important for bistable switching is of course the presence of a bistable surface anchoring energy (responsible for the domain switching observed with the low frequency triangle drive waveform). However, the above analysis implies that in the cells with thin SiO₂ layers, the surface anchoring energy is so small that the threshold voltage inferred from the FLC cell’s response to 1 ms pulses is likely dominated by dynamics and not by the voltage needed to switch the FLC at the cell’s surfaces.

Of course, instead of being in a bookshelf configuration as in the above discussion, the smectic layers of real cells will be in the chevron configuration which will affect details of how switching occurs. Nevertheless, general conclusions regarding the relative importance of dynamics, anchoring energy, and voltage drops across the alignment layers should still be valid. How far a real cell deviates from the simplified bookshelf model will depend on the chevron energy, the difference between chevron angle and FLC tilt angle, and of course on details of the surface anchoring energy. A low chevron energy coupled with a chevron angle many degrees less than the tilt angle might be expected to behave very bookshelf-like, whereas if the chevron and tilt angles are nearly equal and with high chevron energy, the surface anchoring will play a much more important role because it has to counteract the tendency of the chevron to “unswitch” the cell surfaces. Although potentially significant, these details are beyond the scope of this investigation.

V. CONCLUSION

In conclusion, we have studied the effect of deposition parameters of obliquely evaporated SiO₂ on the threshold voltage of bistable SSFLC display devices. The lowest values of threshold voltage (~4 V) were obtained for thin SiO₂ films (~5 nm). An increase in threshold voltage with an increase in SiO₂ thickness is mostly related to the voltage drop on the SiO₂ film that acts as a voltage divider and to polar dipole-dipole interactions between surface and FLC molecules, which increase with the thickening of the SiO₂ film. However, for thin SiO₂ aligning layers, as effects of the voltage divider and polar interaction are strongly reduced, we have shown that the pulse response threshold voltage is primarily controlled by the material properties of the liquid crystal.

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